

Cave and Karst Science

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Tiankengs: Special Issue

Cave and Karst Science

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Scientific papers, normally up to 6,000 words, on any aspect of karst/speleological science, including archaeology, biology, chemistry, conservation, geology, geomorphology, history, hydrology and physics. Manuscript papers should be of a high standard, and will be subject to peer review by two referees.

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Cave and Karst Science

TRANSACTIONS OF THE BRITISH CAVE RESEARCH ASSOCIATION

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Cover photo:

Huangjing Tiankeng, in the Leye karst of Guangxi, China. With vertical walls over 120 m high round its entire perimeter, this is a splendid example of the type of giant collapse doline that is best known as a tiankeng - a new word that enters karst literature straight from its Chinese origins.

Photograph by Tony Waltham.

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Tony Waltham

Tiankengs are huge collapse dolines that are among the most spectacular of karst landforms. They have been late to enter the karst lexicon because most of them have only recently been "discovered" by karst geologists in the remoter parts of China's vast landscapes of limestone. The "arrival" of tiankengs has been a by-product of the current explosive development of China's economy and infrastructure - only recently have these great karst landforms become accessible. They now go under their name in Chinese - *tiankeng*, which loosely translates as *sky hole*.

Since the mid-1980s, a few giant shafts have been explored by British and French cavers working within China, and the megadolines of the Nakanai karst in New Guinea had found by other French cavers. Inside China, explorations were co-ordinated by Prof Zhu Xuewen and his team at the Institute of Karst Geology in Guilin, and the later discoveries (of the largest of the tiankengs) prompted them to recognise the tiankeng as a distinctive karst landform. The various Chinese sites, and a smaller number in other countries around the world, were embraced by the concept of the tiankeng, and this was then accepted within China.

To take the tiankeng concept to the outside world, Prof Zhu and his team organised the Tiankeng Investigation Project in 2005 when an international group of delegates visited some of the key sites in China and then produced the documentation that forms this issue of *Cave and Karst Science*.

The tour of the tiankengs that Zhu Xuewen organised was a serious contender for the title of the world's best-ever karst field trip. Delegates saw an incredible suite of truly spectacular tiankengs, visited some fabulous caves and traversed some of the world's most magnificent karst terrains. With banquets every evening, and excellent hotel accommodation, this was hardly a normal geological field trip. Many evenings also included structured meetings with officials from local government, when the foreign delegates presented informal oral reports on the sites visited that day. This provided some of the essential feedback to the local hosts, as they greatly valued international input to their plans for expanding karst geotourism, which is of considerable economic significance in the rural areas where mountainous karst terrains hamper agricultural development.

A prime outcome from the 2005 Project was intended to be this publication - which would bring tiankengs to the attention of the wider international community of karst geoscientists. This issue of *Cave and Karst Science* opens with three papers that review the tiankeng tour, summarise the research on tiankengs within China, and then overview tiankengs outside China. A fourth paper collates data and opinions in order to provide a more formal description and definition of the tiankeng as a karst landform. The eight following papers were prepared by the foreign delegates, each exploring some aspect of tiankengs both inside and outside China. The first four papers may be regarded as consensus opinions of the members of the 2005 Project (listed in the first paper), while the following eight are the opinions of their own authors.

All twelve papers are being simultaneously published in Chinese in *Carsologica Sinica* (Volume 25, 2006), and will then appear in *Speleogenesis* (Volume 4, Issue 2), the virtual scientific journal at www.speleogenesis.info.

Prof. Zhu hosted his magnificent field trip and subsequent meeting in order to spread the word on tiankengs. He did this in the grandest style imaginable. Delegates returned home from the event with a new understanding of the great importance of China's karst and especially its tiankengs.

Footnote on references to Chinese authors

It should be noted that Chinese names are written with the family name first, followed by the given name. Therefore a citation of *Zhu Xuewen*, should be *Zhu X.*, and should not be *Xuewen, Z.* No comma is needed after *Zhu*, as the name has not been reversed. Because so many Chinese family names are very common, it is normal in Chinese scientific literature to cite the complete name, as *Zhu Xuewen*, but it should be noted that this is still indexed under *Z* and not under *X*. Some Chinese academics working outside their home country have westernised their names, so that they appear in the form of *Xuewen Zhu*; this could lead to confusion in indexing, but is commonly resolved because all Chinese family names are a single syllable, while most (but not all) given names are two syllables.

The 2005 Tiankeng Investigation Project in China

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Abstract: A summary report of the Tiankeng Investigation Project, hosted by Prof. Zhu Xuwen in China in 2005. This included an extremely successful field tour to tiankengs (giant collapse dolines) in the karst of Chongqing and Guangxi, and an indoor meeting in the Karst Research Institute in Guilin when the definition of a tiankeng was formalised.

Key words: tiankeng, karst, doline, China

(Received: November 2005)

Since 1992, a small number of giant collapse dolines have been found in various parts of the limestone karst in southern China. These are very large and truly spectacular landforms (measuring hundreds of metres deep and wide), and they are now recognised in China under the name *tiankeng*.

Tiankengs have only recently been recognised in China because they have only recently been seen by karst geomorphologists. They all occur in remote parts of the highland fengcong karst that were, quite simply, not visited by outsiders in previous years. But China's current explosive development has provided roads that reach close to most of the tiankengs, and their absence from the karst literature is now being remedied. There is also huge local enthusiasm to increase the tourism economy by creating access to any spectacular landscape features, and many of the tiankengs are now star attractions within national, provincial and local parks and geoparks. Consultancy on these new developments has been through Prof. Zhu Xuwen and Chen Weihai, leaders of the speleology team at the Institute of Karst Geology in Guilin, who have therefore visited all the sites in a protracted programme of field research.

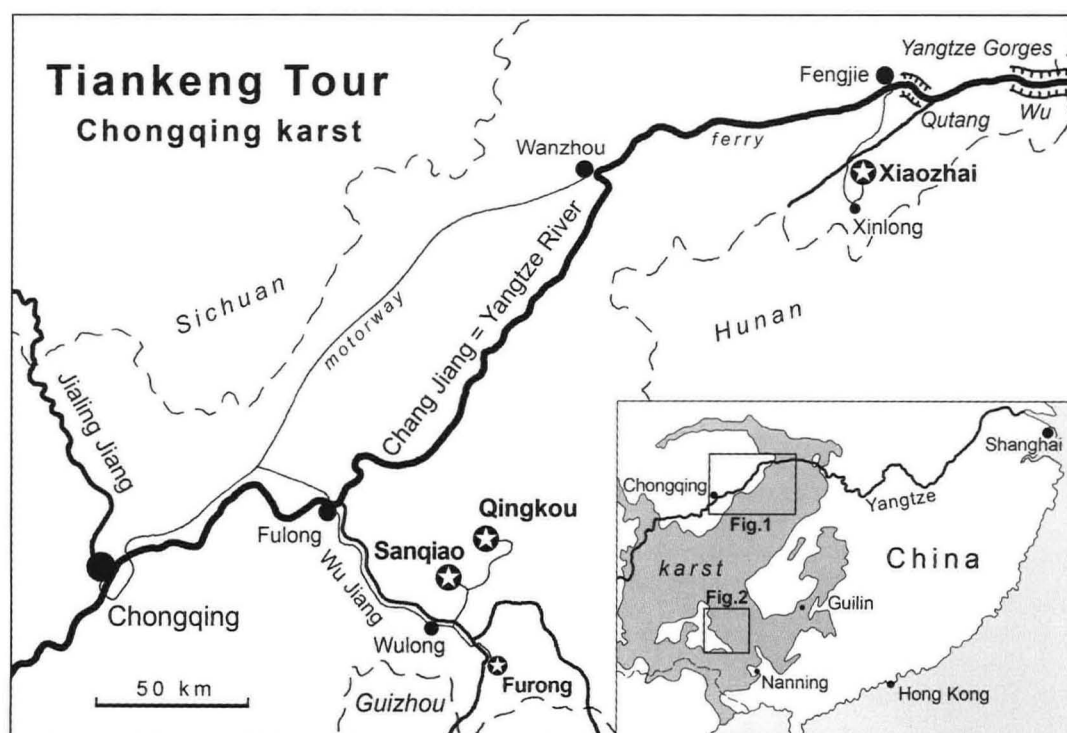
Though the Institute team had published various papers and books in Chinese, Prof. Zhu was concerned that tiankengs were still little known outside China. Almost the only foreigners to have seen the Chinese tiankengs were cavers (largely on the China Caves Project), who had made just passing reference to a few of the sites. Scientists had visited almost none of China's tiankengs, and there

was minimal published comparison with the scatter of giant collapse dolines elsewhere in the world, notably those in the Nakanai karst of Papua New Guinea. Prof. Zhu therefore instigated progress in 2005 by creating the Tiankeng Investigation Project, whereby a group of foreign cave scientists could see the finest of the Chinese tiankengs and then discuss their geomorphology in a wider context.

The 2005 event was in two halves. A magnificent field excursion visited China's most important tiankengs and passed through some of the world's finest karst landscapes. This was followed by a conference in Guilin when the geomorphology and hydrogeology of tiankengs were fully discussed in an international context.

The delegates invited to the 2005 Project were - Art and Peggy Palmer from the State University of New York (USA), Will and Beth White from Pennsylvania State University (USA), Andrej and Marija Kranjc from the Karst Research Institute (Slovenia), Alexander Klimchouk from the Institute of Geological Sciences (Ukraine), Julia James from the University of Sydney (Australia), John Gunn from Huddersfield University (UK), Andy and Lilian Eavis from the International Union of Speleology and the China Caves Project (UK), and Tony and Jan Waltham from Nottingham Trent University (UK). They were joined and hosted in China by Zhu Xuwen, Chen Weihai and Liu Zaihua. It had been hoped that Paul Williams, Derek Ford and Claude Mouret could join the Project to represent their own countries, but personal circumstances precluded their participation.

Figure 1. Route of the tiankeng tour through Chongqing.



THE TIANKENG TOUR

The Tiankeng Project in 2005 started with a field tour to visit and investigate some of the largest and finest of the tiankengs in China's limestone karst. Delegates converged on the city of Chongqing on Tuesday 18th October. Unusually inclement weather then set in, with almost continuous low cloud and grey skies, until everyone departed from Guilin twelve days later. The field tour started in the karst within the province of Chongqing (which separated out of Sichuan province in 1997), before moving south into the province of Guangxi (Fig. 1). It was an incredibly spectacular field trip, which visited some of the finest karst landforms and karst landscapes that the world has to offer. Further data on the tiankengs are provided in the following paper, by Zhu & Chen, within this volume.

Tiankengs in Chongqing

On the Wednesday morning, the tour started by bus along a motorway from Chongqing to Fuling, and then south up the gorge of the Wu Jiang (Wu River) to Wulong. The first visit was to Furong Dong, an excellent tourist cave, distinguished by massive stalagmites, incredible helictites and beautiful aragonite crystals in a large, abandoned phreatic tunnel that loops up and down in the dipping limestone. The afternoon visit was to the Wulong Sanqiao (Three Bridges) National Park and Geopark. The fragmented remains of a major trunk cave system now forms a karst gorge with an underfit stream. Three natural bridges survive across the gorge and separate the two tiankengs of Qinlong and Shenying, each over 200 m across and ringed by vertical cliffs 200 m high. Between a descent into the gorge via a lift and steps, and a cable car ascent, the tourist path across the tiankeng floors and beneath the high rock bridges provides a truly spectacular walk (Fig. 2). The clean and vertical cliffs exhibit traces of the gently dipping bedding planes that were the likely sites of the initial cave development, indicating various degrees of roof collapse to leave the remnant bridges and the open tiankengs. The night was spent at the splendid Fairy Mountain Resort.

On Thursday morning, a string of 4WD cars took the group up to Houping, where the mountains were shrouded in cloud but were largely of sandstone that caps the limestone. At the end of a very muddy road, a short walk across the fields led to a cliff edge where a bamboo viewing platform had been specially built for the group's visit. It overlooked the huge Qingkou Tiankeng - which was unfortunately lost in thick cloud. A further drive on muddy tracks then took the group to a fire-cracker welcome at the tiny village in front of the entrance of Erwan Dong, part of the large cave system being mapped by the Hong Meigui Cave Exploration Society. The guides in the cave were Erin Lynch (who had taken time off from her current Hong Meigui project to join the tour for the day) and a horde of villagers (mostly without lights). Villagers and international

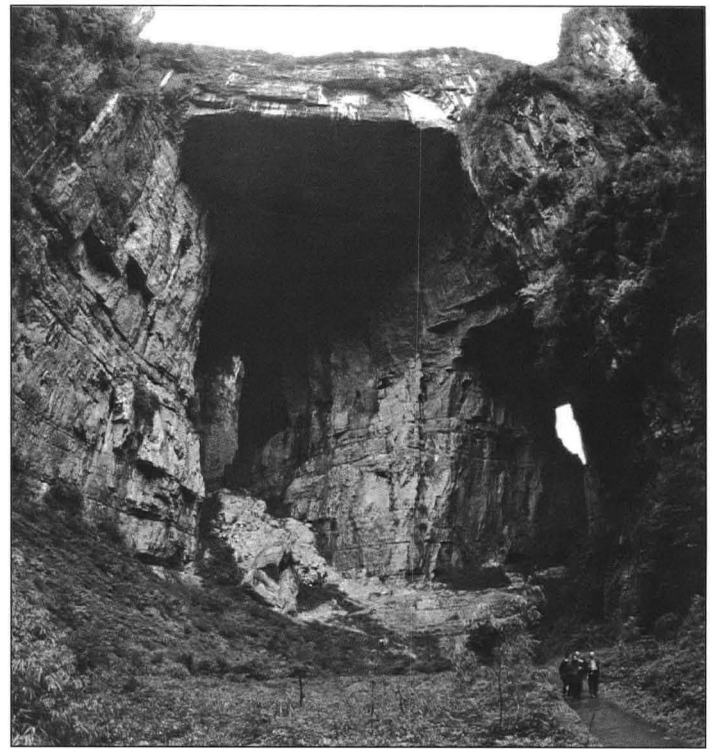


Figure 2. View along the floor of the Qinlong Tiankeng, towards the natural bridge at its western end, in the Wulong Sanqiao Park.

delegates alike traversed 3 km of old, high-level, phreatic tunnels (mostly around 10 m high and wide) to reach the foot of the Qingkou tiankeng. Waterfalls drop small streams nearly 200 m down the tiankeng walls, but their tops were lost in clouds on the day. Though Qingkou is described as an erosional tiankeng, it appears to have origins in the large trunk cave at its foot, which predates the collapse and surface breach.

The night's hotel was back in Wulong. On Friday the route doubled back to Fuling, and onto a new and empty motorway east to Wanzhou. There the group boarded an express ferry (shuifeuchuan = water-fly-boat = a Ukraine-built hydrofoil) down the Chang Jiang (Yangtze River) to Fengjie. A bus ride south into the mountains and darkness took everyone to a hotel in Xinlong.

On Saturday, the group took the new tourist road to Xiaozhai (= Little Village), which stands just above the world's finest tiankeng. Xiaozhai Tiankeng is 662 m deep from the top of the cliff faces broken into the two conical hills that have collapsed into it, and is 511 m deep from the lowest point on its rim (Fig. 3). Its upper



Figure 3. Xiaozhai Tiankeng seen from the southern rim; the path down the stone steps is obscured by trees and shrubs - it curves round to the right and descends the steep debris fan inside the lower pit.

section is 600 m in diameter. The lower section is 300 m across, with vertical cliffs over 300 m high round its entire perimeter, except where a steep fan of collapse debris is banked against its northern wall; they are scored by at least three sub-vertical faults. In the wet weather of the visit, a small river swirled from the tall canyon of the upstream cave, crossed the tiankeng floor, and cascaded into the downstream cave (explored and mapped by the China Caves Project in 1994 for 4 km to the cliff resurgence). The tiankeng now has a stone path that winds down to a viewpoint and restaurant that overlooks the lower shaft, and stone steps also zigzag down the debris fan to the floor; there are 2800 steps from rim to floor. The visit to Xiaozhai was memorable - it offers one of the most impressive karst sights in the world. The afternoon was spent in the accessible parts of the Tianjingxia (Tianjing Gorge, sometimes known as the Great Crack), around the sinks that feed drainage into Difeng Dong and thence into the base of the Xiaozhai tiankeng. It was a late return to Fengjie.

Sunday and Monday were largely spent travelling (between more splendid hotels and sociable banquet dinners). The express ferry back to Wanxian was followed by the long bus ride to Chongqing for the night. A morning flight of 750 km south to Nanning was followed by a long bus-ride north to Baise and then to Lingyun (offering distant views of fenglin then fengcong karst), before reaching Leye after dark (Fig. 4).

Tiankengs in Guangxi

On a warm and slightly brighter Tuesday morning, the group first visited the excellent Tiankeng Geopark Museum in Leye, with display material (in both Chinese and English) that largely originated from the Institute of Karst Geology. Almost behind it lies Luomei Lianhua Dong (Lotus Cave), a fine tourist cave in a passage just above the level of the Leye polje floor, normally dry though it does carry floodwater. It is notable for its many fine, circular shelfstone deposits up to 2 m across that were formed in pools (now drained) around stalagmite stumps (often known as lotus deposits in China or as lily pads in the West). From the back exit of the cave, the tour bus took the group to Chuan Dong, a truncated fragment of ancient trunk passage that was walked through from the valley side to a ledge 100 m up in one wall of the Chuandong Tiankeng. Steps to the floor revealed a breakdown-choked cave below and a large side chamber with a skylight that heralds further collapse in the future.

The tour then continued further into the spectacular Leye karst - distinguished by high fengcong cone karst, a suite of large tiankengs



Figure 4. Route of the tiankeng tour through Guangxi.

and major cave systems that are only partly explored. Leye must rank among the most extreme karst terrains in the world (*i.e.*, extremely mature without degrading into old age), yet it has only been known to the outside world since Prof Zhu was shown it in 1998. There were glimpses of rims and walls of various tiankengs, with roadside stops above the degraded Datuo Tiankeng and another at the lip of Maoqi Dong. The bus then dropped off delegates to walk around the rim of Dashiwei Tiankeng. Along with Xiaozhai this is the giant of tiankengs, 400-600 m across with unbroken, vertical perimeter walls that cut through three conical hills (and the three intervening dolines) with a maximum height of 613 m (Fig. 5). It is a fantastic sight, but perhaps not as awesome as Xiaozhai. A long section of downstream river cave lies below the edge of the breakdown pile on the tiankeng floor. The group returned to Leye after a fabulous day in fabulous karst.

Wednesday was another grey morning, for a visit to Huangjing Tiankeng. Though only 160 m deep, this is a beautiful sight, with a flat floor inside a circle of vertical perimeter cliffs over 200 m across

Figure 5. Dashiwei Tiankeng, in the Leye karst, with some scale given by the road on the right.





Figure 6. Huangjing Tiankeng, with its perimeter cliffs all over 120 m high.

(Fig. 6). The cliffs are all limestone but the tiankeng has breached the feather edge of a sandstone caprock that supports stream channels and modest allogenic inflow from the north and west. An adjacent, large, old, decorated cave passage descends steeply, and a short mined tunnel from its foot gives access to the tiankeng floor. In the past, villagers lowered pigs and deer down the cliff to graze the perfectly enclosed field on the tiankeng floor. This was the last tiankeng that was visited, and a return to Baise was made in the afternoon.

On Thursday the tour bus took the scenic route back to Guilin, via backroads linked by new sections of tourist highway that wound through the magnificent fengcong karst of Bama and Fengshan, sadly all in rather grey weather. There was a stop at Sanmenhai Dong, for a show cave boat ride through the lake chambers on the resurgence below the large abandoned passages of Mawang Dong. A second stop was for a visit to the very impressive new show cave of Yuanyang Dong, which has two large chambers adorned with numerous stalagmites 20 and 30 m tall. Impressive fengcong karst was then crossed to Donglan, before heading through darkness to Guilin. Friday was a relaxation day, with a tour of the equally magnificent fenglin karst around Yangshuo.

THE TIANKENG CONFERENCE

The Saturday was spent in indoor meetings at the Institute of Karst Geology in Guilin. In the morning, the foreign delegates each made short presentations on concepts of tiankeng development and their knowledge of tiankengs and very large dolines in other parts of the world. These are published in the following pages of this volume, each in a form abridged in the light of our new observations of the tiankengs of China. Prof Zhu's contribution on tiankengs in China was taken as read from his initial presentation in Chongqing prior to the field tour. An overview of tiankengs in foreign lands was an additional project contribution, but was prepared subsequently, and only for publication. The tiankeng session closed in the late afternoon with an open discussion on the status, definition, geomorphology and evolution of tiankengs; the conclusions of this meeting are also published in this volume.

In the early afternoon, Prof Liang Yongning (from Kunming University) made a presentation on the forthcoming application for World Heritage inscription for the South China Karst. The group currently preparing the nomination were meeting at the Institute at the same time as the tiankeng group, so some joint discussion was welcomed. The South China Karst is a serial-site WH nomination with nine elements - that include selected tiankengs at Wulong, Fengjie and Leye. The work of the WH group was applauded and supported by the delegates from the tiankeng project. Without going into details on the various sites, the delegates unanimously agreed in principle that the South China Karst was an essential element of the WH portfolio.

The intended outcome of the Tiankeng Investigation Project was to recognise, establish and define the tiankeng as a significant karst landform in an international context. It was the consensus of opinion among the foreign delegates that this had been satisfactorily achieved. The work on tiankengs by Prof Zhu and his colleagues at the Karst Research Institute should be both recognised and applauded by karst geo-scientists around the world.

ACKNOWLEDGEMENTS

The twelve days in China's karst were rendered both productive and enjoyable by the generous and almost overwhelming kindness, logistical support and hospitality from the local people. The entire Tiankeng Project team offers sincere thanks to the leaders and local governments of Chongqing, Wulong County, Fengjie County, Xinlong Town, Beise City, Leye County, Fengshan County and Hechi City, and to the staff and management of Furong Dong, Wulong Tiankeng Sanqiao National Park and Dashiwei National Geopark, and also to the hospitable local people who we encountered at every turn. In addition, the foreign delegates record their warmest thanks to Zhu Xuewen, Chen Weihai and Liu Zaihua who were magnificent hosts and ever-attentive guides throughout their stay in China, and also to the Institute of Karst Geology (at Guilin), of the Chinese Academy of Geological Sciences, for its overall support.

Tiankengs in the karst of China

ZHU Xuewen and CHEN Weihai

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Abstract: China has the most extensive and diversified karst terrains in the world and most of them are rich in caves and dolines. The cone karst (*fengcong*) and tower karst (*fenglin*) developed in the humid climate in southern China form the most distinctive karst landscapes. Tiankengs are giant dolines that are a feature in some areas of the cone karst. In recent years, more than fifty tiankengs have been discovered in the cone karst in southern China, notably in the provinces of Chongqing, Guangxi, Sichuan and Guizhou. Current research indicates that tiankengs develop in specific environments of geomorphology, geology and hydrogeology, and are therefore distinguished from normal karst dolines.

Key words: karst, doline, discovery, tiankeng, geomorphology

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INTRODUCTION

In carbonate rock terrains, one kind of negative karst landform has not previously been recorded because it is relatively rare and occurs only in more remote regions. It is the great or giant doline, with steep walls and several hundred metres in depth and diameter; it is a collapse doline distinguished by its very large size. This landform was first observed by geologists in China in the early 1980s, in the Xingwen karst in Sichuan, in an area that was being developed for tourism. It was not mentioned in the hydrogeological investigation reports throughout China in 1970s-1980s, and therefore had no scientific explanation.

In the past 20 years, many more of these great karst dolines have been discovered in southern China. Some, including Xiaozhai, Dashiwei, Qingkou and Haolong, have been found by vigorous tourism development that has been searching for spectacular features in the more remote karst areas. Others have been found during explorations by the China Caves Project, and this has led to considerable research to identify the special features of the giant dolines that distinguish them from normal, smaller, dolines.

In the world's karst literature there is extensive discussion on normal doline development, but there is little on the development of giant dolines. One exception is Crveno jezero (Red Lake) in Croatia, which was investigated in summer 1998 (Garasic, 2001), with the important discovery that there is an underground waterway through the bottom of the lake; the water is flowing, and the lake is formed in a chamber that measures 400×300×500 m; the Croatian understanding of a great collapsed doline accords with concepts held in China.

This kind of giant doline is distinguished from normal dolines by its size, and also by major differences in basic characteristics, geomorphic evolution and hydrogeological conditions. The understanding of its geomorphology and its importance matured through the 1990s. In October 2001, it was proposed that this giant doline could be distinguished from normal dolines, and a new term, *tiankeng*, was proposed for the karst literature (Zhu, 2001).

Tiankengs have also been recorded as giant dolines outside China, including Crveno jezero in Croatia, Minyé in Papua New Guinea, Garden of Eden in Malaysia, and El Sotano in Mexico.

There are two types of tiankeng - collapse tiankengs and erosion tiankengs. The former developed by dynamic underground water flow, while the latter were formed by allogenic surface drainage that fed into an underground river in the karst. Collapse tiankengs are much more widespread and more numerous than the erosional forms.

Distribution of tiankengs in China

Current records show that the tiankengs in the karst of China are mainly in the south of the country, especially in the cone karst terrain, although some lie outside this core zone. The distinctive

cone karst of southern China covers an area of about 150,000 km², mainly in northern and western Guangxi, southern Guizhou, around the Yangtze Gorges, and across southeastern Chongqing, northern Guizhou, southeastern Sichuan, western Hunan and western Hubei, as well as in southeastern Yunnan.

Relationships between tiankeng development and the intense erosional power of underground water explain the spatial relationship between tiankengs and large underground river systems, especially in cone karst areas where cave river systems are very well developed. According to the national hydrogeological investigation in China in the 1970s-1980s, there are 2836 underground rivers within Guangxi, Guizhou, Sichuan, Chongqing, Hunan, Hubei and Yunnan, with a theoretical total length of 13,919 km. It appears that a very important condition for the development of tiankengs is the development of both cone karst and major cave river systems.

The typical cone karst (peak-cluster depression, *fengcong* in Chinese) is formed in carbonate rocks that are continuous and pure over a stratigraphic thickness of more than 200-300 m, where the adjacent surface rivers are deeply entrenched, where the vadose zone is more than 100-300 m deep, and where the climate is humid and rainy. The most marked hydrogeological feature is a well-developed subterranean river system, and the lack of surface rivers. Cone karst is one of the important environments for development of collapse tiankengs, but this does not imply that tiankengs are formed in all cone karst terrains with cave river systems. Tiankeng development is restricted to sites with favourable hydrogeological conditions and favourable geological structure. The erosion tiankeng is developed by an allogenic surface river where there is a deep vadose zone in



Figure 1. Locations of tiankengs in southern China.

Tiankeng	Length x Width m	Area m ²	Depth max m	Depth min m	Volume Mm ³
<i>Xinlong karst, Fengjie, Chongqing</i>					
Xiaozhai	625 x 535	274,000	662	511	119.3
Xiaokeng	330 x 180	45,000	286	137	12.0
Chongtianyan	300 x 160	41,500	168	103	7.0
Luokuangyan	135 x 100	10,800	101	100	1.1
Wujiazhai	200 x 150	24,000	103	47	2.5
Daqinkeng	200 x 150	8,000	137	66	1.1
<i>Qingshui, Yunyang, Chongqing</i>					
Longgang	350 x 170	53,000	350	250	9.2
<i>Houping, Wulong, Chongqing</i>					
Qingkou	250 x 220	40,700	295	195	9.2
Niubizi	380 x 100	27,000	195	100	3.5
Taipingmiao	180 x 180	26,400	420	300	9.9
Daluodang	240 x 220	32,400	372	282	10.4
Shiwangdong	170 x 150	25,900	252	172	5.1
<i>Sanqiao, Wulong, Chongqing</i>					
Zhongshiyuan	565 x 555	278,200	214	75	34.8
Xiashiyuan	990 x 545	352,100	373	50	31.5
Qinlong	520 x 200	194,000	276	195	31.7
Shenyang	300 x 260	51,200	285	190	9.7
<i>Xingwen karst, Sichuan</i>					
Xiaoyanwan	625 x 475	200,000	248	178	36.0
Dayanwan	680 x 280	164,000	110	40	15.0
<i>Dashiwei group, Leye, Guangxi</i>					
Baidong	220 x 160	22,000	312	263	5.8
Chadong	400 x 350	80,500	25	165	13.3
Chuangdong	370 x 270	73,000	312	175	11.7
Dacao	300 x 140	30,000	92	56	1.3
Dalong	240 x 200	35,000	125	95	3.3
Dashiwei	600 x 420	167,000	613	511	75.0
Datuo	530 x 380	149,000	290	263	32.7
Dengjiatuo	370 x 240	128,200	278	222	26.2
Diaojing	290 x 280	86,300	170	145	12.6
Gaicao	440 x 95	24,700	120	90	2.2
Huangjing	320 x 170	51,700	161	140	6.3
Jiameng	90 x 80	8,800	271	211	1.6
Ladong	202 x 125	21,600	215	146	2.8
Laowuji	300 x 275	75,600	171	110	8.3
Longtao	210 x 175	14,400	115	95	1.4
Luoja	140 x 100	10,200	128	71	0.7
Lanjiawan	150 x 115	10,700	130	67	0.6
Shenmu	370 x 340	70,900	234	186	13.2
Shizilu	130 x 70	7,000	120	90	0.6
Shuijia	245 x 135	23,700	167	111	2.6
Xiangdang	310 x 230	45,000	146	80	12.6
<i>Bama karst, Guangxi</i>					
Haolong	800 x 600	320,000	509	185	110.0
Jiaole	750 x 400	220,000	325	283	67.0
<i>Dongdang, Shuitang and Yijiehe groups, Guizhou</i>					
Detian	200 x 130	20,000	145	115	2.5
Dachang	550 x 180	80,000	320	160	10.0
Bajiao	280 x 160	24,300	195	150	4.0
Tongtian	210 x 130	20,000	370	360	7.2
Xiaoshui	180 x 130	13,000	230	210	2.8
Dacaokou	920 x 240	140,000	220	160	25.0
Xiaocaokou	300 x 120	22,000	180	120	3.3
Bandong	190 x 100	15,000	240	225	2.0

Table 1. Dimensions of known tiankengs in China; those with names in italics are degraded tiankengs.

carbonate rocks, with good drainage through the karst. Worldwide, tiankengs are rare because large cave river systems in cone karst are less common than they are in the Chinese karst. The important tiankengs discovered so far in China are those described below, and these are located on Figure 1.

THE MAJOR TIANKENGs IN CHINA

Except for the Xiaoyanwan and Dayanwan tiankengs in the Xingwen stone forest tourism area in Sichuan Province, which have been known for many years, the important discoveries of tiankengs have occurred since 1994. In that year, the largest tiankeng, Xiaozhai, was discovered near the Yangtze Gorges during the search for a new exploration site for British cavers in the China Caves Project. In 2001, a group of 26 tiankengs was discovered in the Leye karst in Guangxi during investigations for karst tourism resources and the search for another venue for cavers on the China Caves Project. The discoveries of this special karst feature generated interest in scientific research, which was pursued in subsequent years. Almost at the same time, Qingkou Tiankeng was discovered by the senior author in the Wulong karst, and was later explored by the Hongmeigui Cave Club. Around its vertical walls there are several hanging waterfalls and these converge on the floor and flow into a large cave passage. Qingkou Tiankeng was the first erosional tiankeng to be recognised. The 49 known tiankengs are listed in Table 1.

Tiankengs are best described as collapse dolines that are more than about 100 m wide and deep, and this is recommended as the internationally accepted definition of a tiankeng (Zhu & Waltham, this volume). There are however many more features that are between 50 m and 100 m deep and wide, and these are already widely known as tiankengs within China; they have been referred to as "small tiankengs" (Zhu, 2001). These include three small tiankengs in the Mengzi basin, within the karst of Yunnan. Though many of these smaller features are very significant karst landforms, they are all omitted from Table 1 and the descriptions that follow.

Tiankengs of Xingwen, Sichuan

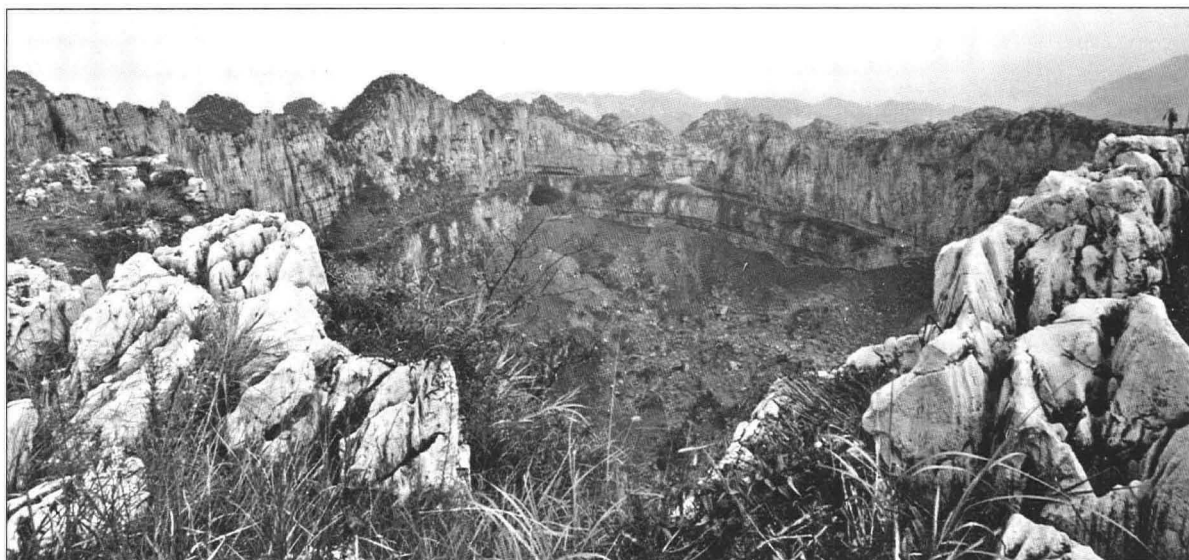
These two tiankengs are situated in the stone forest tourism area of Xingwen, in Sichuan Province. They lie within a karst escarpment with an area of 40km² and an integrated drainage system from the Shunhe river sink to the Donghe resurgence. The karst is developed in limestone and dolomitic limestone of the Lower Permian Qixia and Maokou formations. In September 1992, a British cave expedition team explored the underground river and cave systems to reveal the hydrogeological characteristics of the karst (Waltham and Willis, 1993; Waltham et al, 1993; Zhu et al, 1995). More than 30 km of passages were surveyed in 89 caves; the two longest caves Tianquan Dong (8100 m) and Zhucaojing (8800 m) both have passages opening directly into the sides of the Xiaoyanwan tiankeng.

The Shunhe-Donghe drainage area is a cone karst of low relief, influenced by the carbonate lithology and the low-dip escarpment's stratigraphy, and its vadose zone is 150-300 m deep. The modern hydraulic gradient is 3-5%, and the limestone to sandstone-shale ratio in the catchment is 1:1.08, so that there is abundant allogenic water which is advantageous for tiankeng development.

Xiaoyanwan Tiankeng is roughly circular in plan, 625 m from east to west, and 475 m across; its vertical walls are 60-130 m round the entire perimeter. The maximum elevation on the rim is 870 m, and the lowest point in the tiankeng floor is at 622 m, giving a maximum depth of 248 m, and the total volume is 40M m³ (Fig. 2). The major cave systems of Tianquan Dong and Zhucaojing have large, old, abandoned passages that were parts of the same ancient trunk system, and appear to have a close relationship with the development of Xiaoyanwan Tiankeng. The modern cave river passes beneath the tiankeng at a depth of about 70m below its floor.

Dayanwan lies 400 m to the west of Xiaoyanwan, and is 680 m long east to west, 280 m across, 110 m deep and 15M m³ in volume. It is a heavily degraded tiankeng, with only a gentle slope on its western side and a deep sinkhole developing in its eastern sector; the extensive breakdown and collapse blocks on its floor are partly covered by later alluvial sediment.

Figure 2. Xiaoyanwan Tiankeng, Xingwen.



The surveys by the British caving team in 1992 (Fig. 3) clearly show two stages of development in the Xingwen caves. The first stage had Tianquan Dong and Zhucaojing developing together, with Dayanwan and Xiaoyanwan being developed at the same time. The second stage has the modern trunk drainage route developing from the Shunhe river sink, with a tributary from the Heping Dong area passing through part of Zhucaojing, all feeding to the modern resurgence at Donghe.

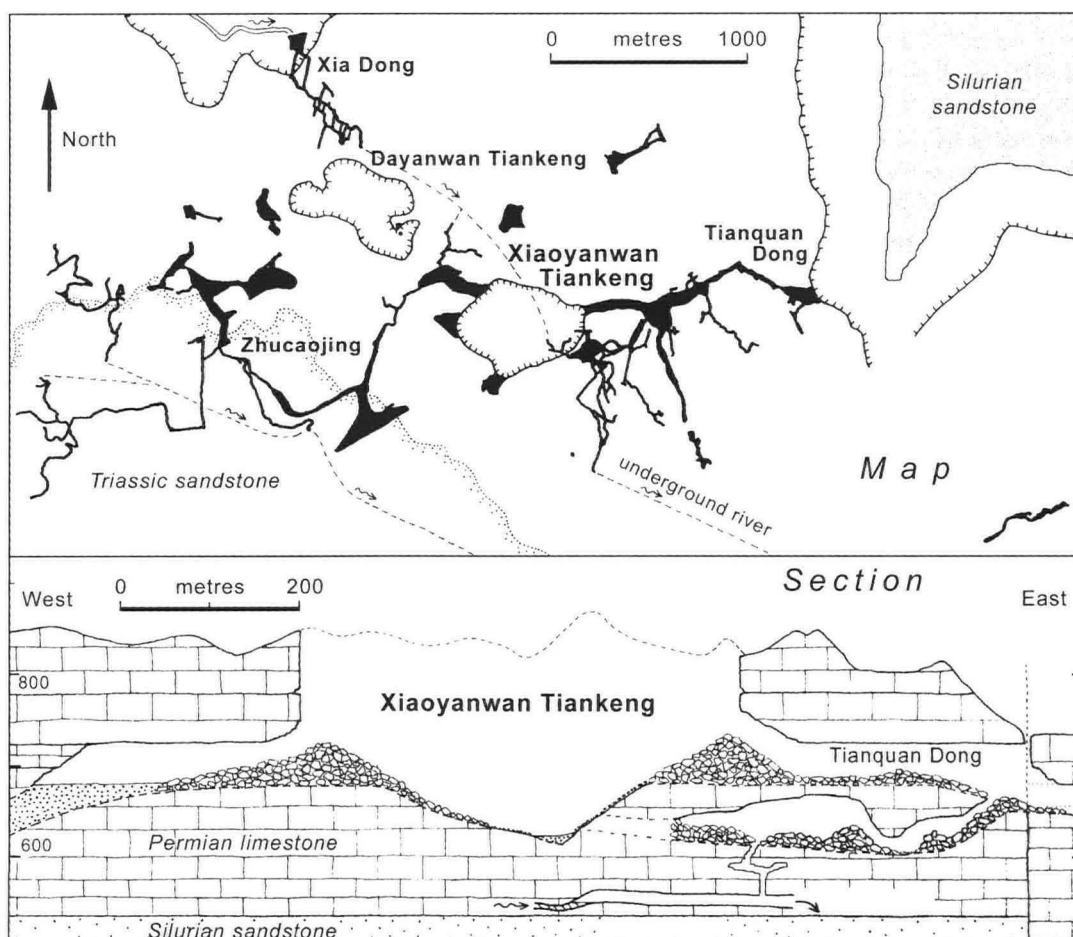
The eastern entrance of Tianquan Dong could have been the entrance for water flowing into the cave in the earlier stage, instead of it being a truncated exit. The large entrance tapers into a passage with sands and pebble beds, and wave scallops point to the west along the main upper passage and then south along the large Southeast Passage. The Dayanwan and Xiaoyanwan tiankengs appear to be older than many of the other tiankengs in China, but cannot yet be dated; clearly Dayanwan formed earlier than Xiaoyanwan since it is so degraded.

Xiaozhai Tiankeng, Fengjie, Chongqing

Located near Xinlong town in Fengjie county, the Xiaozhai tiankeng is in the karst on the right bank of the Jiupan River, a tributary to the Yangtze River. Developed in gently dipping Lower Triassic limestone, the area is a typical cone karst at elevations of 1300-2000 m. Xiaozhai Tiankeng lies in a karst drainage basin with an area of 280 km² from Maocaoba to the Migong River. This has a broad valley in its upstream section, draining into a deep square-cut gorge and then into the narrow fissure gorge of Tianjingxia in the middle section, before draining underground through Difengdong in its lower section, with a total drop of 1600 m (Fig. 4). The tiankeng is developed over the Difeng cave section (Senior, 1995).

Xiaozhai Tiankeng may rank as the largest tiankeng in the world, with an entrance diameter of 537 to 626 m, a depth of 662 m and a volume of 119.35M m³ (Fig. 5). In profile, it has a double nested structure; the upper bowl is 320 m in depth, and the lower shaft is a rectangle 342 m in depth and 257-268 m across; the

Figure 3. Xiaoyanwan and the adjacent caves in the Xingwen karst.



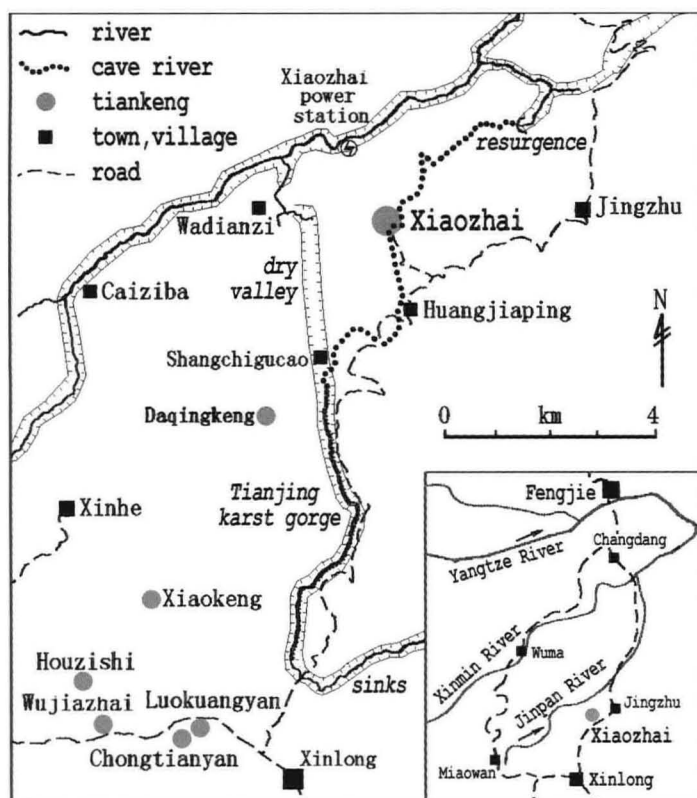


Figure 4. Xiaozhai Tiankeng, the Di Feng cave and the Tianjing gorge, in the Fengjie karst, Chongqing.

sloping ledge between these two parts is formed at the level of a muddy limestone (Fig. 6). Across the floor of the tiangkeng, a cave river has a maximum discharge of 174 m³/sec. The sink of this cave river is in the Tianjing fissure gorge, and its resurgence is in a vertical cliff above the Migong River; the length of the underground passage is 8.5 km, with a fall of 364 m, giving a hydraulic gradient of 4.3%. The cave river is a powerful force in removing material from Xiaozhai Tiangkeng.

Within the karst around Xiaozhai tiankeng there are six other tiankengs of medium-size and 101-170 m deep; these are Chongtianyan, Luokuangyan, Wujiazhai, Houzishi, Xiaokeng and Daqinkeng (Fig. 4; Table 1). They all appear to have developed at an earlier stage than Xiaozhai tiankeng, and all of them are of the collapse type. Longgang Tiankeng lies further west, near Qingshui in Yunyang county, and is distinguished by a very narrow ridge that separates it from an adjacent valley (Fig. 7).

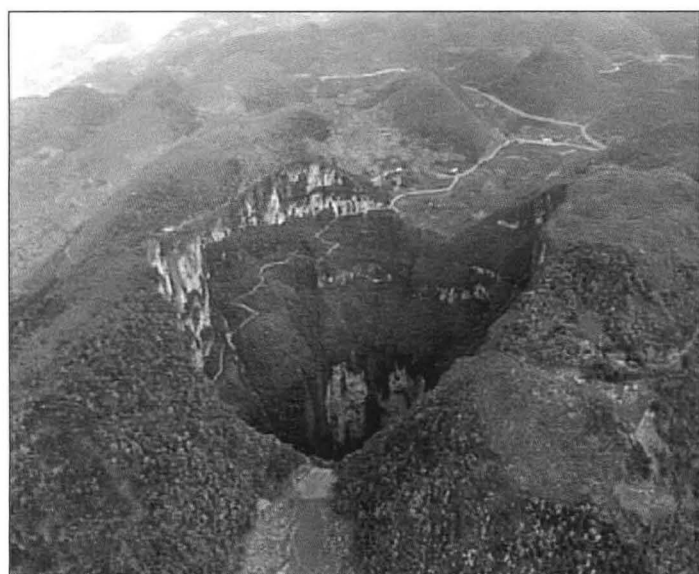


Figure 5. Air view of Xiaozhai Tiankeng, Fengjie.

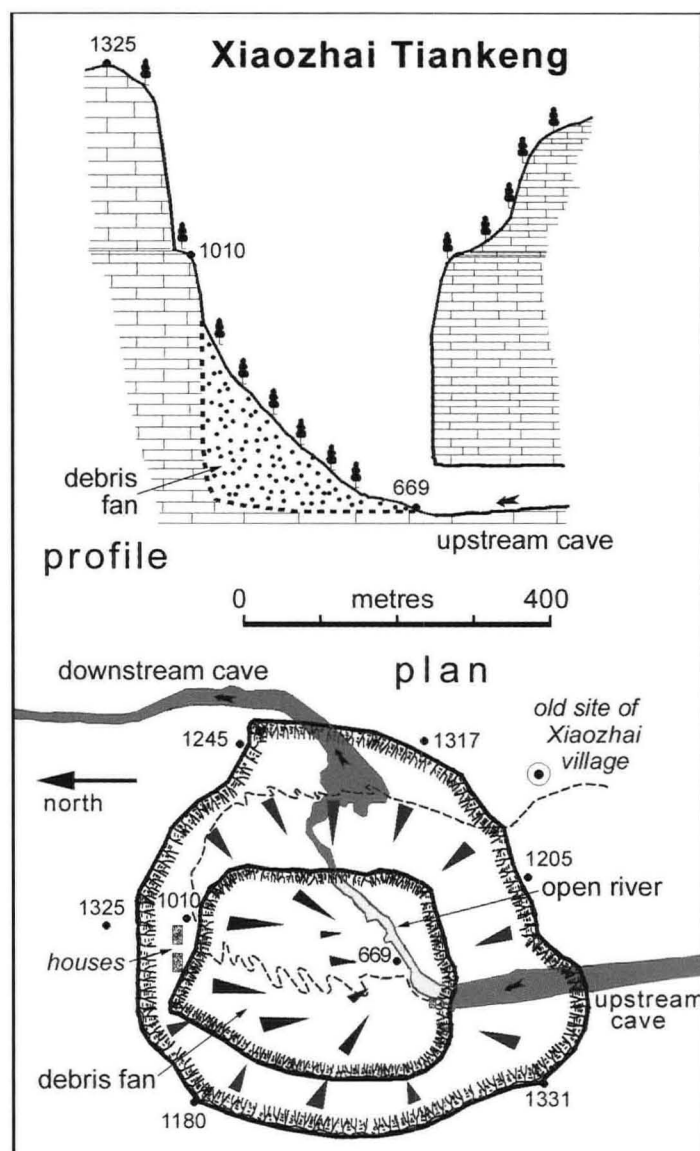


Figure 6. Plan and profile of Xiaozhai Tiankeng.

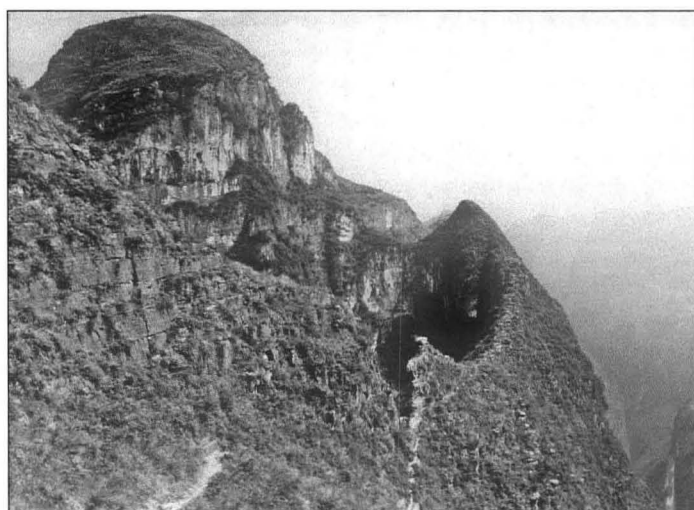


Figure 7. Longgang Tiankeng in Yunyang county, Chongqing.

Dashiwei tiankeng group, Leye, Guangxi

The Dashiwei group of tiangkengs lie in a complex anticline of gently dipping Carboniferous and Permian limestones exposed in a S-shaped inlier beneath Triassic clastic rocks. The karst is drained by the large Bailong underground river, and has a vadose zone that is 400-800 m deep. Cone karst is developed across the carbonate outcrop at elevations of 1300-1500 m, and the site is ideal for tiangkeng development (Fig.8).

Figure 8. Tiankengs of the Dashiwei group and the Bailong underground river system within the Leye karst (Guangxi); only marginal faults, some major cave passages and selected roads are indicated; the exposed karst continues to the south.

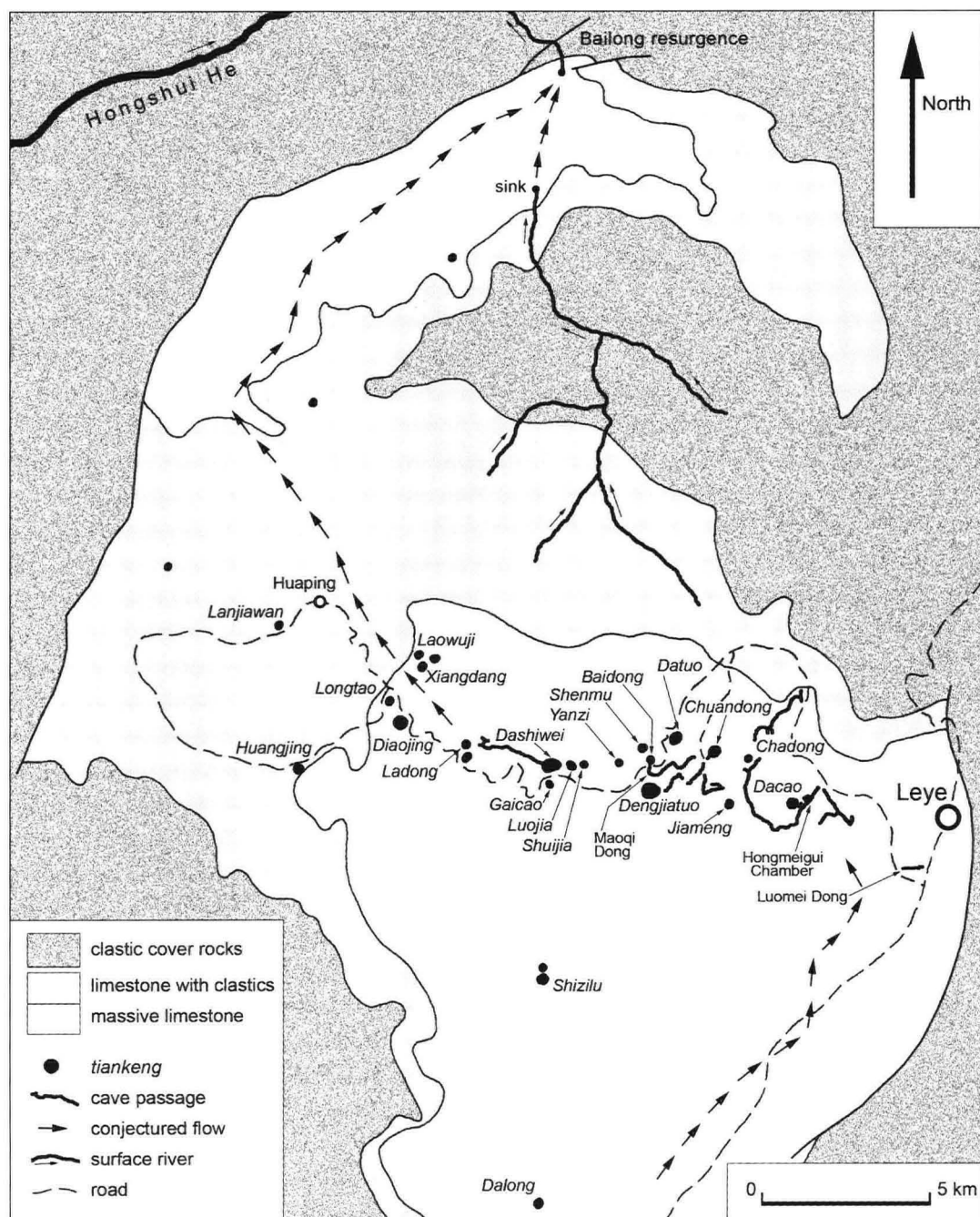


Figure 9. Air view of Dashiwei tiankeng, Leye.



The large group of tiankengs that includes Dashiwei lies in western Leye county, close to Tongle town (Zhu et al, 2003b). There are 26 tiankengs discovered so far. The largest is Dashiwei Tiankeng, which is pear-shaped in plan, 600 m long from east to west, 420m wide from north to south, 1580 m around the perimeter, and 613 m at its maximum depth. It is surrounded by vertical cliffs (Fig. 9) and its floor is covered by a ramp of collapse debris more than 100 m high that slopes steeply down from east to west and is covered by flourishing secondary forest. The cave river is accessible at the lowest point of the tiankeng floor (Fig. 10), under its western wall; it emerges from a pile of collapsed rocks, and 6000 m of passage has been mapped downstream, as far as a point where the river drops into deep, narrow and inaccessible fissures.

All the tiankengs in the Dashiwei group are of the collapse type, though Huangjing Tiankeng has been modified by allogenic water, since its collapse development, and is intermediate to an erosional type of tiankeng (see below). Of the 26 tiankengs in the Leye karst, Dashiwei is classified as a very large tiankeng. Chuandong, Datuo and Dengjiatuo are all large, though only Chuandong Tiankeng has vertical walls on its entire perimeter, while the other two have degraded to leave debris slopes round about half their perimeters. These and 17 other tiankengs of normal size are listed in Table 1. The other five sites each have some dimensions less than 100 m; they would therefore be described only as very large collapse dolines in the international context (Zhu & Waltham, this volume), though they are known locally as small tiankengs. These six do include some significant landforms; Yanzi Tiankeng is a fine open shaft into the roof of a large chamber, but it only opens to larger dimensions offset from the entrance.

The main features of the Dashiwei group are very significant to the study of collapse tiankengs -

- A large number of tiankengs lie closer to each other than do others in China;
- The tiankengs lie mainly over the middle section of the Bailong underground river, of which just parts of the river passage have yet been mapped;
- The tiankengs that lie at higher elevations are more degraded and may be older.
- The larger tiankengs lie along the course of the active underground river;
- The ratios of entrance area to floor area of most of the tiankengs is close to unity, due to the almost vertical walls;
- The tiankengs are clearly unrelated to the surface topography of the karst, and their growth has therefore destroyed a variety of surface karst landforms, including dolines, depressions and dry valleys, as well as peaks, hills, cones and mountains;
- Baidong Tiankeng is adjacent to the large chamber with the Maoqi Dong skylight entrance in its roof, and Dacao Tiankeng is adjacent to the large Hong Meigui Chamber in the same cave system;
- The Dashiwei group shows the stages of development from an underground river passage to a cave chamber to a tiankeng;
- Primary or secondary forest develops on the collapse debris in the tiankengs.

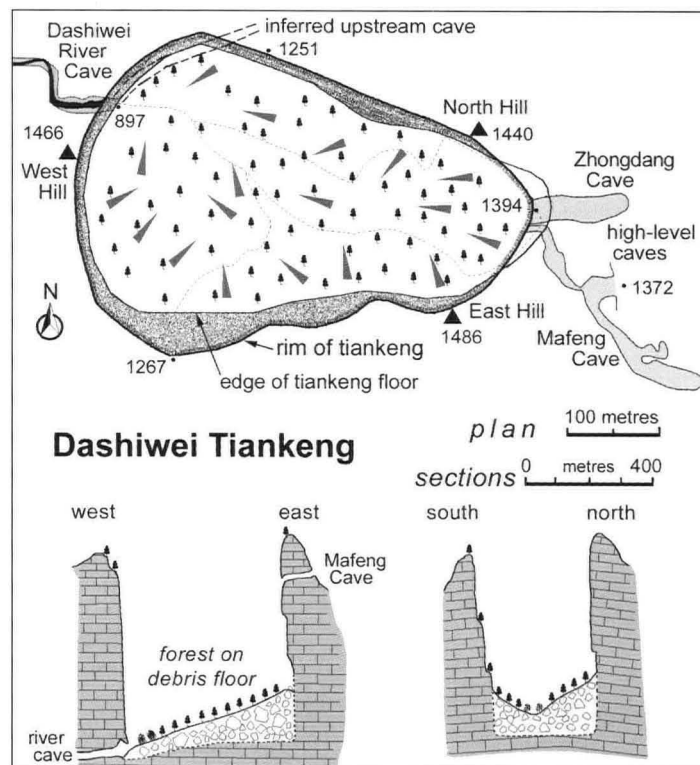


Figure 10. Plan and profile of Dashiwei Tiankeng.

Tiankengs at Bama, Guangxi

Haolong Tiankeng lies northeast of Longzhong village in Bama county, Guangxi, and is one of the largest tiankengs in the world. In plan it is 800 m long from east to west and 600 m wide, with a maximum depth of 509 m and a volume of 110M m³. A river flows across the tiankeng floor from west to east. It has developed partly in a large dry valley aligned from east to west, so that only its northern half retains spectacular vertical walls (Fig. 11); its southeastern half is largely degraded, so that is now exploited as fields by the local farmers and the primary forest has been destroyed (Fig. 12).

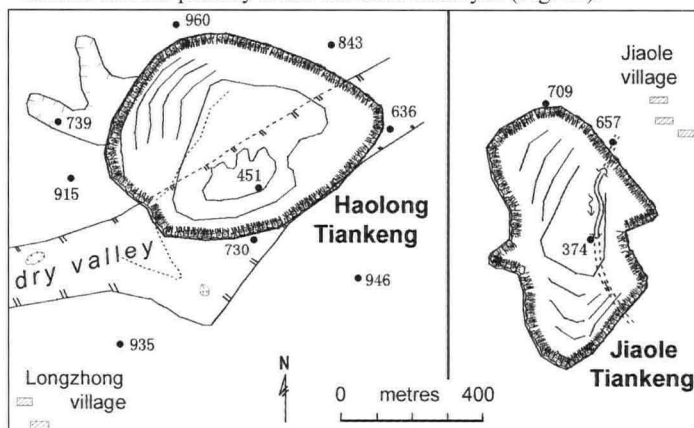


Figure 11. Plans of the Haolong and Jiaole tiankengs, Bama.

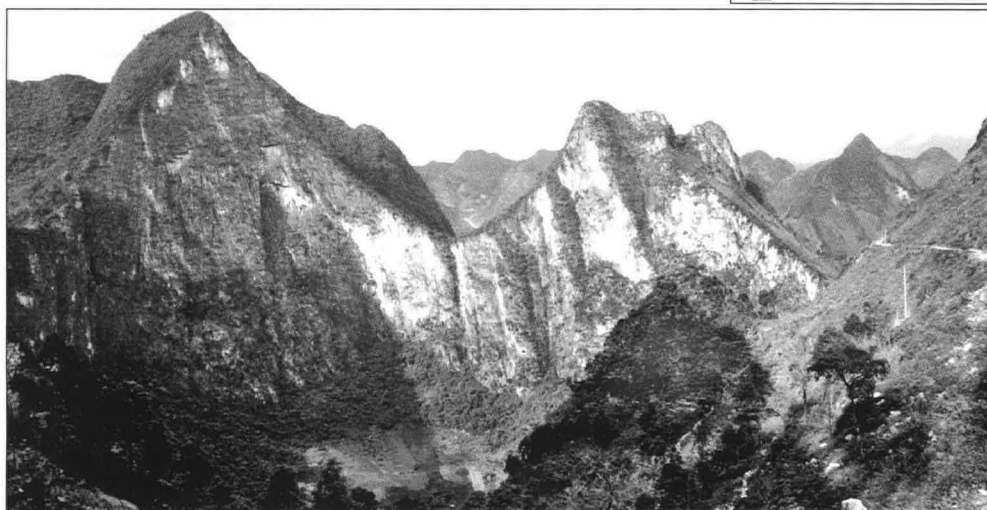


Figure 12. Haolong Tiankeng, Bama.

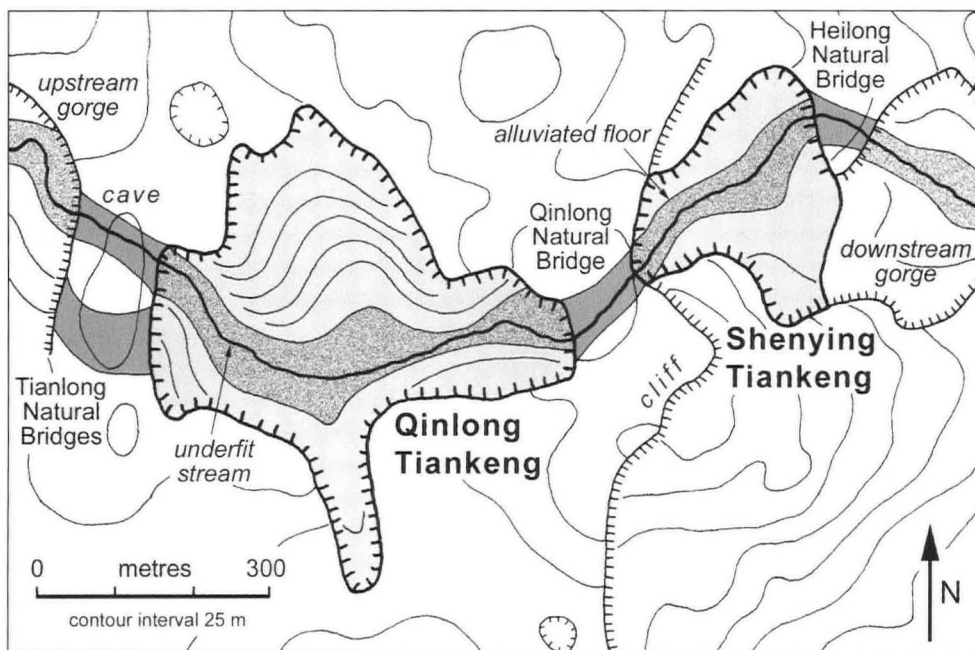


Figure 13. Qinlong and Shenying Tiankengs between the three natural bridges in the Wulong karst.

Jiaole Tiankeng lies 2 km southwest of Haolong. It is 750 m long from south to north, 400 m wide, and 283 m deep, with a volume of 67M m³; a karst dry valley is developed across it from east to west. The tiankeng has the shape of a boat, and is distinguished by a clean-cut vertical wall across its northeastern side as the result of collapse guided by a major fracture. The cave river is exposed to daylight for more than 200 m across the tiankeng floor (Fig. 11).

Both these tiankengs are developed along an old course of the Laolongdong River; part of this survives as the Laolong cave, with a passage that once carried a large allogenic river into the karst.

Tiankengs of Wulong, Chongqing

Around Wulong, the terrain along the banks of the Wu Jiang, a tributary of the Yangtze River, is a typical fengcong cone karst that is deeply dissected by a river valley. The major local relief creates a vadose zone up to 1000 m deep in the succession of carbonate rocks of Cambrian, Permian and Triassic age. This karst contains Qikeng Dong, which is 920 m deep and is the deepest cave yet found in China.

A number of collapse tiankengs have been recognised in the karst of Wulong county, in the natural bridges tourism area and close by it. The most important are Zhongshiyuan, Xiashiyuan, Qinlong and Shenying Tiankengs. Xiashiyuan is the largest of the tiankengs and is 1 km long. Both the Qinlong and Shenying Tiankengs developed in the dry valley that originated as a major cave passage over 2 km long and is now spanned by three natural bridges (Fig. 13). It appears to be a youthful feature that dates from the late Pleistocene or the Holocene. With its underground river, natural bridges, tiankengs, dry valleys, caves and shafts, this site clearly shows the development stages and typical evolution relationships between the different karst landforms (Fig. 14). Xiashiyuan and Zhongshiyuan Tiankengs both have vertical perimeter walls and are large enough to each contain small villages (Fig. 15); their floors

Figure 16. Zhongshiyuan Tiankeng, Wulong.



Figure 14. Shenying Tiankeng, Wulong.

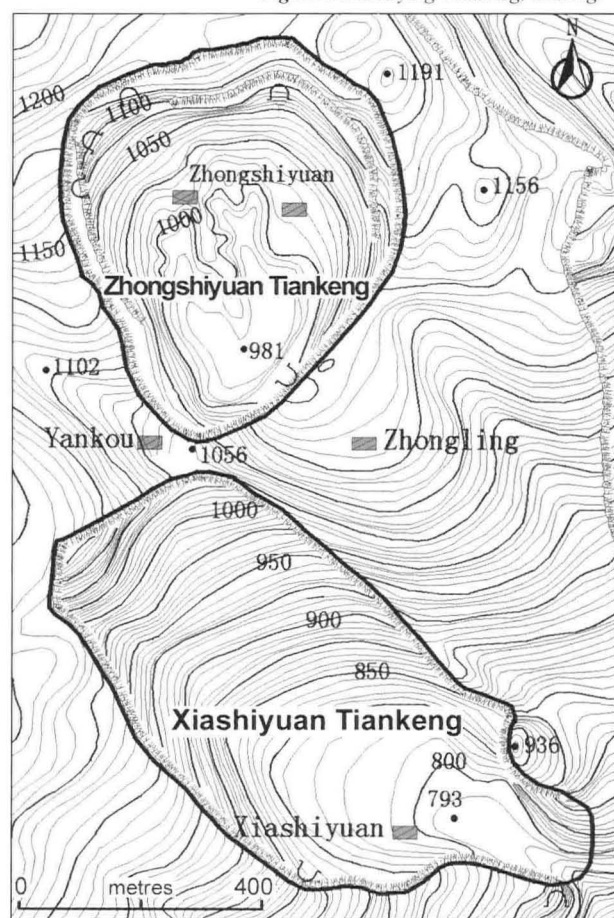


Figure 15. The adjacent tiankengs of Zhongshiyuan and Xiashiyuan, Wulong.

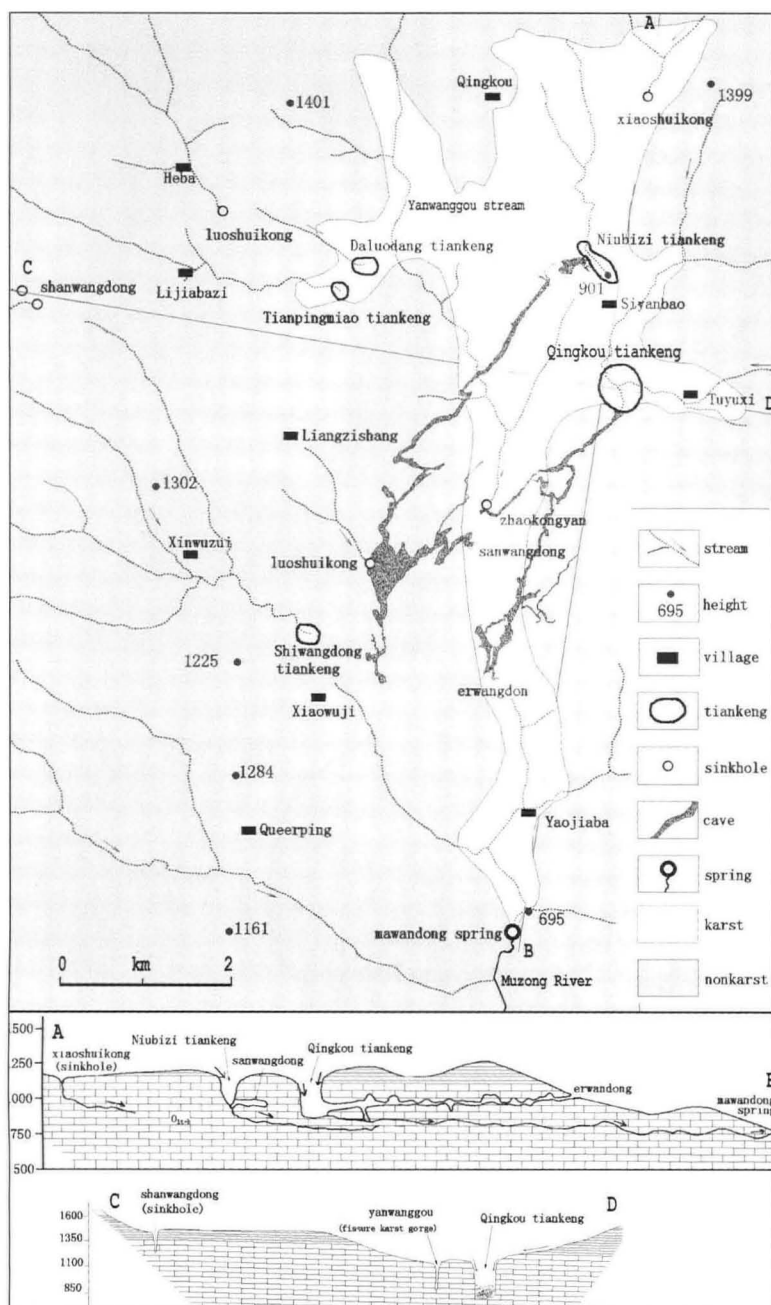


Figure 18. The waterfall down into Qingkou Tiankeng.

Figure 17. Hydrogeology of the Qingkou tiankeng group in the Wulong karst.

slope down to small areas at their lowest points, and their nature requires further investigation (Fig. 16).

Qingkou Tiankeng is the finest example of an erosional tiankeng yet discovered in China. It has been formed by a concentrated flow of allogenic surface water draining into karst with a deep vadose zone. It lies within an extensive outcrop of gently dipping, Palaeozoic sandstone and shale on the watershed between the Wu Jiang and the Chang Jiang (Yangtze River) near Houping village. The terrain is incised by dendritic valley systems, so that almost all the surface water drains into a north-south trough valley floored by an inlier of thick, Lower Ordovician limestone. The limestone aquifer was deeply entrenched by the Muzong River in the south to create a deep vadose zone, which provides a very advantageous geological and hydrogeological environment for the development of erosional tiankengs.

The tiankengs of Qingkou, Niubizi, Daluodang and Taipingmiao were developed at the sandstone-limestone boundary within a broad valley (Fig. 17). Of these, Qingkou Tiankeng is the largest and most mature (Fig. 18); it is 250 m wide across and 295 m deep (Table 1). This type of tiankeng differs from the collapse form because it has been formed by erosion from the surface into the limestone vadose zone by an allogenic surface stream. It is the less common type of tiankeng. Caves have developed at different levels in the Qingkou tiankeng karst, and a cave system about 10 km long discharges southward to the Mawandong rising of the Muzong River (Fig. 17).

Tiankengs in Guizhou

For many years there was limited data on the karst landforms, and especially on tiankengs, in Guizhou, but a number of tiankengs in the karst of the Meng Jiang river basin on the left bank of the Hongshui River (Fig. 19) have now been recorded.

The Dongdang tiankeng group lies in thick, massive, Triassic limestone along the course of the Daxiaojin underground river in Luodian county. Detiandong Tiankeng lies in a hillside in cone karst, 300 m from the exit of Dajin underground river; it is 130-192 m across and 145 m deep, with steep walls and a floor of collapsed rocks. An adjacent shaft is separated from it by a natural bridge, and a cave at its foot connects with the Dajin Underground River. Dachang Tiankeng also lies in a hillside in cone karst, and also has a cave passage connecting it to the Dajin Underground River about 1 km from the exit; it is 180-500 m across and 320 m deep, with a sloping floor of rock collapse debris. Bajiao Tiankeng forms a large skylight into the old high-level passages of Xiangshui Dong. Its entrance is nearly 200x300 m in plan and is 230 m deep, with vertical walls to a floor of breakdown debris (Zhang and Barbary, 1988); an adjacent smaller tiankeng, 100x150 m in plan, connects into the same cave.

The Shuitang tiankeng group lies in the Getuhe cave tourism scenic area formed in thick, massive, Middle Carboniferous limestone in Ziyun County. Tongtian Tiankeng lies just above the sink entrance of the Getu Underground River; its entrance is 200 m

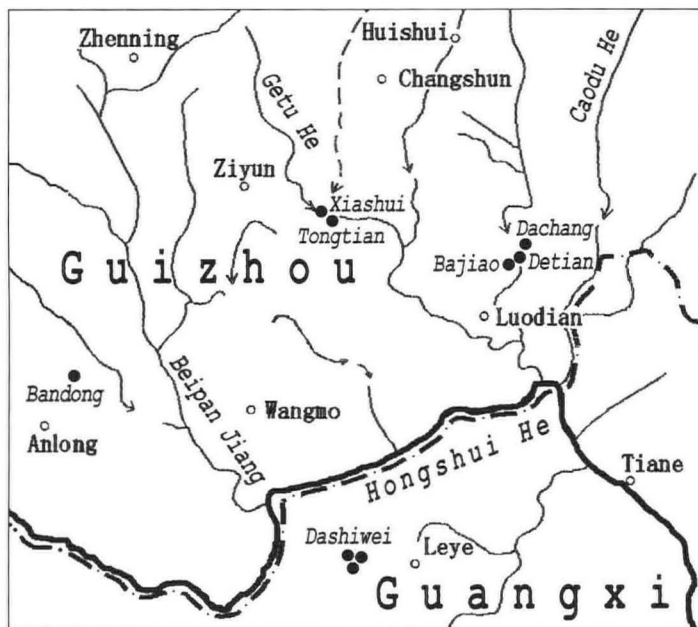


Figure 19. Locations of tiankengs on both sides of the Hongshui River.

across and it drops 370 m with largely vertical walls to a ramp down to the underground river (Barbary et al, 1991). Nearby, Xiaoshui Tiankeng is over 100 m in diameter and drops 210 m straight into the downstream passage of the Getuhe Cave, which also contains the very large Miao chamber.

The Dacaoou and Xiaocaoou Tiankengs are in Zhijin county in central Guizhou, within the Chang Jiang catchment. They lie between two short sections of cave and a massive natural bridge, all traversed by the Yijie River (Zhang & Barbary, 1988), and the site is similar to that at Sanqiao in Chongqing. Dacaoou is the larger of the two tiankengs, over 900 m long, with vertical cliffs above scree ramparts that close to each bank of the river. Bandong Tiankeng is a major collapse in Anlong county; it drops into an inactive cave system that extends through to the Anhe mega-doline and also contains Titan Chamber, 300 m long and 150 m wide (Dunton and Laverty, 1993).

Within Guizhou, 73% of the land is karst, developed on carbonate rocks of more than 1200 m thick that range from Sinian (Precambrian) to Triassic in age. However, tiankengs are not widely distributed, since many parts have disadvantageous conditions, including thicknesses of pure, continuous carbonate rocks of less than 100 m due to non-karst interlayers of sandstone, shale, and mudstone, complicated geological structure, changeable structural dips, and shortage of trunk rivers along the watershed between the Yangtze and Pearl rivers. Conditions advantageous to tiankeng development are cone karst, dissected by rivers to create a vadose zone more than 100 m deep in gently dipping, continuous carbonate



Figure 20. A typical normal doline in fengcong karst.

sequences more than 100 m thick. It is therefore expected that more tiankengs could be formed in the dissected areas of the Wu Jiang drainage basin in northern Guizhou and also along the southern edge of the Guizhou plateau, especially over the courses of major underground rivers.

DISCUSSION

Dolines and tiankengs

A doline is a natural, closed depression in a karst terrain (it is generally called a sinkhole in North America). It is usually close to circular or polygonal in surface shape, with a diameter of tens to hundreds of metres and a depth of metres to tens of metres (Fig. 20); its shape is generally that of a rounded bowl or an inverted cone, and it is always formed in or over soluble rocks (Williams, 2004).

Dolines can be classified into six main types - solution, collapse, caprock, dropout, suffosion and buried dolines (Fig. 21), though the dropout and suffosion dolines are two types of subsidence doline (Waltham et al, 2005). It is significant that any doline is clearly related to fissures or caves in soluble rocks beneath it. The doline is one of the main karst landforms in the karst areas of strong, pre-Triassic carbonate rocks in China, especially in the humid subtropical karst south of the Yangtze River. The most abundant are solution dolines, notably well developed in the fengcong cone karst and in the mountain karst belts. The second most common are the dropout dolines formed in the clay-rich cover soils, especially in the alluvial plains of the between towers in the fenglin karst; many are formed naturally, but many have been induced by pumped abstraction of underground water, mine drainage and other disturbing factors. Collapse dolines in bare karst are relatively few in number.

A tiankeng is a large negative landform in a specific type of karst terrain. It is generally roughly round or oval in plan shape, with very steep, vertical or overhanging walls (so that the area of its floor is similar to that of its surface footprint), and there is a clear break between the foot of its walls and its floor. Tiankengs are 100 m to 1000 m in diameter, and >100 m deep; the deepest reaches a depth of nearly 700 m. Most tiankengs are essentially very large collapse dolines, though a few relate to very large caprock dolines (Fig. 21).

Current research suggests that tiankengs in carbonate rocks may be divided into two types - collapse tiankengs and erosional tiankengs. The former are much more widespread and numerous than the latter (Zhu et al, 2003a, 2003b, 2004).

Collapse tiankengs

Collapse tiankengs have been formed in soluble rocks where massive amounts of rock material have been dissolved and eroded away at depth by a powerful and dynamic underground drainage system, notably through a large cave river passage. Under specific geologic and hydrogeological conditions, a cave chamber evolved as its roof failed gradually while the fallen rock debris was carried away by water; eventually, the chamber roof opened out to the ground surface. A collapse tiankeng is characterized as follows:

- It is ringed by steep or precipitous cliffs, which originated when it collapsed into a roughly conical void; it may have a collapsed triangular profile, a striking feature of many tiankengs. It normally has a clean break at the foot of the perimeter walls, though a gentle slope formed by later debris accumulation is a mark of relatively old age in a tiankeng.
- The floor of the tiankeng is composed mainly of boulders and breakdown blocks. Where there is an active cave river at the bottom, most colluvial debris and breakdown has been carried away, so that the cave river channel is exposed across the tiankeng floor. Alternatively, the colluvium thickness is smaller where the tiankeng is in a depression, or where colluvium remains in high terraces. Where breakdown is banked against the marginal cliffs, collapse is a continuing process. Where there is a great thickness of accumulated debris, forming a gentle slope or covered by sand and clay, the course of the underground river has changed, and debris transport through the cave conduit has basically stopped.
- A subterranean river flowing through the bottom is an essential feature of a collapse tiankeng, for it is the cave river that is the

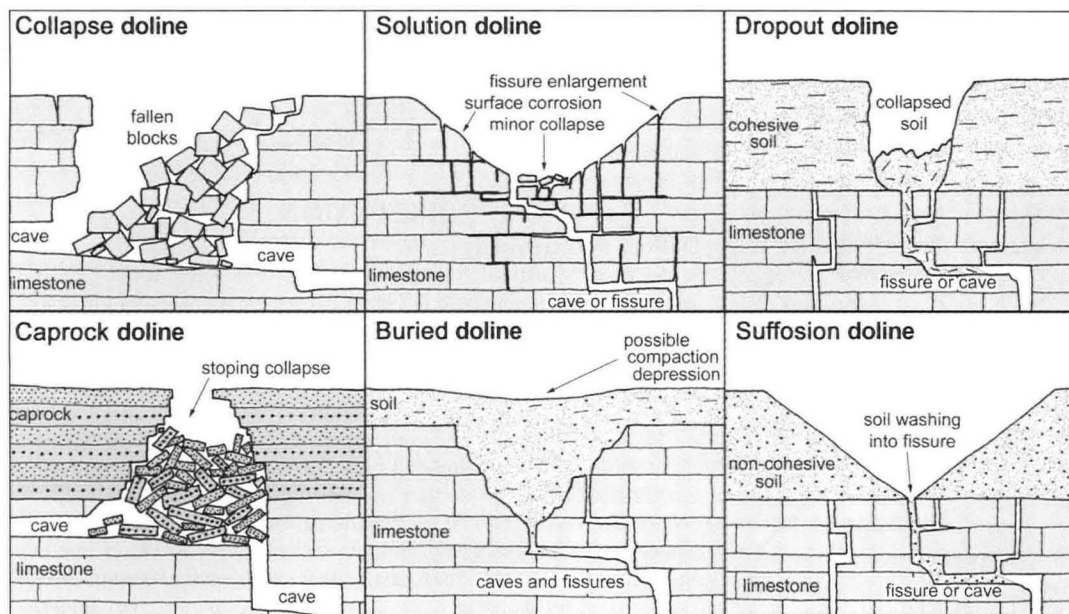


Figure 21. The six types of doline (from Waltham et al, 2005).

dynamic source of dissolution and erosion and carries away a great deal of the breakdown material (Fig. 22). An old tiankeng may have lost its underground river, and may retain its vertical walls before they start to degrade.

- Tiankengs of different sizes or different stages have distinctive morphologic features. The smaller or more youthful tiankengs are usually shaped like an inverted cone, i.e. the ratio (M) of the area of the surface entrance to that of the floor is less than 1 ($M < 1$). Larger tiankengs are like a well with walls close to vertical, where $M \approx 1$. Very large tiankengs mostly have profiles that approach those of a doline, where $M > 1$.
- An important feature of collapse tiankengs is that there is no relationship between the tiankeng entrance position and the surrounding surface geomorphology and karst landforms. A collapse tiankeng can develop in any terrain location, and it always destroys the surface karst landform as it evolves and expands. A collapse tiankeng can destroy depressions, dolines, wind gaps, blind valleys and any positive landforms, because it develops from underground towards the ground surface.
- There are three main stages of development in a tiankeng - a cave with a large river passage, then a large cave chamber, then a tiankeng that is open to the surface.
- The skylight collapse tiankeng, such as Huangjing Tiankeng in the Dashiwei group, is a variety of collapse tiankeng developed in carbonate rocks covered by thin sandstone. It has a flat floor because there is a flow of allogenic surface water carrying in sand and clay sediments that cover the breakdown debris. This is a type of tiankeng formed essentially by collapse but then modified in the style of an erosional tiankeng. Allogenic water has contributed to its present morphology, but the bulk of the feature was developed as an underground cave chamber before collapse breached its roof and also the thin sandstone cap.

Erosional tiankengs

This second type of tiankeng is developed in the vadose zone of soluble rocks by allogenic water that dissolves and erodes the rock in its vertical descent from the surface. They are rare because of their special environmental conditions, but are characterized as follows:

- There may be a stream falling down the steep or vertical wall, or there are erosional features or hanging tufa deposits. However, there is not necessarily a perennial flow of water vertically into the tiankeng. It is unusual to have either a collapse triangular profile or any great amount of collapse debris on the floor.
- In contrast to the development of collapse tiankengs where the surface hole opened abruptly from beneath, erosional tiankengs are formed gradually from the surface to the floor. Excavation downwards by stream erosion, and fluvial removal of debris and solutes, complement each other.
- An erosional tiankeng lies at the head of an underground river,

and there is generally a large inlet cave entrance in one side of the tiankeng.

- Erosion and dissolution are the primary and dominant processes that excavate an erosional tiankeng, in contrast to the importance of collapse in the development of collapse tiankengs. An erosional tiankeng has development stages that differ from those of a collapse tiankeng; it starts with a stream sink into a conduit, and this enlarges gradually, and then deepens and widens into a tiankeng.
- Erosional tiankeng develop at the boundary between soluble and non-soluble rocks, and can be classified into two types by their geological structure - in horizontal beds, such as Qingkou Tiankeng, and in dipping beds, such as Garden of Eden in Sarawak. The Huangjing skylight tiankeng formed under a sandstone caprock, but developed largely by collapse before the allogenic water could reach it, and is therefore classified as a collapse tiankeng.

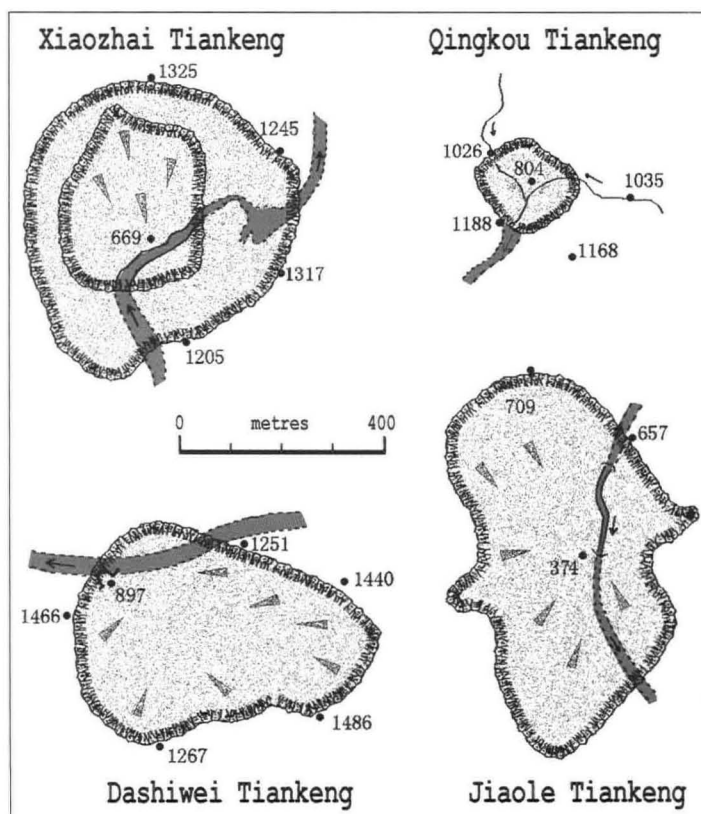


Figure 22. Streams and rivers draining across the floors of four major tiankengs; three are collapse tiankengs, but Qingkou is an erosional tiankeng.

Morphological contrasts between dolines and tiankengs

The main features of a tiankeng are its very large size (>100 m wide and deep) and its perimeter walls that are close to vertical. In contrast, most bedrock dolines in karst are bowls or shallow basins where the width is greater than the depth; some have steeper profiles and a depth similar to their width, but they are much smaller than a tiankeng.

The profile of a tiankeng has a clear break between its walls and its floor, while most karst dolines do not. A tiankeng has steep walls, a thick layer of collapse breakdown on its floor, and also a large underground conduit flow, while the karst doline typically has gentle slopes, thick soil on its floor, and a small stream sink.

The development of dolines in karst is closely related to the surrounding surface topography, the negative doline always being in harmony with the positive landforms. Collapse tiankengs develop with no direct relationship to surface landforms, as they form anywhere and destroy any other landforms of the surface karst, including dry valleys, depressions, dolines or cone karst, either individually or collectively.

Most dolines in bedrock formed in the epikarst and shallow vadose zone by rainfall dissolution, without any direct relationship to the aquifer and its cave rivers. Tiankengs developed within deep unsaturated zones, by active conduit flow within the aquifer aided by concentrated surface inflow. Collapse tiankengs and erosional tiankengs formed by underground flow and surface river flow respectively, and both are directly related to large underground conduit flows in the aquifer.

The development of the common solution doline is a long slow process that proceeded as part of long-term karst landform evolution. In contrast, tiankeng development is mostly abrupt, in the case of a collapse tiankeng, or relatively rapid in the case of an erosional tiankeng. Tiankengs are generally among the youngest of large negative karst landforms.

NOMENCLATURE AND DEFINITION OF TIANKENGs

Tiankengs have different names in different parts of the world, but the terms are synonymous. In China, they are called yanwan, shiyuan, longgang, shiwei, tiankeng, karst tiankeng, cao, dong, dang among other terms, that all have the similar meanings of big pit, deep doline or collapsed doline. In Slovenia, they are called kukave, kolisevye, vigedi or various other terms, and in Mexico they are called sotanos. It is proposed that tiankeng becomes the international term.

The definition of a tiankeng

Based on the research and conclusions outlined above, it is proposed that the definition of a tiankeng is - "a large, steep-walled, pit-like, negative, karst landform that opened from beneath towards the surface, with both its depth and diameter more than 100 m, developed in a great thickness of continuous soluble rocks within a deep vadose zone of the aquifer and connecting with an active cave river at its foot". A tiankeng is characterized by its tourism values of rarity, grandeur and spectacular magnificence, and also by its special ecological environment. These are all characteristics that differentiate between tiankengs and normal karst dolines.

The tiankengs recognized throughout the world to date had been classified into four size groups - oversize, large, medium and small (Zhu et al, 2003). But it is now proposed (in accord with Zhu & Waltham in this volume) that those in the smallest group are no longer defined as tiankengs as they are <100 m deep and wide. The nomenclature is therefore adjusted to define three size groups -

- Very large tiankengs, more than 500-600 m in diameter and depth, are very rare worldwide, and there are only three known so far in China - Xiaozhai, Dashiwei and Haolong.
- Large tiankengs, 300-500 m in diameter and depth, are also few in number around the world.
- Normal tiankengs, 100-300 m in diameter and depth, are more numerous and more widely distributed.

Development environments of tiankengs

Collapse and erosional tiankengs have some features in common, but

also have some important differences in their development conditions. There are five essential environmental conditions.

1. A great and continuous thickness of soluble rocks. Soluble sedimentary rock (generally carbonate rocks in China) is the first requirement for tiankeng development. The large and deep tiankengs have developed within the larger thicknesses of soluble rock that are unbroken by any significant impermeable interbeds, so allowing the establishment of a unified vadose zone within the aquifer.

2. A deep vadose zone in the karst. Tiankengs have largely developed in the vadose zone of an aquifer above a deeply buried water table, where the depth of the vadose zone is nearly equal to or greater than the depth of the tiankeng. Tectonic uplift and rejuvenation caused entrenchment of the surface rivers and a major lowering of the regional water table, thereby increasing the depth of the vadose zone. Tiankengs are most common in areas of tectonic uplift.

3. A favorable geological structure. The two kinds of tiankeng are formed mainly in karst regions with gently dipping or horizontal rocks which have wide outcrops. Structural fissures, notably long and deep faults and vertical joints allow development of strong hydrodynamic systems in the aquifer. A structure with gently dipping beds and networks of joints and faults favors progressive breakdown of the roof of large cave chambers at depth. Dipping beds are eroded to outcrops with long contacts to insoluble rocks, and so favor development by allogenic drainage of erosional tiankengs, including Qingkou tiankeng.

4. A highly active hydrodynamic system with underground conduit flow in cave rivers. A tiankeng is one of the largest closed and negative landforms in karst, involving the removal of up to 1000M³ of rock by breakdown, dissolution and fluvial transport. This clearly requires a powerful hydrodynamic system in the form of active conduit flow within a cave river system in the karst aquifer. The known tiankengs have all developed in association with major underground river systems. The cave river is the critical factor in tiankeng development, including for erosional tiankengs - where the river is the result of the tiankeng development and not its precondition.

5. Favorable climate and hydrogeology. A humid and rainy climate supplies plentiful rainfall and biogenic carbon dioxide for dissolution and river flow, and encourages high erosional intensity and a high rate of tiankeng development. Tiankeng distribution is related to the zones of humid climate and abundant precipitation.

These environmental factors are all optimally developed in the karst of southern China, especially in the cone karst areas with high relief - which include the most important tiankeng sites in the world.

The geological age of tiankengs

Tiankengs provide data for research of karstification intensities and rates, and offer a new way to study time-scales of karst geological process. The features below are the key to discussion and understanding of tiankengs:

- Tiankeng development requires the removal of massive volumes of rock. The largest known tiankengs, in terms of volume and rock tonnage removed, are Xiaozhai (Chongqing, China), 1.2×10⁸ m³, 3.22×10⁸ tonnes, and Garden of Eden (Mulu, Sarawak), 1.5×10⁸ m³, 4.05×10⁸ tons (though the Garden of Eden is an old feature that has been enlarged by fluvial erosion during its degradation, and is now best regarded as a mega-doline).
- Depths of tiankengs are close to the thicknesses of the local vadose zone, so that they reach down to the karst water table. The deepest is Xiaozhai Tiankeng, 662 m deep (Fig. 23).
- Collapse tiankengs have developed in any location among the surface landforms, thereby destroying any negative or positive karst landforms of greater age.

It is suggested that the tiankengs in China are among the youngest negative landforms of the karst. Ongoing research is relating the high intensities and rates of karstification to the relatively young geologic ages of the tiankengs. Tectonic uplift of the karst region of southern China dates only from the Himalayan orogeny in the early Quaternary. This caused the deep incision by surface trunk rivers (including the Yangtze, the Wu and the Hongshui, each with their deep gorge sections), and the consequent



Figure 23. The very large and very deep Xiaozhai Tiankeng.

decline of the karst water table (and increase in vadose zone thickness) caused development of the underground rivers and formation of the tiankengs. This suggests that the tiankengs in China formed mainly in the late Pleistocene, within the last 128,000 years.

The active tiankengs whose underground rivers have not switched to newer routes, such as Xiaozhai and Dashiwei, may have been open to the surface only for some tens of thousand of years. It is probable that the large cave chambers developed at these sites at much earlier ages (as they normally evolve over very long time-scales), when the ground surface was higher, and only the surface collapse (when the cave chambers evolved into open tiankengs) was a Holocene process at some sites.

CONCLUSIONS

The doline is one of the most familiar and distinctive landforms in karst terrains. There are several doline types that form in soluble rock terrains (mainly of carbonate rock and gypsum), including the solution, collapse and subsidence dolines. Collapse dolines are karst bedrock collapses (and caprock dolines involve collapse of insoluble rock that covers a buried karst), but the sizes of all dolines do not match the size of a tiankeng. Dolines in carbonate rocks generally have diameters and depths up to about 100 m. Very large, vertical-walled, karst depressions differ from all the main doline types, though some have been called just large dolines or large collapse dolines. These are distinguished by not only their size but also by their development mechanisms and conditions, so it is proposed that they should be separated from dolines and referred to as tiankengs.

Distinctive features of a tiankeng

A very large doline is now called a tiankeng for certain basic reasons:

- A tiankeng develops in special environmental conditions that integrate aspects of geology, geomorphology and hydrogeology, but a normal doline develops in a much wider range of karst environments. Consequently, dolines and collapse dolines are widespread while tiankengs are very few within the world's karst.
- A tiankeng differs greatly from dolines and collapse dolines in its development and erosional mechanisms. A collapse doline forms by dissolution and suffosion in normal geological and hydrodynamic environments. Collapse tiankengs have developed through an unusual hydrodynamic combination of erosion, dissolution and collapse, where three evolutionary stages may be distinguished, from a cave river passage, to a large cave chamber, to a tiankeng open to the surface.
- A tiankeng is very much larger than a normal collapse doline. It is more than 100,000 m³ in volume, 1000-100,000 m² in area at both the surface level and its floor, and more than 100 m in depth.
- A tiankeng differs from normal dolines in its development processes. Tiankengs have close relationships with the regional development of cave river systems, and their distribution, evolution, age and development rates are not comparable to those of normal karst dolines.

The importance of the scientific study of tiankengs

The study of tiankengs has important scientific implications for karst hydrogeology and geomorphology, and for studies of karst processes and neotectonics.

Where tiankengs develop within a regional karst drainage system, they indicate the presence of a powerful karst hydrodynamic system, and they relate to the input and output balance of material and energy in a strong conduit flow or cave river in the karst aquifer. This can supply valuable data towards research into the basic characters of an aquifer and into the evolution and variance of conduit flow in drainage areas where tiankengs occur.

The evidence to date suggests that collapse tiankengs develop anywhere they can, and always destroy any surface karst landform, including depressions, dolines, wind-gaps, blind valleys, cones, hills, towers and any other positive landforms. It appears that tiankengs are among the younger karst landforms, and a negative feature of 10 to 100 million cubic meters volume developed in a short geological time gives us a new concept of intensity, mode and rate of karstification. It appears that the tiankengs of southern China have largely or entirely developed within the later Pleistocene, and the oldest tiankeng appears to be no more than 128,000 years old.

Finally, local neotectonic uplift appears to have contributed to the critical environment for tiankeng development. Conversely, tiankeng research can supply important information for the study of the rates and characteristics of neotectonic movement.

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Tiankengs of the world, outside China

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Abstract: An inventory of tiankengs that are known outside China is accompanied by brief descriptions and comments on their features and origins. Available data suggests that there are only 26 known tiankengs outside China. Some other very large collapse dolines are compared.

Key words: tiankeng, karst, doline, world

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Though tiankengs were first distinguished and described from the karst of China, a small number of comparable features can be seen in various karst regions around the world. This paper simply records the very large collapse dolines that have been documented outside China, and which may justifiably be described as tiankengs in the context of the landforms in China. A tiankeng is defined as a collapse doline at least 100 m long, wide and deep, and with perimeter walls that are close to vertical (Zhu and Waltham, this volume).

The paper was prepared at the request of Prof. Zhu for the 2005 Tiankeng Investigation Project, and is presented as a companion paper to that on the tiankengs inside China (Zhu and Chen, this volume). It includes reference to various very large dolines that do not quite fit the definition of a tiankeng, but it excludes features that are less than about 100 m deep and wide, even though some of these would be known as small tiankengs within China.

There are probably more tiankengs that are yet to be discovered. Unseen tiankengs could await discovery in some of the more remote karst highlands of the tropics, and more may be found in the forested mountainous karsts of China and New Britain. Satellite imagery is making such discoveries less likely, but this inventory cannot yet be regarded as complete.

KNOWN TIANKENGs

Nakanai, New Britain

The one karst terrain of the world that compares to those in China, in terms of the large underground rivers and many tiankengs, is the Nakanai Mountains of New Britain, the island off the north coast of Papua New Guinea (Maire, 1981; Audra et al, 2001). Unlike the

precipitous Chinese fengcong karst, the Nakanai is a polygonal karst with modest cone development and local relief of about 100 m, and it still bears the remnants of a clay cover. However, it is broken by eight deep canyons and at least eight giant dolines (Table 1).

Minyé is a large tiankeng, and is one of the largest and finest in the world (Fig. 1). Almost circular, it is entirely ringed by tree-covered walls that are precipitous but only vertical in parts (Fig. 2); the Minyé floor is crossed by a river of 25 m³/s, though the explored cave passages are neither large nor long. Naré is smaller (Fig. 2), but its vertical and overhanging walls perhaps make it even more spectacular (Fig. 3); it drops straight into a river passage some 50 m high and wide that can be followed in both directions, though the flow of 15 m³/s provides endless difficulties.

Bikbik Vuvu has almost vertical tree-shrouded limestone walls tapering slightly down to a bedrock floor; its downstream cave is a canyon 15 m wide and 40 m high, while a subaerial slot canyon carries a flood river into the upstream side of the tiankeng. Poipun is more degraded, so that accumulated breakdown debris obscures any access to the cave below. Kea 2 has vertical walls, but its floor is partly alluviated. Within the Nakanai karst, there are many other collapse dolines of only slightly smaller dimensions; some of these would be described as small tiankengs in China, but do not match the 100 m dimensions of a normal tiankeng.

Minyé and Naré are classic, active and mature tiankengs, while Bikbik Vuvu and Poipun are of only slightly lesser stature. These Nakanai tiankengs compare well with the sites in China, in that they are all youthful features in a very active karst with deep vadose drainage. However, they show more solutional activity than collapse

Figure 1. Looking down into the Minyé tiankeng, in the Nakanai karst in New Britain. (Photo: Jean-Paul Soumier)



Tiankeng	length x width m	area m ²	depth max m	depth min m	volume Mm ³	size	type
<i>Nakanai, New Britain</i>							
Minyé	350 x 350	75,000	510	400	26.0	L	
Naré	150 x 120	13,000	310	240	4.7		
Poipun	150 x 150	17,000	160	110	1.7		
Bikbik Vuvu	190 x 120	15,000	225	190	1.5		
Kea 2	130 x 110	11,000	125	100	1.2		
Lusé	800 x 600	350,000	250	224	61.0	L	D
Kavakuna	380 x 300	80,000	480	360	12.0	L	D
Wunung	500 x 400	160,000	160	150	24.0	L	D
Ora	900 x 550	240,000	275	270	26.0	L	D
<i>S E Asia Islands</i>							
Kukumbu (New Britain)	1000 x 700	380,000	300	280	75.0	L	
Yogoluk (West Papua)	180 x 180	25,000	240	230	4.0		
Sendirian (Sarawak)	115 x 90	12,000	240	180	2.0		I
RMAF Hole (Sarawak)	150 x 120	13,000	110	80	1.3		
Himbiraga (Papua New Guinea)	400 x 200	72,000	>100	100	~5.0		
<i>Slovenia</i>							
Velika Dolina	300 x 170	30,000	165	120	3.5		
Mala Dolina	170 x 120	14,000	130	95	1.0		
Lisičina	400 x 200	60,000	115	80	2.0		D
<i>Croatia</i>							
Crveno Jezero	450 x 400	140,000	528	431	30.0	L	
Modro Jezero	700 x 400	190,000	290	160	22.0		D
<i>Mexico</i>							
El Sotano	440 x 210	70,000	455	310	16.0	L	
Golondrinas	300 x 130	26,000	400	355	5.0		I
<i>Brazil</i>							
Peruaçu North	450 x 200	85,000	170	130	10.0		
Peruaçu South	400 x 180	55,000	150	70	5.0		D
<i>Puerto Rico</i>							
Tres Pueblos Sink	190 x 180	25,000	120	90	2.5		
<i>Madagascar</i>							
Mangily	700 x 500	280,000	140	100	25.0		
Styx 2	400 x 300	88,000	140	100	8.0		
<i>Other sites</i>							
Pozzatina (Italy)	675 x 440	240,000	130	104	14.0		
Pulicchio (Italy)	710 x 550	280,000	100	90	15.0		
Garden of Eden (Sarawak)	1200 x 800	750,000	300	150	150.0		
Sarawak Chamber (Sarawak)	700 x 300	165,000	200	90	15.0		
Lago Azul (Brazil)	200 x 140	18,000	280	265	4.3		

Table 1. Dimensions of known tiankengs outside China and some comparable features. The quoted data are the best available estimates, either previously published or measured off surveys; except for the depths at some sites, all figures are only approximations, as the wall profiles have not been mapped in detail. L = large; D = degraded; I = immature

in their evolution. The inlet river to Bikbik Vuvu means that it may be classified as an erosional tiankeng, if that distinction is accepted.

With a volume of about 61M m³, Lusé is the largest of three degraded tiankengs. More than 600 m across, it is floored by breakdown debris and dense forest with no visible river, and there are hardly any surviving cliffs around its perimeter (Maire, 1981). Wunung is rather smaller (Table 1), but does have steeper walls on parts of its perimeter. Kavakuna has a vertical wall on one side, but this faces a massive debris slope that reaches from lip to floor on the other side, and the cave passage is offset below. Though significantly degraded, these three sites have profiles that are comparable to some of the degraded tiankengs in China. Ora is a fourth degraded doline, and is a double feature with a central rock bridge (Audra et al, 2001); it clearly developed in association with the cave river that crosses the floor. Ora is a large tiankeng, but its side slopes are now so degraded and flared out that it stands on the boundary between a tiankeng and a mega-doline.

Southeast Asia Islands

On the mainland of Papua New Guinea, the Muller Range contains perhaps the world's greatest density of giant dolines on the Mamo Plateau (James, this volume, Fig. 4). They are mainly giant caprock dolines, and their perimeters lack major cliffs because they are degraded in the weak and thinly bedded caprock. Some large solution shafts, open to daylight in the underlying limestone, have the profiles but lack the dimensions of tiankengs, and none is known to be associated with a major cave river. Most of these dolines have only been seen from the air, but future fieldwork on the ground may reveal that some of them could be described as degraded erosional tiankengs. On the adjacent Atea Plateau, a giant doline near the

Himbiraga dry valley has been visited, and does have a perimeter of sub-vertical cliffs; very rough estimates of its dimensions are therefore included in Table 1.

On New Britain island, Papua New Guinea, the Whiteman Range lies far to the west of Nakanai. Within its extensive karst, the Kukumbu tiankeng is a massive and partially degraded collapse feature a kilometre long (Table 1), midway along the large, multi-level passages of the Arrakis cave system (Beck, 2003).

In central West Papua (previously known as Irian Jaya, the Indonesian section of the New Guinea main island), the Wamena karst contains the tiankeng of Yogoluk, formed by roof collapse into a fragment of very large, abandoned cave passage (Fig. 4). Its depth is partly obscured by a debris pile around 80 m high (White, 1986). Another large collapse doline, seen from the air on the forest-covered plateau to the south, may also be a tiankeng (Fig. 5).

Only two tiankengs have been discovered to date in the steep, forest-clad mountainside that surface the very well developed and highly cavernous karst of Mulu, in the Malaysian sector of Borneo. Sendirian (also known as Solo) is a massive hole about 100 m across with overhanging walls that bell out below in the profile of an immature tiankeng (Fig. 6); it is around 200 m deep except for the massive debris pile on its floor (Brook and Waltham, 1978). RMAF Hole is a little wider though not so deep (Table 1), and has vertical or overhanging walls (Eavis, this volume, Fig. 4). Both tiankengs have formed by collapses into old, phreatic, high-level passages of the Clearwater Cave system.

Dinaric karst

In the heart of the Dinaride mountains, the Imotski karst lies in southern Croatia, very close to the border with Bosnia. Crveno

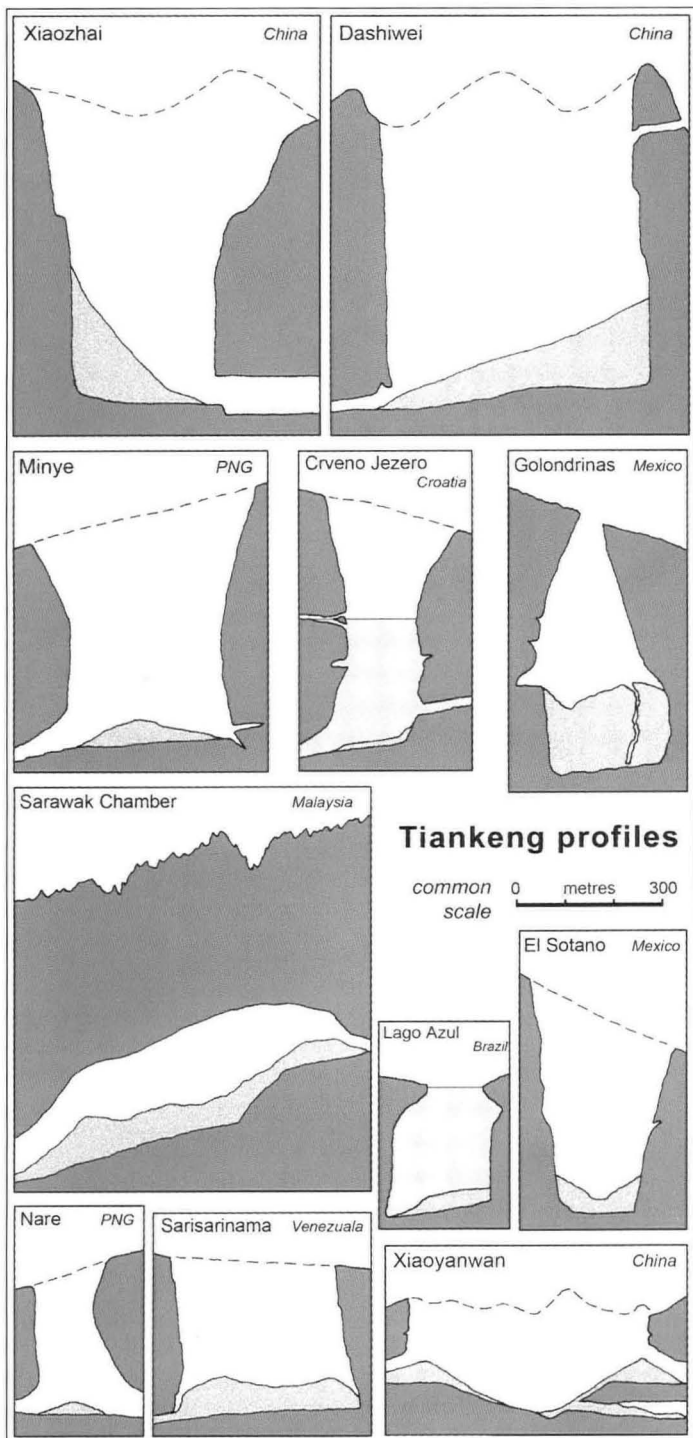


Figure 2. Profiles of some tiankengs and giant dolines; rock profiles beneath debris are conjectured.



Figure 5. An unvisited collapse doline on the plateau south of Wamena in West Irian. (Photo: Andy Eavis)

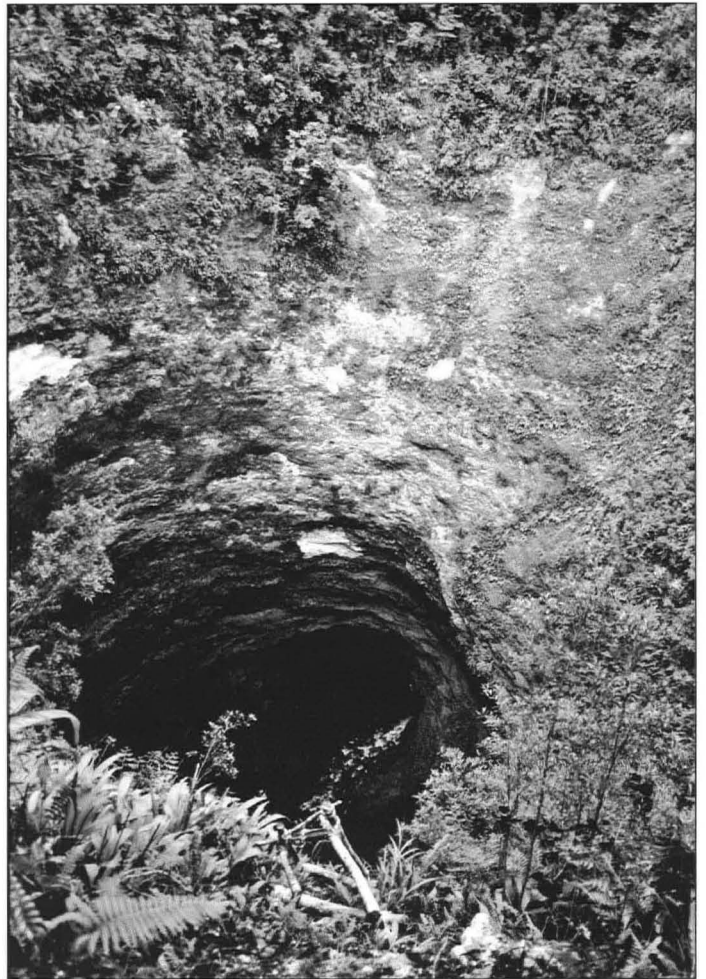


Figure 3. Looking down the Naré tiankeng (Nakanai) towards the downstream river cave. (Photo: Jean-Paul Sournier)



Figure 4. The tiankeng of Yogoluk in the Wamena karst of West Irian. (Photo: Andy Eavis)



Figure 6. The Sendirian tiankeng in the Mulu karst of Sarawak. (Photo: Andy Eavis)

Jezero (Red Lake) takes its name from the towering, red-stained, limestone walls that surround its dark lake (Kranjc, this volume, Fig. 3). This is a classic tiankeng, 400 m across at its rim and half that size at the lake surface over 200 m down (Fig. 2). The lake is over 200 m deep, with vertical walls to a sloping debris floor; these are broken by flooded caves that provide through-flow drainage. Less than a kilometre to the east, Modro Jezero (Blue Lake) is a partially degraded tiankeng whose open aspect allows sunlight to colour its lake (Fig. 7). Vertical walls around most of the rim stand over ramps of scree that descend into the lake, whose depth varies from 100 m to nil in response to seasonal rainfalls. This appears to be an older tiankeng that was, before its degradation, very similar in size and shape to the present Crveno Jezero (Table 1).



Figure 7. The tiankeng of Modro Jezero (Croatia), with its lake about 80 m deep, though it can drain down to a dry floor almost level with the floor of the Imotsko polje (visible in the background).

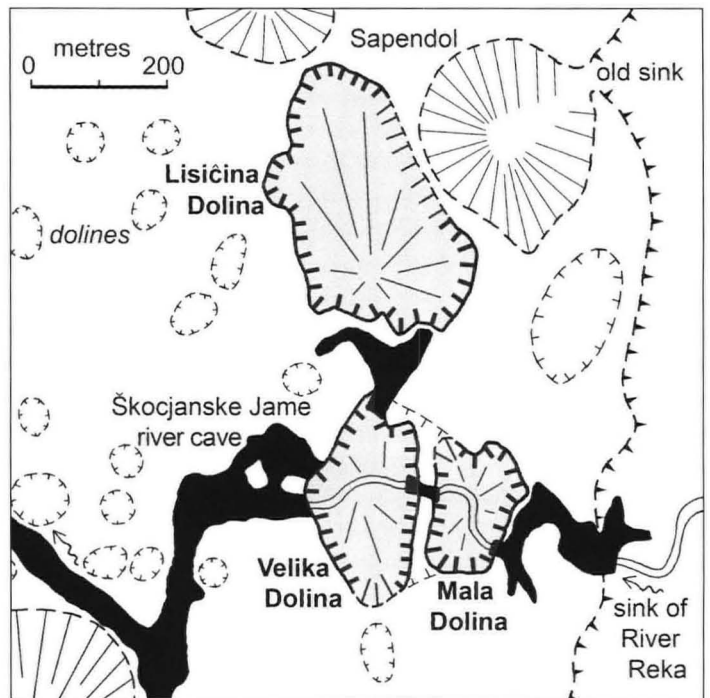


Figure 8. Outline map of the cave passages and tiankengs at Škocjanske Jama, Slovenia.

On the margin of the Kras (the classical karst) in Slovenia, Škocjanske Jama is a famously large cave that breaks through two tiankengs just downstream from its sink (Fig. 8). Velika Dolina (Great Doline) is 170 m across and 155 m deep, with broken cliffs, partly clad in trees, around much of its perimeter (Table 1). Mala Dolina (Small Doline) is about 130 m wide and deep, and also has a perimeter that is a mix of vertical cliffs and tree-clad slopes. The two tiankengs are separated by a massive rock bridge over the cave river (Kranjc, this volume, Fig. 1). It is clear that both these tiankengs have collapsed into the cave passages of Škocjan, which include large old high-level galleries as well as the active and very large streamway (Habic et al, 1989). The adjacent Lisičina collapse doline is a third tiankeng, but it is inactive and partly degraded; cliffs now form only part of its perimeter. It lies on the line of an abandoned input cave from the limestone margin at an earlier ponor that has now evolved into the Sapendol doline (Fig. 8), and their floors only descend to the altitude of the old high-level passages in Škocjanske Jama. When these three tiankengs coalesce by further wall retreat, they could appear as a single mega-doline 800 m long and 300 m wide, though by then this will have degraded beyond description as a tiankeng.

The Dinaric karst terrains are punctuated by many more very large dolines. Those on the Kras plateau are degraded to gentle profiles and most are now less than 100 m deep, so they no longer warrant description as tiankengs (Kranjc, this volume). Further very large dolines also lie round the two tiankengs in the Imotski karst, and around the western end of Imotsko Polje; these include some that could be regarded as incipient or degraded tiankengs.

Mexico

The Sierra Madre Oriental is a major karst mountain range with many long and deep cave systems and also a small number of very large shafts and dolines (Hose, 2004a). El Sotano (also known as Sotano del Rancho del Barro) is a huge gash in a steep hillside. It is about 440 x 210 m at ground level, and tapers to half those dimensions at its floor (White and White, this volume, Fig. 13). Its sloping rim stands 310–455 m above the floor, where bedrock is masked by breakdown debris (Table 1, Fig. 2). Nearby, Sotano de las Golondrinas has an opening only 65 m long and 50 m wide, but its clean rock walls overhang so that the floor dimensions are about 130 x 250 m. It is 400 m deep, but fissures that have been followed in its floor to a depth of 512 m may indicate a deep mass of collapse debris (Fig. 2).

Both these giant shafts have only some of the characteristics of tiankengs. El Sotano tapers downwards in solid rock, which is not typical of stoping collapse; Golondrinas is immature, but wall collapse will eventually flare it out so that its surface opening is the diameter of a normal tiankeng. Neither site has any known cave passages into or out of it, and neither has any known river caves, nor lies in the catchment of one. They could be past sites of major stream sinks in a karst topography now changed by prolonged evolution, but some early history of hydrothermal enlargement cannot be ruled out.

There are other very large shafts and dolines in the Sierra Madre karst. Sotano de la Cuesta has two small skylights 170 m above the floor of a chamber 320 x 90 m in plan, and Hoya de las Guaguas has a large shaft from the surface with a large chamber off-set below it. Near to El Sotano, Culebra is a wide shaft 300 m deep with only a small roof opening to daylight. Further rock collapse may eventually turn all three of these features into tiankengs.

Brazil

The Peruacu karst in Minas Gerais is well known for the Gruta do Janelão (Cave of the Windows), which has a massive river passage 3 km long and approaching 100 m high and wide. Associated with the cave are two giant collapse dolines that qualify as tiankengs (Table 1). The northern feature appears to be the collapsed remains of an old, abandoned, curving loop, nearly 500 m long, off the Janelão river cave (Fig. 9). It is bordered by cliffs that rise 150 m high to the plateau level, but both cliffs and floor are shrouded in primary forest; at the ends, they are broken by giant windows into the cave, and a third window into the cave lies at high level near the northern end. The southern feature is smaller and may be the

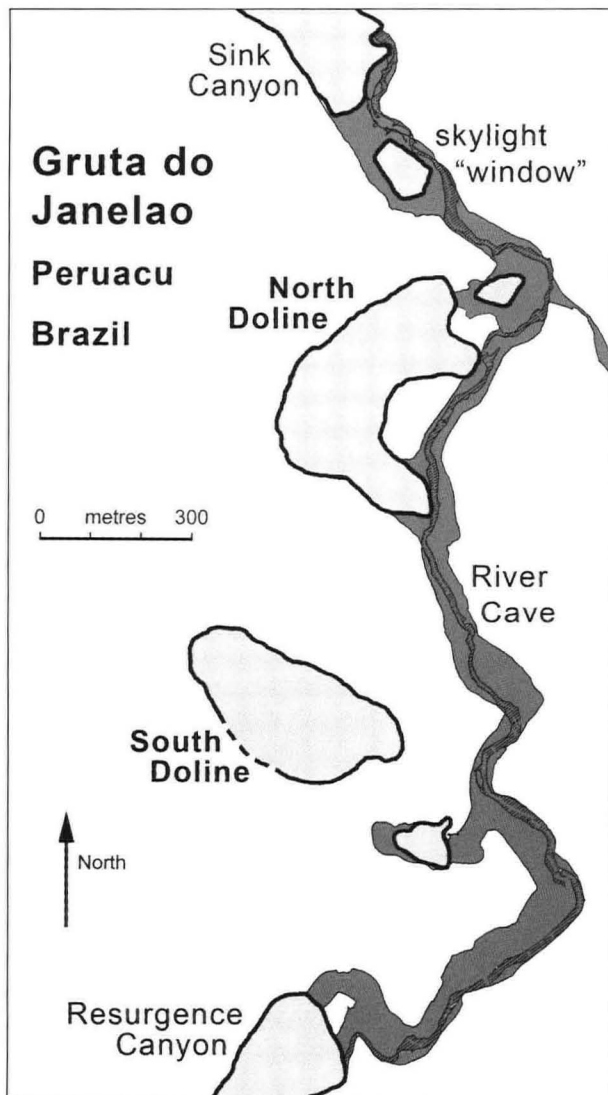


Figure 9. Outline map of the tiankengs at Gruta do Janelão, Brazil.

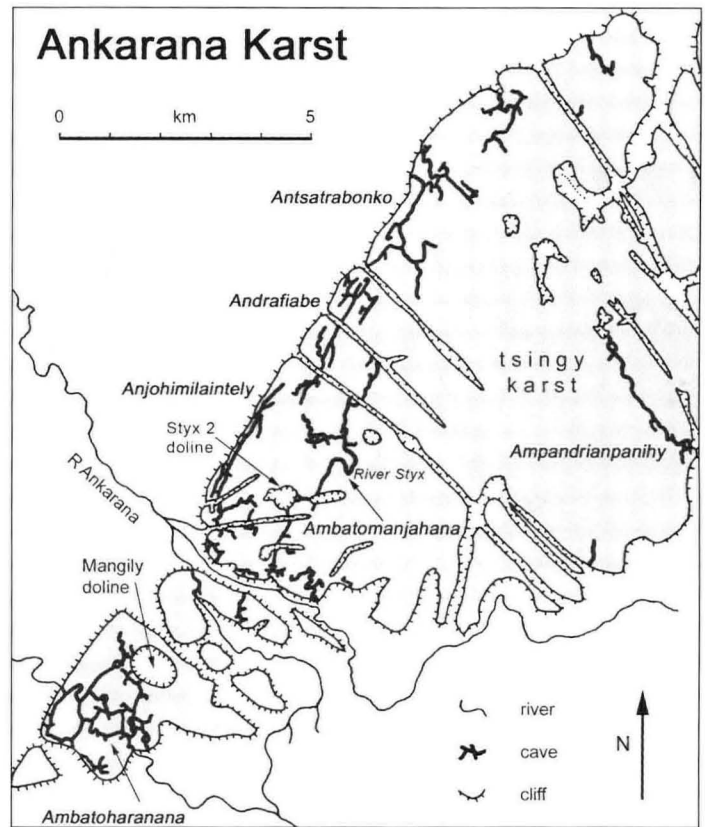


Figure 10. Outline map of the major caves, canyons and tiankengs in the Ankarana karst, Madagascar.

collapsed remains of a large tributary passage; its perimeter cliffs are degraded along the southern side. These two dolines appear to be tiankengs of typical Chinese characteristics. Two more roof collapses have created dolines and windows into the cave, but have not yet widened to the dimensions of tiankengs.

Puerto Rico

In the western part of the limestone belt across the north of the island, Tres Pueblos Sink is a perfect collapse tiankeng in a terrain of low-relief cone karst (Table 1). It is almost perfectly round, 180 m in diameter, with vertical walls about 100 m high (White and White, this volume, Fig. 10). At the foot of a ramp of tree-clad breakdown debris, the Rio Camuy flows across the floor between portals to cave passages that are each about 10 m high and 30 m wide. There are various other collapse dolines along the same cave river, but none is as large (Gurnee et al, 1967).

Madagascar

The karst plateau of Ankarana, in northern Madagascar is well known for its stone forest (locally known as tsingy) and for its large caves inhabited by crocodiles (Peyre, 1982; Middleton, 2004). The plateau is broken by long, fault-guided canyons and a number of large collapse dolines (locally known as sunken forests), all of which have the river caves entering and leaving them at floor-level, beneath broken limestone cliffs that reach to about 150 m high. The largest doline, Mangily, is over 500 m across (Table 1). Another large collapse is the second window along the River Styx passage in the Ambatomanjahana cave, which is over 300 m across (Fig. 10). Both these dolines have perimeter walls over 100 m high, and they do appear to be related to major collapses of the large cave passages. They therefore qualify as tiankengs, though they do not lie in fengcong karst. The Styx 1 and Styx 3 windows are both segments of canyons that are enlarged joint rifts. There are other large collapse dolines, east of the Styx and further northeast on the plateau, and roof collapse has created a doline and skylight 70 m across into the Andrafiabe cave.

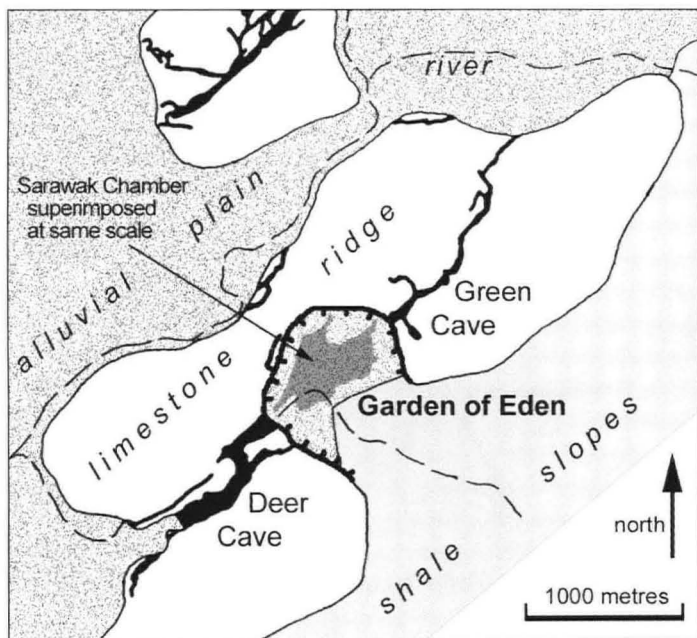


Figure 11. Outline map of the Garden of Eden mega-doline in the Mulu karst, Sarawak, with the outline of the nearby Sarawak Chamber superimposed at the same scale for comparison.

VERY LARGE COLLAPSE DOLINES

Dolines comparable to tiankengs

Within the Mulu karst, in Sarawak, the Garden of Eden is a mega-doline that breaks the course of a very large, old, phreatic trunk passage, remnants of which are now known as Deer and Green Caves (Fig. 11). This mega-doline is about a kilometre across. Round half of its perimeter (the section close to the line of the original cave passage), steep and vertical limestone cliffs rise 150–300 m. However, the other side of the doline, along with part of the doline floor, is a rising shale slope scored by allogenic streams draining out of the rain forest. The site could therefore be described as a blind valley that happens to have breached a large cave passage. Alternatively, the Garden of Eden may be regarded as a highly degraded erosional tiankeng, with a volume of about 150M m^3 . Deer Cave is 100 m high and wide, and collapse of its continuation at the junction with an inlet river passage fed from the shale slopes could have created a very large doline. Such a massive collapse feature could be regarded as unlikely, until comparison is made with the nearby Sarawak Chamber (Table 1, Fig. 2), which will one day collapse on this sort of scale.

In southern Italy, the Gargano and Murge karst plateaus are broken by some very large dolines (Table 1). The largest is the Dolina Pozzatina on the Gargano (Fig. 12). Over 500 m across, it is little over 100 m deep, and is heavily degraded; only short sections of cliff project from slopes of wooded scree that descend to a flat floor over 100 m across. The Murge plateau has two very large dolines, each about 300 m in diameter, of which the deeper is the Pulicchio, 100 m deep from a very level rim. Perimeter cliffs drop



Figure 12. The Pozzatina doline in the Gargano karst, Italy. (Photo: John Middleton)

20–30 m from the rims, to slopes of scree down to the wide flat floors. This type of large doline (locally known as a pulo) may have formed by multiple collapse and disintegration of a network of small caves, like those seen in the margin of the smaller Pulo di Molfetta; but the puli may also have origins in paleokarst dissolution features (Castiglione and Sauro, 2000). The perimeter cliffs could be due to a cap of stronger limestones higher in the horizontal sequence. With no evidence of any associated large river caves, these puli lack features of a tiankeng, and are best regarded as very large dolines.

In Brazil, a low-lying karst 200 km northwest of Brasilia contains the beautiful but innocuous blue lake known as Lago Azul. This has been dived to a sloping debris floor at depths of 220–274 m (Fig. 2); the overhanging walls flair away from the dive lines and have not been mapped in detail. The dimensions of this huge flooded shaft are therefore very close to those of Golondrinas (Table 1). Lacking a vadose environment and any known cave river, Lago Azul is not a typical tiankeng. However, after drainage due to regional rejuvenation, modification by inevitable wall collapse, and perhaps invasion by a vadose stream, its morphology would be indistinguishable from many recognised tiankengs. In Mexico, the giant cenote of Zacaton is a similar flooded cave; its diameter is less than that of Lago Azul, but its lake is 329 m deep. Unless vadose chamber development is deemed diagnostic of a tiankeng, it may be appropriate to regard both Lago Azul and Zacaton as proto-tiankengs, albeit of a slightly unusual type.

The great quartzite plateaus known as tepuis in southern Venezuela are broken by a surprising number of large shafts (Galan and Lagarde, 1988). Most of these are giant fissures, but the Sima Mayor de Sarisarinama is almost circular in plan, 300 m across and over 230 m deep (Fig. 2); it has vertical perimeter cliffs overlooking a floor of breakdown blocks shrouded in rain forest. Caves have developed along fissures in the quartzite where chemical weathering at grain boundaries leaves loose grains that are then mechanically removed by piping processes. Development of a doline with a volume of 18M m^3 , is a very slow process, even with collapse modification, but the tepuis are ancient structures of Precambrian rock. If Sarisarinama was in limestone instead of quartzite, it would be regarded as a splendid tiankeng, though it does lack any large cave river (both now and in the past).

Other very large dolines

The various karst regions of the world contain shafts and dolines of every shape and size, except that they do not match all the morphometric and genetic features of a tiankeng (Zhu and Waltham, this volume). However, some or all of them may be genetically related to tiankengs. The processes behind their development and evolution may be pertinent to debate over the genesis of the true tiankengs.

In western Asia, Oman has some remarkable desert karst terrains. In the Dhofar karst of southern Oman, Tawi Atair is a collapse doline 210 m deep with largely vertical perimeter walls (Fig. 13); it is 130 m across at ground level, but its lower half is an

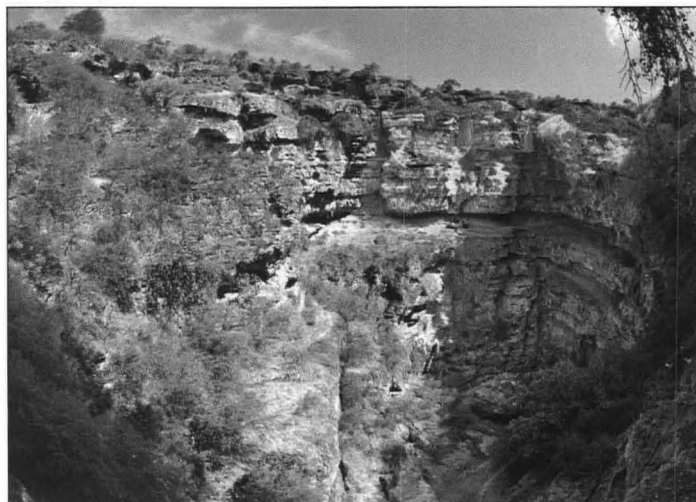


Figure 13. The large doline of Tawi Atair, Oman, with the lower shaft dropping out of sight towards the right.

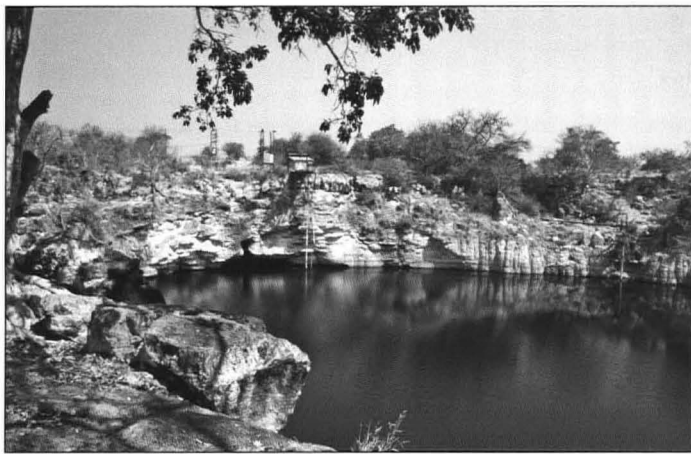


Figure 14. The deep cenote of Lake Guinas, Namibia, with an old water supply pumping station on the far side.

internal shaft only about 70 m in diameter. The Selma karst, in northern Oman, is broken by large shafts into both a dendritic cave system and also into the separate Majlis al Jinn (Hose, 2004b). The latter has a chamber over 200 m in diameter and 120 m high beneath a roof just 40 m thick, and this will eventually fail to create a deep collapse doline of tiankeng dimensions. All these features of the Oman karsts appear to date from wetter climates in the past, though some early hydrothermal activity could have contributed to the anomalous size of the Majlis al Jinn chamber.

Europe has some very deep shafts in its alpine karsts, including the remarkable Vrtiglavica 643 m deep in Slovenia's Kanin massif, but these are vadose features with minimal collapse modification and few are more than about 15 m across. France's Gouffre de Padirac is more like a tiankeng and is 100 m deep, but it is less than 50 m in diameter.

North America has little of the deep karst where a tiankeng could form. Cedar Sink, in Kentucky, is an impressive doline, 250 m long and 180 m across, formed by collapse into passages within the Mammoth Cave System, but it is only 50 m deep. Deeper karst basins with partially cliffed perimeters include Grassy Cove and Icy Cove in Tennessee (White and White, this volume, Fig. 9). These are kilometres long, and have evolved by wall retreat, so that any initial cave collapse was only a small component of their development; they are not tiankengs. There are also some deep shafts and collapse dolines, but none has the width or volume of a tiankeng.

The well-developed karst of northern Jamaica contains the Linton Park Light Hole, a forest-floored collapse doline 400 m across and completely ringed by vertical cliffs that stand 45-200 m high. Nearby the Asuno and the Volcano are shafts each more than 120 m deep but only about 50 m across. These three sites are all in the catchment of the Cave River, but none qualifies as a tiankeng.

The limited extent of karst in southern Africa is distinguished by some deep flooded shafts. Lake Guinas, in Namibia, is 145 m long

and 70 m wide, but it is a giant cenote 132 m deep (Fig. 14). In South Africa, Bushmangat is a flooded cave chamber 264 m deep; it is 240 x 75 m in plan at the -100 m level, but its entrance is a vertical hole only 30 m long and 12 m across. These features are not tiankengs, but they do stand comparison with Lago Azul and Zacaton (see above).

The Nullarbor karst in Australia is well known for its scatter of large collapse dolines associated with cave passages that are up to 40 m wide. None matches the size of a tiankeng. Furthermore, most are now largely choked with their own collapse debris, which is not being removed in the current environment of minimal groundwater flows. Away from the Nullarbor, the Big Hole, in New South Wales, is a large caprock doline with spectacular perimeter cliffs of sandstone; it is 115 m deep but only about 60 m across. There is no evidence of a large river cave under the Big Hole, but a large solutional shaft reaches up to the base of the sandstone caprock in the nearby Wyambene Main Cave.

In Papua New Guinea, both the Mamo and Atea plateaus, in the Muller Range, have many very large dolines, most of which lack the vertical perimeter walls of a true tiankeng (James, this volume). These include the spectacular sink of the Atea River, in a doline that matches the size of a tiankeng, though it is open on one side; with its sinking river draining off a caprock, this could be equated to the erosional sub-type of tiankeng that is recognised in China. Further northwest, on the Hindenburg Plateau, Girtol and The Sting are the two largest known collapse dolines, but both are smaller than normal tiankengs (Brook, 1976).

Comparable collapse features outside limestone

The low mechanical strength of gypsum makes it an unlikely environment for a tiankeng, except perhaps for a rather short-lived collapse feature. In the Turkish gypsum karst near Sivas, the Kizilcam doline is 350 m across and over 50 m deep to its lake. It is clearly a degraded collapse doline (Waltham, 2002), and cliffs that form many sections of its perimeter make it comparable to some of the landforms known as small tiankengs in China. The Vermillion Creek doline is a spectacular caprock doline in more than 100 m of cover shales above gypsum in northern Canada (Ford and Williams, 1989); its vertical walls are 40 m deep to a lake surface. Also in Canada, collapse features that are kilometres wide and deep over the Prairie evaporites have little or no surface expression; they are breccia pipes, and as such are clearly distinct from tiankengs.

The only exposed collapse features that do stand comparison to the limestone tiankengs are calderas that have formed by loss of support when magma pressure is reduced under a volcanic edifice. However caldera floors appear to have descended as integral blocks inside perimeter faults, due to a slow decline of magma support. This contrasts the total breakdown when a cave chamber roof collapses long after most of its support was eroded away. Most calderas are so old that they are greatly degraded, and many now have lakes in them, best known at America's Crater Lake and China's Tian Chi (on the frontier to North Korea). Katmai, in Alaska, is among the least

Figure 15. The caldera on the Katmai volcano in Alaska, with its internal glacier right of the lake.



degraded of calderas, as it was only formed during its 1912 eruption; nearly 3 km across, this caldera is 600 m deep, though it now contains a lake 300 m deep beneath its precipitous perimeter cliffs (Fig. 15). Though much older, the Trou au Natron caldera, in the Chad sector of the Sahara Desert, also appears fresh because it is little eroded. Over 6 km across and about 1000 m deep, it retains almost vertical walls above ramparts of scree that reach only half their height.

TIANKENGs AND COLLAPSE

By December 2005, 49 tiankengs had been identified in China (Zhu and Chen, this volume, Table 1) together with another 26 tiankengs in the rest of the world (Table 1). They all lie inside the latitudes of the tropics, except for those in China and the Dinaric karst - and these two regions are those with the greatest thicknesses of limestone in the world. All tiankengs have developed in the mature karst terrains - either those that have developed rapidly within the wet tropics, or those that have evolved slowly through huge thicknesses of limestone. Most of the known tiankengs are in well-developed fengcong cone karst, though many of the host terrains lack the local relief (cone heights) of China's fengcong. Tiankengs are undoubtedly a feature of karsts that are extremely well developed.

The world's karst contains numerous large collapse dolines, in addition to those cited in this brief but representative inventory. Many are massive, spectacular and very significant landforms, but none meets all the criteria for recognition as a tiankeng. In addition, there are many more giant dolines whose genesis is not entirely clear. Most of these are generally regarded as large solution dolines, but all have some element of rock collapse within their evolution. Where the role of cave collapse can be shown to be major, some of these large dolines could be regarded as greatly degraded tiankengs. However, this may not be helpful, as it blurs the distinctiveness of the tiankeng.

Since the fortunate demise of those uninformed times when so many limestone gorges were wildly described as "collapsed caverns", collapse has been somewhat denigrated as a major process in karst landform evolution. Slow dissolution has been seen as more important. Recognition of China's tiankengs, and subsequent re-appraisal of very large dolines in China and elsewhere, may have turned the tide in geomorphological thought. It is now difficult not to conclude that large-scale collapse of large cave passages is a very significant process in many karst terrains.

Acknowledgements

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Tiankeng: definition and description

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Abstract: A tiankeng is a type of very large collapse doline that has evolved by roof collapse over a large cave chamber where a huge mass of breakdown debris has been removed by a substantial cave river. Described first in China, the term *tiankeng* is recognised as a useful term within the world's lexicon of karst.

Key words: karst, doline, tiankeng, China, definition

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Tiankengs have been recognised in China as very large collapse dolines that have both significant scientific value and also considerable economic value as spectacular sites within the country's expanding tourist industry (Zhu, 2001). It is now proposed that the term should be recognised and accepted as a part of the international karst lexicon.

The word *tiankeng* is a transliteration from two Chinese characters, that roughly mean *sky hole* or *heaven pit*, or some similar variation on that double theme. The vagaries of the pinyin spelling unfortunately misrepresent the Chinese spoken word, and its correct pronunciation is more like *tiengkung*.

It is suggested that a tiankeng is a karst landform that is distinctive enough to warrant its own name. In broad terms, it is a collapse doline at least 100 m wide and deep, that has formed by rock failure into a large cave. However, a tiankeng needs to be defined appropriately and described adequately. This definition must be morphogenetic, so that it takes account of both the landform's morphology (and morphometry), and also its origin and development (in both the geomorphological and the hydrological contexts). The examples cited to demonstrate features within the following text are all briefly described in the two preceding papers in this volume, on tiankengs in China (by Zhu and Chen) and tiankengs elsewhere (by Waltham).

TIANKENG MORPHOLOGY

In morphological terms, a tiankeng is a collapse doline that is more than 100 m deep and wide and has a steep profile with vertical cliffs around all or most of its perimeter. Dashiwei Tiankeng in China and Tres Pueblos Sinkhole in Puerto Rico are fine examples.

Tiankeng dimensions

Defining minimum dimensions is necessary, as size is a diagnostic feature of a tiankeng, but the 100 m limit is arbitrary. The definition should be interpreted with discretion, especially in those cases of very obvious collapse dolines that just fall short in one dimension. The diameters (or length and width) can only be measured with a degree of approximation where the edges are degraded and rounded, as is the case on all but a handful of very fresh features. Depth is more easily measured. However, Chinese statistics tend to cite the maximum depth from the highest point on the rim. Where the rim breaks through a series of hills in fengcong karst, this figure is very different from the minimum depth, from the lowest point on the rim, as is generally cited in Western statistics. The 100 m minimum is normally applied to the maximum depth, but discretion is required to ensure that this is truly indicative of any particular landform's morphology. Smaller depressions formed by collapse are best described just as large collapse dolines. It is gigantism that relates tiankengs to specific conditions of formation and separates them from other types of collapse dolines.

A minimum volume could be a better way of defining a tiankeng by its morphometry. However, volume data are rarely available, except as a gross approximation, because wall profiles of dolines and tiankengs are not normally measured in adequate detail. A perfect

cylinder of the minimum depth and diameter has a volume of about 800,000 m³; a realistic minimum for the volume of a tiankeng is about 1M m³.

The depth/width ratio of a tiankeng lies between 0.5 and 2 (0.5 < d/w < 2.0), where the width refers to the maximum width, length or diameter of the feature, measured at rim level. Again these arbitrary limits should be interpreted with discretion. Most karstic depressions with depths significantly greater than double their widths (d/w > 2) are best described as shafts, with the genetic implication that their origin owes more to dissolution by descending water than to rock collapse. Some tiankengs have a lower depth to width ratio (d/w = 0.5–0.2), where they are either significantly degraded or are multiple features. A degraded tiankeng has only limited remnants of cliff sections within its profile, as in Lusé in New Britain. A multiple feature is one formed by coalescence of a series of collapses into a large cave passage, as at Qinlong Tiankeng (Chongqing); this may therefore be very long, but its width and its cross-profile remain typical of a tiankeng. Other large karstic depressions with these depth/width ratios include large solution dolines, some poljes and genetically ambiguous mega-dolines, but these lack the collapse mechanism that formed a tiankeng. Any shallower depression (d/w < 0.2) cannot warrant description as a tiankeng.

The ratio of the diameters of a typical tiankeng at its top (rim) and at its bottom (floor) lie between 0.7 and 1.5 (0.7 < w_t/w_b < 1.5), but these limits are also arbitrary and open to interpretation. Vertical perimeter cliffs in the ideal tiankeng create a ratio of exactly 1. Various tiankengs in China have w_t/w_b in the range 1.5–2.0, and Lusé, in New Britain, has a ratio of about 2. Floor diameter is increasingly difficult to define in degraded tiankengs where aprons of scree debris merge into a rounded floor profile. Conversely an incomplete roof collapse in what may be regarded as an immature tiankeng has w_t/w_b < 0.7. Golondrinas (in Mexico) has a large opening with walls bellling out in an even larger shaft, so that w_t/w_b ~ 0.15. Along with a few other sites, Golondrinas is best described as an immature tiankeng. Maoqi Dong, in the Leye karst, could be regarded as a proto-tiankeng; its huge shaft is 300 m deep and 200 m wide but has only a small skylight in its domed roof, so w_t/w_b < 0.05 (Fig. 1).

Tiankeng profiles

A tiankeng is distinguished by having vertical or sub-vertical walls for much of its depth and round most of its perimeter. They are among the clearest evidence of collapse origins, though they may be due either to failure into an underlying cave or to subsequent face retreat. Vertical cliffs are dependent on geological structure; they develop best in strong and massive limestones, and primarily where fractures are close to vertical, which tend to be more dominant in beds of low structural dip. Limestones dipping at around 45° tend to have similarly inclined fractures that preclude development of steep tiankeng profiles. Tiankengs with depths greater than their widths tend to be the more spectacular, but the key factor in the visual spectacle is the completeness of a ring of high cliffs (Fig. 2);

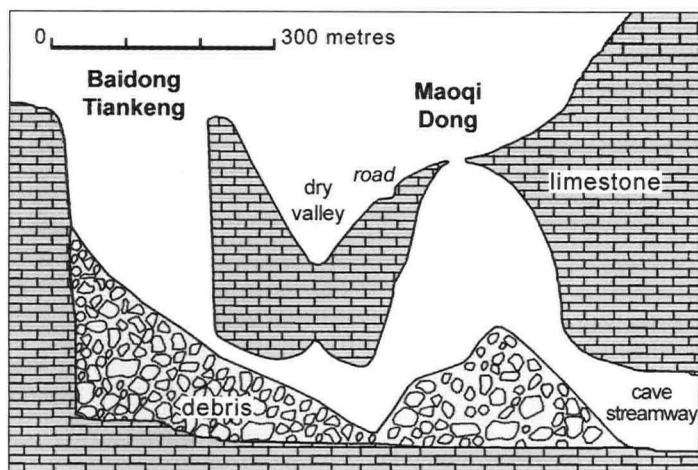


Figure 1. Section through Baidong Tiankeng and the adjacent skylight chamber of Maoqi Dong which may be regarded as a proto-tiankeng; the bedrock profile beneath the debris piles is conjectured.

Huangjing Tiankeng (Guangxi) and Minyé (New Britain) are therefore prime examples.

Degraded tiankengs are those that have lost a significant proportion of their perimeter cliffs. The inevitable retreat of an exposed face, by weathering and successive rockfalls, creates an apron of scree debris at the base of the cliff. In an active tiankeng, rockfall debris is removed by the cave river, so that only modest scree ramparts of debris remain beneath the cliff faces, as at Xiaozhai Tiankeng (Chongqing) and Velika Dolina (Slovenia). Where the cave river is too weak or is lost to a by-pass route, breakdown debris accumulates until it may mask much, or all, of the cliff faces. Progressive degradation sees the perimeter cliff faces reduced in height and perhaps also broken by gully development. There is an inevitable evolution from a tiankeng like Naré (New Britain), to a degraded tiankeng such as Datuo (Guangxi), and then

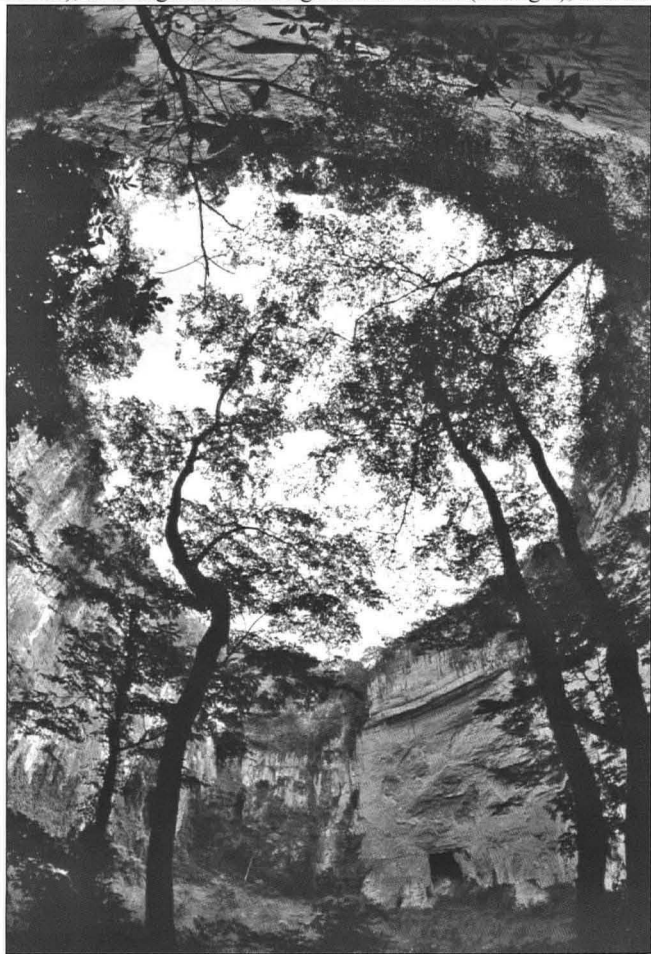


Figure 2. The complete ring of vertical cliffs of Huangjing Tiankeng, Guangxi, seen in a very wide upward view from the floor.

to a mega-doline such as Garden of Eden (Sarawak). There are no clear boundaries between the three forms (see below).

The bedrock floor of a tiankeng is largely or wholly masked by broken rock debris as an inevitable consequence of its collapse origins. This may be a single pile or ramp of breakdown from a cave roof failure. It is more commonly a convergent series of fans and aprons of debris created by subsequent failures of the retreating perimeter cliffs. Some active tiankengs have an exposed cave river across their floors; others only have an underground river flowing through their floor debris, and this may or not be accessible. Tiankengs such as Qinlong (Chongqing) have small or underfit rivers flowing between dominating ramps of debris, while most degraded tiankengs no longer have any sign of a cave river. Entrances to cave passages should be a feature of any tiankeng, but they are commonly obscured behind accumulated rockfall debris; these should include active inlet and outlet caves at floor level, and may include older passages at higher levels, as at Xiaoyanwan (Sichuan).

TIANKENG DEVELOPMENT

A tiankeng is a collapse features formed over a large underground cave passage. It may develop by collapse of a single large chamber, as appears to be the case at Xiaozhai Tiankeng in Chongqing. Alternatively, a tiankeng may form by collapse at the junction of a series of large passages, which includes collapse through superimposed levels of passages that are of varied ages, as at Xiaoyanwan in Sichuan. Cave roof collapse normally involves prolonged roof stoping and upward cavity migration. Within this, a long sequence of progressive failures cause small quantities of rock fall from the tensile zone beneath the compression arch (which creates the stable roof span within the rock spanning the void). The ultimate failure through to the ground surface may then be a single event. Alternatively, the surface failure may be by multiple events, with coalescence of smaller collapses. Some tiankengs are elongate due to collapse along the line of very large cave passages; Qinlong Tiankeng (Chongqing) and Dacaoakou (Guizhou) provide fine examples (Fig. 3). The very large size of some tiankengs suggests that they are multiple failures; they are inordinately larger than known cave chambers, and much of their volumes is accounted for by the removal of debris from the base by dissolution and erosion. The rounded shape of many tiankengs is likely to have evolved by cliff retreat (where stress distribution favours failure towards a stable circle).

Most observed tiankengs expose within the limestone one or more structural weaknesses, notably sub-vertical faults and joints. Xiaozhai Tiankeng (Chongqing) provides an example, where the cave river crossed intersecting, sub-vertical fractures that appear to be small-displacement faults (Fig. 4). These facilitated the processes of vertical expansion by roof stoping, as well as lateral expansion by wall retreat and coalescence of collapses. Such structures are however not unique to tiankengs, as nearly all cave passages and chambers have developed at some form of structural weaknesses.

A large underground river is an essential feature of an active tiankeng, as it provides the only means by which the huge volumes of missing rock can be removed, either in solution or as clastic sediment. This is commonly a vadose cave river, but the flow may

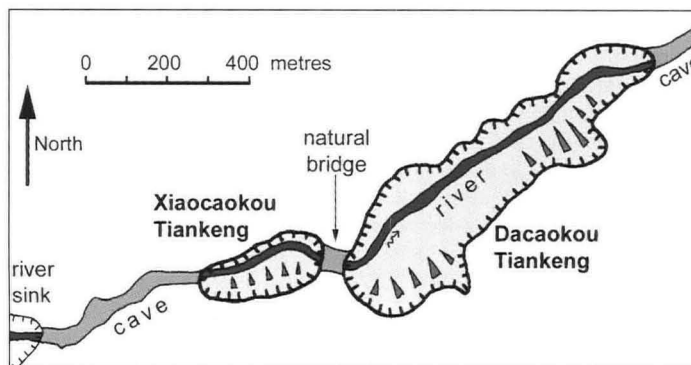


Figure 3. The tiankengs of Dacaoakou and Xiaocaokou, separated by a natural bridge, all formed on the course of the Yijie underground river in Guizhou.

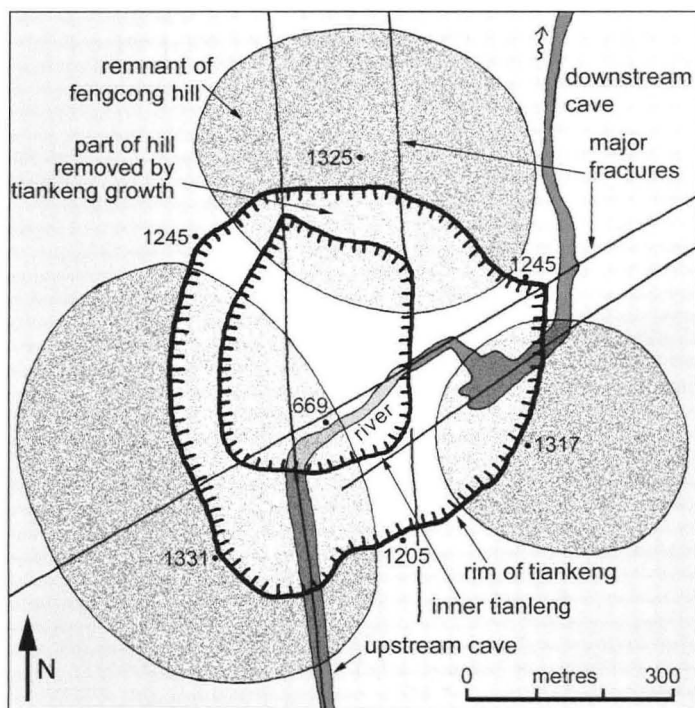


Figure 4. Structural interpretation of Xiaozhai Tiankeng, Chongqing, with the observed fractures that may have initiated tiankeng development over the Difeng cave river and beneath a doline between three hills within the fengcong karst. The fracture traces are simplified; those along the cave passages are multiple fracture sets, and the SW-NE fractures may break into en echelon series.

be phreatic. The erosional ability of the cave river relies on the supply of broken rock that is provided by progressive roof stoping and wall failure. Steeper hydraulic gradients through a breakdown pile also enhance rates of dissolution and erosion (Palmer and Palmer, this volume). Large wall undercuts are common in tropical caves where water flow is deflected around a pile of collapse debris; they contribute to the enlargement of cave chambers and tiankengs alike. Wall undercutting is also enhanced on the outside of a bend in a cave passage, as may be the case at Xiaozhai (in Chongqing). Roof stoping and cave river transport are synergic in tiankeng development - which only proceeds when both processes are active on a large scale.

The relationship of tiankengs to large underground rivers ties them to the wet tropical environment or to situations in other climates where allogenic rivers are swallowed into karst to produce large cave river passages. This criterion also separates tiankengs from other giant collapse features, including caprock collapses over evaporites (as in Canada and Russia) and large collapses over hydrothermal cavities (as in Oman), which do not classify as tiankengs.

The huge, circular, collapse doline of Sarisarinama, in Venezuela, has developed in quartzite by piping and clastic sediment removal on a massive scale. Except for the fact that it is not in limestone, it would be regarded as a tiankeng, yet there is no cave river associated with it. This may be explained by an exceptionally long period of very slow evolution, but the site may have implications with respect to the processes that develop tiankengs in limestone.

Development in the vadose zone

Tiankengs are deep open holes that lie within the vadose zone of the karst. An active tiankeng may have a cave river across its floor (or through the debris on its floor); this cave drainage is normally vadose, but is phreatic at some sites. Vadose conditions also maximise stress on a cave chamber roof, which lacks the buoyant support of a completely phreatic chamber. But a tiankeng may not be a wholly vadose feature. Of the recorded tiankengs, about half have no known cave river flowing through them or directly associated with them. However, half of these river-less tiankengs do have associated cave passages that carried underground rivers in the past,

and some may have rivers that pass unseen through their floor debris. Some tiankengs, including Xiaoyanwan in Sichuan, formed by collapse into large phreatic passages, where there is no sign that they have positively evolved within the vadose zone. Crveno Jezero (Croatia) has active phreatic cave drainage that is removing the collapse debris beneath the water-table.

Any large cave chamber may collapse to form a tiankeng, as long as through-drainage removes enough of the breakdown material to create a deep open hole. Furthermore, virtually all caves and cave chambers have some phreatic origins that were developed prior to their drainage. Vadose modification of a large, open, de-watered shaft or collapse doline is inevitable, but vadose erosion may not be the dominant process that forms a tiankeng. Lago Azul, in Brazil, has the dimensions of a tiankeng, but is clearly phreatic because it is full to the brim with water. Eventually, regional rejuvenation will cause its drainage, and it will then have a morphology very similar to that of Golondrinas, in Mexico. This may be an extreme case of early phreatic enlargement - that will be unrecognisable once the feature is in vadose zone and is modified by vadose erosion and wall collapse. Lago Azul may warrant description as a proto-tiankeng. The same applies to the very deep cenote of Zacaton, in Mexico, but this may partly owe its size to corrosive waters rising from a volcanic source rich in with hydrogen sulphide. These sites questions whether, or to what extent, vadose development should be an essential criterion of a tiankeng.

It is debatable to what extent solution dolines have contributed to the development of tiankengs. The growth of a doline would reduce roof thickness over an underlying cave chamber, thereby hastening the eventual collapse, and it would also direct more drainage into the site, thereby enhancing localised rock dissolution. A solution doline could be expected to form on the same structural weaknesses that guide the chamber development underneath it. The cave of Zhucaojing in the Xingwen karst of Sichuan (Waltham, this volume) has deep solution dolines above its large chambers, and appears to be a clear example of imminent tiankeng development.

In contrast, some tiankengs in China breach steep hillsides where no large solution dolines are likely to have developed. Many tiankengs in China appear to be completely independent of the surface morphology, in that their walls cut through dolines and conical hills alike (Fig. 5). However, cutting into the cones is enhanced by the wall retreat that expands the tiankengs. At many sites, the distribution of the cone remnants cut by the perimeter walls does leave space for the tiankeng to have originated at a central solution doline within the fengcong terrain (Fig. 4). It appears that solution dolines have contributed to the development of many tiankengs, but they were not essential features; the evidence was destroyed by the collapses that eventually formed the tiankengs.

Most of the tiankengs in southern China lie within the terrains of mature fengcong with high local relief that are so typical of the karst region. In New Britain and Puerto Rico, tiankengs lie in cone karst with much less local relief, and those elsewhere lie in karst terrains

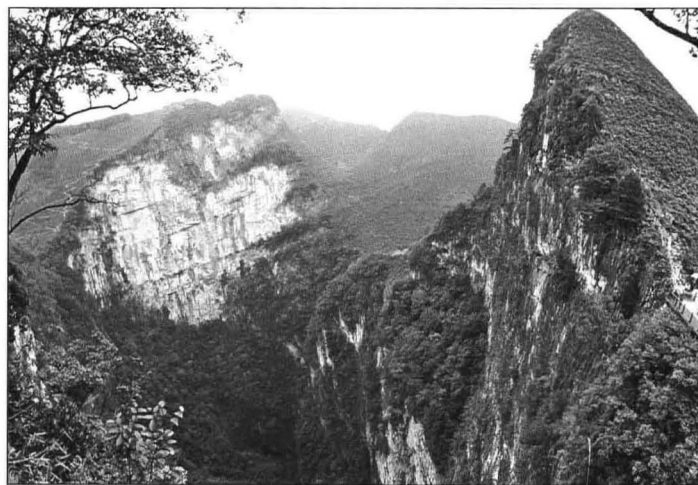


Figure 5. Remains of two fengcong karst hills truncated by expansion of Dashiwei Tiankeng in the Leye karst of Guangxi, seen from the flank of the third hill that has been truncated by collapse.

	<i>collapse tiankeng</i>	<i>erosional tiankeng</i>
<i>gross morphology</i>	vertical or overhanging walls	vertical walls
<i>wall features</i>	collapse scars	waterfall gullies
<i>dominant process</i>	collapse	erosion
<i>origin</i>	collapse of cave chamber	large waterfall shaft
<i>mass transport</i>	by cave river flowing through	by river sinking into cave
<i>growth direction</i>	upwards from cave river	downwards from sink
<i>relationship to cave river</i>	cave river pre-dates tiankeng	tiankeng contemporary with cave river
<i>hydrology</i>	vadose, or partly phreatic	vadose
<i>floor material</i>	mainly breakdown debris	alluvium and breakdown
<i>floor topography</i>	river buried or at margin	river bed to cave outlet
<i>relationship to surface topography</i>	no correlation in fengcong, in doline, valley or hill	in valley or depression, fed by surface stream
<i>abundance</i>	many	few
<i>age (in China)</i>	since early Pleistocene	since late Pleistocene

Table 1. Comparisons between the various features of erosional and collapse tiankengs.

that are not fengcong. Though deeply dissected fengcong may be the ideal environment for tiankengs, it does not appear to be a criterion for their development.

Erosional tiankengs

A sub-class of tiankeng, the erosional type, has been recognised within China as distinct from the more common collapse type (Table 1). An erosional tiankeng develops at the site of a sinking allogenic stream, as distinct from collapse tiankengs that are independent of surface drainage. The erosional type therefore has a cave stream draining from it, but not into it. Qingkou Tiankeng in Chongqing is therefore an excellent example (Fig. 6).

The relative roles of collapse and waterfall erosion appear to vary widely between sites. Some large holes in karst are just greatly enlarged solutional shafts, typically with a high depth/width ratio ($d/w > 5$). There must be some elements of collapse, shaft coalescence and/or wall retreat to enlarge these to the dimensions of an erosional tiankeng, as a single waterfall shaft either retreats into a sinuous canyon or bells out to no more than about 20 m wide. Similarly stream erosion has contributed to the erosion of many collapse tiankengs. Xiaozhai Tiankeng (Chongqing) has three waterfalls descending its walls in wet weather, but these are fed by immediate run-off from the limestone.

Some erosional tiankengs are large caprock dolines, as they have formed by collapse within underlying limestone that has propagated to the ground surface through a cover of insoluble rock. These therefore gather significant allogenic drainage off the surrounding cover. Others only gather allogenic input from adjacent outcrops of cover rock. Furthermore, it is open to debate whether many other tiankengs, especially in the Leye karst in Guangxi, collected allogenic drainage before retreat of the margin of the cover rocks.

The separation of erosional tiankengs from collapse tiankengs therefore appears to be dubious. It is better to regard both as end members of a spectrum of conditions, where collapse and dissolution vary in their relative importance. Both processes contribute to the development of all tiankengs, which may therefore be described as polygenetic.

Degraded tiankengs

An inevitable process in tiankeng evolution is wall retreat, but this only contributes to enlargement while a river is removing the breakdown debris, as is conspicuous at Kukumbu in New Britain. When the rate of debris accumulation exceeds the rate of removal, a tiankeng starts to degrade, as ever larger fans and aprons of scree accumulate at the base of the walls. This rockfall debris from the walls is added to debris remaining from the earlier roof failure. A degraded tiankeng has its perimeter cliffs progressively buried by the aprons of scree, while the rim is being lowered at the same time, and the depth/width ratio therefore decreases ($d/w < 0.5$). Ultimately, trees grow to mask the rock debris. Of the 74 recorded tiankengs, at least 12 are properly described as degraded (Zhu and Chen, this volume, Table 1; Waltham, this volume, Table 1).

There is a clearly recognisable evolution of a tiankeng into a degraded state, and beyond. Ultimately, a tiankeng degrades so much that almost all its perimeter cliffs are lost, and it is then regarded as a mega-doline. Many very large dolines could have



Figure 6. One of the waterfalls that cascade into Qingkou Tiankeng (Chongqing), which all drain out through a large stream cave.

originated as tiankengs, and it may be questioned as to how many deep dolines within very mature, high-relief, fengcong karst originated as tiankengs. However, it may be unhelpful to describe these large dolines as heavily degraded tiankengs, as this blurs the concept of the tiankeng. Similarly, a tiankeng could be regarded as a sub-type, or a stage in the evolution of, a mega-doline, though such would not be the origin of all mega-dolines.

The age of tiankengs requires further investigation. Ages of the large tiankengs in the Nakanai karst on New Britain were estimated at 200–300 ka, but this was only based on the overall rate of surface lowering (Maire, 1981). Most tiankengs in China are relatively youthful features, as they truncate the topography of solution dolines and conical hills within the fengcong karst. However, such evidence only dates the surface collapse that created the open tiankeng, and solutional and stoping development of the underground cavern must have taken longer. The sheer size of many tiankengs suggests a very long history to allow time for erosional removal of the huge volumes of missing rock.

CLASSIFICATION OF TIANKENGs

Tiankengs may be classified as a very large sub-type of collapse doline (Waltham et al, 2005). Some may be classified as caprock tiankengs, and these would include most erosional tiankengs if that sub-type is accepted. They are distinguished from collapse and caprock dolines by their very large size.

It is appropriate to use a three-fold sub-division of tiankengs that is already applied in China (Zhu and Chen, this volume) -

- Very large tiankengs are more than 500 m in diameter and depth.
- Large tiankengs are 300-500 m in diameter and depth.
- Normal tiankengs are 100-300 m in diameter and depth.
- Smaller features are large collapse (or caprock) dolines.

These limiting dimensions should be interpreted loosely and with discretion. A large tiankeng should have its depth and length greater than about 300 m, though its width may reach rather less than that figure. Maximum dimensions of a tiankeng with very irregular shape may give a false impression of its size; Xiashiyuan and Zhongshiyuan, in Chongqing, both have large maximum dimensions that belie their relatively shallow but inclined structure in a slope that follows the limestone dip. The depth would sensibly be measured from the mean level of the rim, and not from the highest point (as is cited in Chinese literature), but the mean figure is rarely available. In theory, the depth of a tiankeng should be measured to the base of the debris pile over its rock floor, but this depth cannot be determined at some sites.

It could be more precise to sub-divide tiankengs on the basis of their volumes. The disadvantage of this is that volumes are not so easily or frequently measured with any degree of accuracy (most of the figures quoted in the tables in this volume are very rough estimates from basic maps). The minimum volumes for normal, large and very large tiankengs are about 1M, 10M, and 70M m³.

Within some karst regions in China, tiankengs have become part of the local culture. Some features so described have depths and diameters of 50-100 m, and are described as small tiankengs, though in other parts of the world these would be described only as large collapse dolines. Because a tiankeng is defined as a large collapse doline, a small tiankeng would be a "small large collapse doline", and this is unacceptable in a widely used term. To include features with all dimensions less than 100 m detracts from the value of the tiankeng as a distinctive feature.

There are 75 recorded tiankengs worldwide, including 49 in China. Of these, only 3 are very large, and are all in China. Then there are 16 large tiankengs, of which 9 are in China. The other 56 are normal tiankengs, of which 37 are in China. There are also many hundreds of large collapse dolines, both within and outside China.

Tiankengs do not lend themselves readily to a Davisian sequence of evolution, due to the instantaneous cave roof collapse by which they are formed. A mature tiankeng is distinguished by its almost complete perimeter cliffs that are close to vertical (Fig. 7). An immature tiankeng is one with overhanging cliffs due to incomplete collapse of the original cave chamber, as a consequence, the surface opening is significantly smaller than the floor area ($w_t/w_b < 0.7$). There is no benefit in retreating further on the evolution chain by defining a youthful tiankeng. A large cave chamber with a thin roof or a small skylight (or a flooded chamber) may eventually collapse to form a mature tiankeng, but is better described as a proto-tiankeng prior to its roof failure; it does not yet have the appearance of a tiankeng. A degraded tiankeng still retain its large dimensions and many sections of perimeter cliff, but its floor is much smaller than its surface area ($w_t/w_b > 1.5$). It has an excess of debris on its floor and in ramps up its perimeter, and has no cave river through it. It could be described as one of old age, but description as degraded is more helpful. There is no clear borderline between a degraded tiankeng and a large doline or mega-doline.

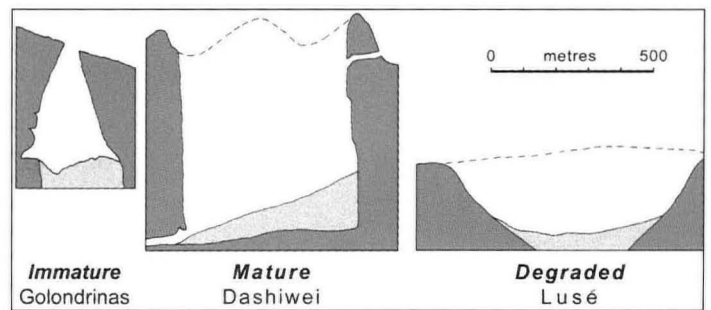


Figure 7. Comparative profiles of good examples of immature, mature and degraded tiankengs.

Tiankeng karst

The concept of tiankeng karst has been considered within China as a term to describe an extremely mature type of karst landscape that has matured beyond normal fengcong karst with high relief. The term could be used to describe the Leye karst in Guangxi, China, and perhaps the Nakanai karst in New Britain, Papua New Guinea, both of which are distinguished by unusually large numbers of tiankengs. However, some mature karst terrains contain just a few tiankengs, notably just two in each of the karsts of Xingwen, Croatia and Mexico, and these question the applicability of the term. Tiankeng karst may be purely descriptive of the Leye and Nakanai terrains, but the term has not yet been shown to have any geomorphological status with reference to karst evolution.

CONCLUSIONS

The tiankeng is recognised as a significant karst landform. The key features of a tiankeng may be summarised as -

- It is a distinctive type of very large collapse doline.
- It is more than 100 m wide and deep, with a depth/width ratio that is close to unity.
- It has vertical cliffs round most of its perimeter.
- It was formed by collapse of a large cave chamber into a large underground river.
- Surface lowering within a solution doline may have contributed to this collapse.
- Tiankeng development is largely in the vadose zone within deeply dissected fengcong karst.
- Some tiankengs are partly eroded by sinking allogenic streams.
- Immature tiankengs bell out to floor areas that are larger than their surface openings.
- Degraded tiankengs have most of their perimeter cliffs masked by rock debris.

These properties constitute an appropriate definition of a tiankeng. It is difficult and unnecessarily pedantic to define absolute limits to large collapse dolines that might be too small or too degraded to be regarded as tiankengs, or may be of a different genesis. Tiankeng is a useful addition to the international lexicon of karst terminology. As a distinctive landform, a tiankeng fits within the spectrum of dolines and karst depressions that characterise karst terrains. Though tiankeng research originated in China, the term is applicable in karst terrains elsewhere.

This paper originated from a discussion meeting held in Guilin at the end of the Tiankeng Investigation Project in 2005. A draft text was circulated to all delegates, and was approved by all after incorporating amendments. Delegates at the meeting were Chen Weihai, Andy Eavis, John Gunn, Julia James, Alexander Klimchouk, Andrej Kranjc, Liu Zaihua, Art Palmer and Will White, and the editors. The paper is therefore intended to accord international recognition to the research and work on tiankengs that was initiated and developed at the Institute of Karst Geology in China.

Large collapse chambers within caves

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Abstract: In the karsts of China and Mulu (Sarawak) large chambers and tiankengs are associated with much smaller cave passages. They have developed mainly on fracture zones, some within the phreatic zone, where rock collapse is not associated only with vadose drainage.

Key words: collapse, fracture, chamber, aven, tiankeng

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Southeastern Asia contains many of the largest caves in the world, including the huge maze passages in the Gunung Mulu National Park in Sarawak, and the many enormous linear passages in southern China. From many personal visits to these caves, a few observations may be pertinent to the debate on the origins of tiankengs.

A notable feature of the caves in both China and Mulu is the number of unusually large collapse chambers, some reaching all the way to the ground surface. It is significant that many of these abnormally large collapse chambers are associated with comparatively small horizontal passages. Sarawak Chamber, in the Gunung Mulu National Park of Sarawak, is the world's largest cave chamber, over 300 m wide (Fig. 1), but the cave passages both in and out of it are mostly less than about 10 m wide. In Guangxi, the Dashiwei Tiankeng, one of the largest in the world, is 400 m wide, while the river passage that drains out of it is only about 30 m wide. Nearby, the 20 km of river passages in the Leye River Cave System are mostly of similar size (Fig. 2), except where they break out into seven large chambers, each about 100 m wide. Two of these have collapsed to create the Dacao and Baidong Tiankengs, and another has only the small surface breach of Maoqi Dong.

Cavers' persistent enthusiasm to discover new passages has pushed the limits of exploration into ever deeper flooded zones, through ever smaller passages, and up ever higher rock walls. In pursuit of new discoveries in high-level passages, climbing techniques have been developed, using battery-powered electric drills to construct bolt ladders up the clean walls of massive underground shafts. It is noticeable that the tops of various of these are completely blind, with no open entry passage from above. In Benerat Caverns, in Mulu, Sarawak, two massive avens (shafts explored or known upwards from cave passages) have been climbed to well over 100m high to stop at blind domes. At many sites, the traditional concept of their development by vertically falling water is inapplicable. In these cases, it would appear that a more likely explanation is rock collapse initiated at the base of the shaft and then working upwards by progressive stoping, matched by erosional removal of the breakdown debris at floor level.

Roof profiles of cave chambers show considerable variation. Only some have the conventional dome profile that is created by tensile failure beneath a compression arch within the rock (Fig. 3). The roof of Sarawak Chamber (Fig. 1) is a complex structure that appears to include a number of stable arches. Most cave chambers

Figure 1. Sarawak Chamber in the Mulu karst of Sarawak, with elements of arch structures within parts of its roof (Photo: Jerry Wooldridge).



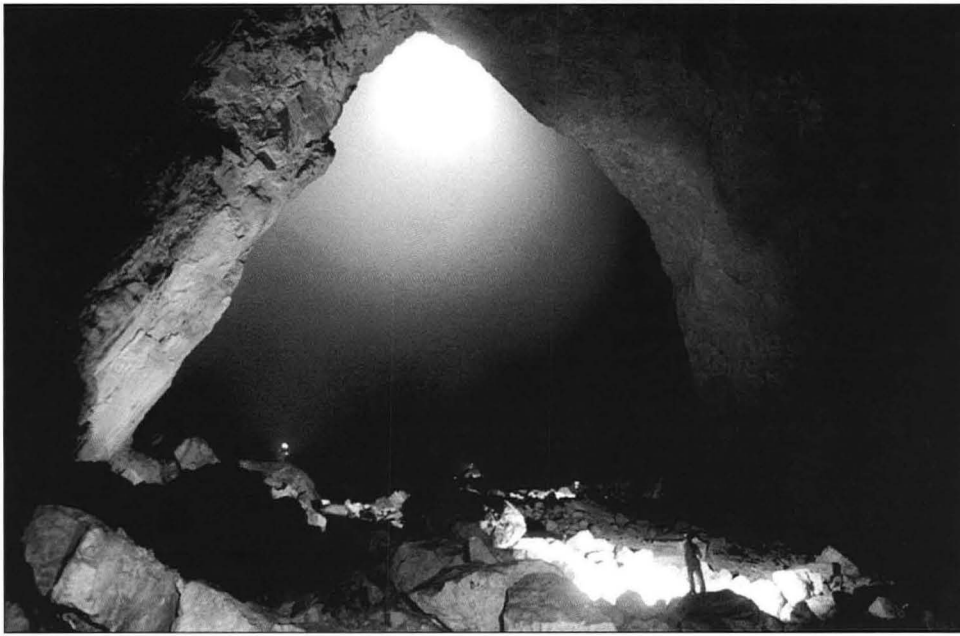


Figure 2. The main passage in Bai Dong, in Guangxi, with daylight pouring in through the Funnel of Light (Maoqi Dong).

are very significantly controlled by structural weaknesses in the limestone, notably faults or major joints. Where solutional enlargement of these fractures creates open fissures, and where a number of fissure sets or zones intersect, a significant weak zone is created within the limestone. Removal of material from the base of this, where it is cut by an active cave passage, may be followed by progressive upward failure. The previously weakened material drops down to leave a vertical shaft, which may be narrow and is excavated totally from the bottom. Some of these shafts continue upwards through to the surface to form sky-holes, and these may then be further developed by surface water.

There are many examples of tall blind chambers, although the structure may not be apparent when exploring upwards from the floor. Some comparatively small chambers have huge echoes from above, and some are very, very high. A large unclimbed and echoing aven in Prediction Cave, in the Mulu karst, appears to be over 100 m high, but could relate to unknown passages at a higher level. Titan Shaft lies on a fracture zone in Peak Cavern, Derbyshire, and has been climbed to a height of 150 m, where there does not appear to be any significant inlet passage.

A huge vertical range of phreatic features is conspicuous in some caves. At some sites in southeastern Asia, there are three-

dimensional, phreatic mazes of tubular passages each of which is 20 to 50 m in diameter. In the Mulu karst, most of Cobweb Cave consists of perfectly circular passages of huge dimensions that form a very complex 3-D maze. Similar phreatic passages in the upper parts of the nearby Clearwater Cave have been breached by the lowering ground surface to create large open collapse features (Fig. 4). Comparable passages have been found within the active phreas of the Tisu catchment, in Guangxi, China. There, divers have entered huge cave passages where the roof is 50 m below the surface of the water and the floor at least 50 m lower. Further exploration of these remains a daunting task.

In conclusion, it does appear that the mechanism for the formation of some steep or vertical blind avens may involve collapse in and around local zones of rock fractures, which may have developed within a very deep phreas at some sites. This may then represent an alternative process whereby tiankeng development is initiated, in contrast to the vadose development that is considered responsible for the typical tiankengs. As cave exploration techniques improve in the future, more blind avens will be climbed and deeper phreatic caves will be explored. It will be fascinating to watch as the story unfolds.

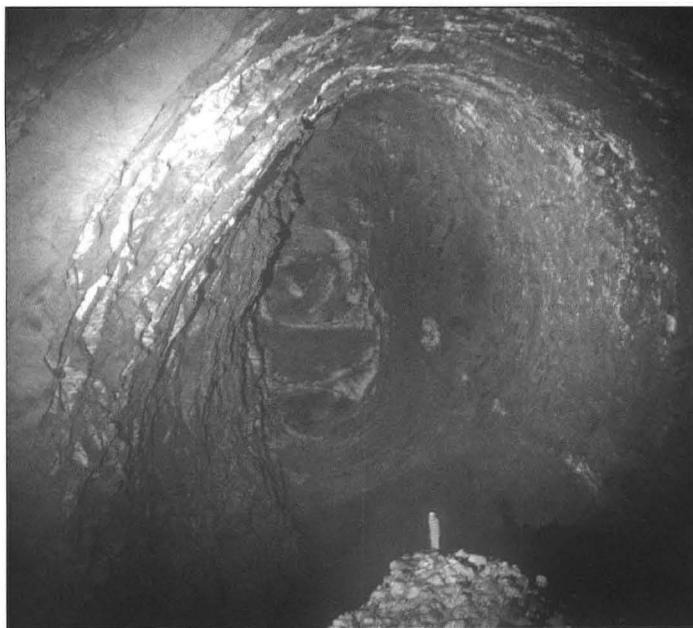


Figure 3. The view upwards into a high chamber with a domed roof in a cave south of Xinlong, Chongqing, China.

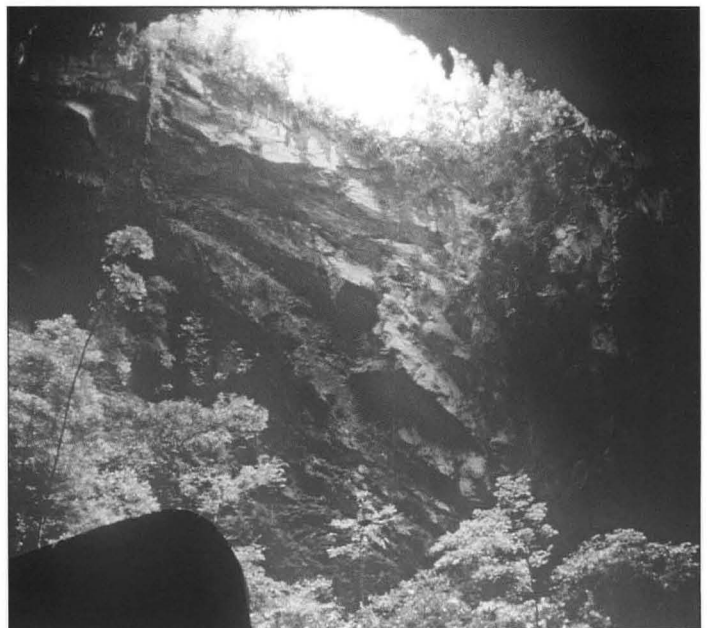


Figure 4. The collapsed chamber of RMAF Hole, a tiankeng formed in the old high-level phreatic passages of Clearwater Cave in the Mulu karst, Sarawak.

Turloughs and tiankengs: distinctive doline forms

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Abstract: Tiankengs lie at one extreme of the collapse doline spectrum, and a key question is whether there is a distinctive 'tiankeng process' or whether the distinction is purely morphological. At the opposite end of the doline spectrum, the turloughs of Ireland are broad closed depressions with seasonal lakes. They may be differentiated from poljes by their smaller dimensions, gentler surrounding slopes and processes of formation. In particular, turloughs are only found in areas where there are glacial deposits and are, at least in part, glaciokarstic landforms whereas poljes occur in many climatic zones and their locations frequently demonstrate a structural influence. Turloughs have been recognised by the European Union as special karst landforms with a distinctive vegetation assemblage, although the term is not widely used because, with one exception, they are confined to Ireland. There are clear parallels with 'tiankeng' the majority of which are in China and which are distinguished from collapse dolines by their large size, and special processes of formation. It is argued that the terms 'turlough' and 'tiankeng' should both become established in the karst geomorphology lexicon.

Key words: turlough, tiankeng, karst, Ireland, terminology

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As discussed in other papers in this volume, the term *tiankeng* (roughly meaning *sky hole*) is used in Chinese to describe particularly large dolines formed by collapse. Zhu and Chen (this volume) propose that there is a distinction between 'normal' and 'giant' dolines, and that the term *tiankeng* should be applied to all of the world's great dolines, not just those in China. Tiankengs clearly lie at one extreme of the collapse doline spectrum, and other papers in this volume examine the question whether there is a distinctive 'tiankeng process' or whether the distinction is purely morphological. The present paper aims to provide some insights from a lateral view of turloughs, which are considered to lie at the other extreme of the doline spectrum, being broad, shallow, depressions that are probably polygenetic in origin.

TURLOUGH DEFINITION

The word *turlough* is commonly reported as being derived from the Irish Gaelic *tuar lough*, meaning a dry lake. However, Coxon (1986), in the most detailed work undertaken on these features, notes that the Gaelic word for *dry* is *tur* and that *tuar* translates as *pasture land*. There are similarities here with the etymology of the word *polje* which translates as a *field*, but has been used in a different sense by karst scientists. It is interesting that the local name for the only turlough recognised outside of Ireland (Pant-y-llyn, in South Wales) has a similar etymology, being translated as *field that is a lake* (Hardwick and Gunn, 1995). An aerial view of a turlough near Ballyshannon in County Donegal, Ireland (Fig. 1) provides an illustration of how this naming has come about. The bare ground that surrounds the lake marks the maximum area of inundation and shows that the turlough is in a relatively early stage of its draining cycle. However, walls can be seen extending across the area that is still inundated and these will delimit fields when the lake finally dries up.

Turloughs are defined primarily on the basis of their hydrology and ecology, although it is clear that they are also karst landforms. For example, in Guidance Document no. GW9 of the Irish Working Group on Groundwater Sub-committee on Turloughs (URL 1, undated) a turlough is defined as "A topographic depression in karst which is intermittently inundated on an annual basis, mainly from groundwater, and which has a substrate and/or ecological communities characteristic of wetlands".

Hydrologically the key feature is the lake itself, which is:

- ephemeral, the majority being seasonal with an autumn fill cycle that is commonly rapid (hours to days) and a late spring to early summer drain cycle that may take several weeks;

Coxon (1986, 1987a, 1987b) suggests that the lake must be at least 0.5 m deep at its maximum, and that most turloughs dry completely each year although some contain residual pools;

- fed partly direct precipitation onto the depression in which it is located but primarily by groundwater which commonly enters from discrete conduits; the water chemistry reflects the groundwater source being close to saturation with respect to calcium carbonate;
- in its natural state has no natural surface outlet but drains via swallow holes or by estavelles; however, some turloughs have been partly drained to improve agricultural productivity.

Ecologically, turloughs are defined by their vegetation communities which show a distinct zonation determined by water depth and the frequency and duration of filling. Turloughs are listed as priority habitats under Annex 1 of the European Union (EU) Habitats Directive (92/43/EEC; Habitat 3180), and are listed as Groundwater Dependent Terrestrial Ecosystems under the EU Water Framework Directive. Many have been designated as Special Areas of Conservation, the highest level of protection of any natural site in EU countries.

TURLOUGHS AS LANDFORMS

In contrast to the relative ease with which turloughs can be described hydrologically and ecologically there are many difficulties in understanding their geomorphology. A particular problem is that most descriptions focus on the area inundated by water, and the topographic catchment of that area is rarely mentioned. An exception is Guidance Document no. GW9 (URL 1) in which it is suggested that turlough catchments can be divided into two broad types: (a) those where groundwater flow is shallow and entirely within the epikarst and (b) those where groundwater flow is deeper and more complex. The catchment for type a turloughs is likely to be local but type b turloughs are part of a larger groundwater system and may receive recharge from losing and sinking streams some distance away from the topographic catchment of the depression in which the lake is formed.

Turloughs are most commonly found in lowland areas where there is a cover of glacial drift and relatively little local relief. Indeed, Williams (1964, 1970) argued that many turloughs have formed in hollows in glacial drift and hence they should be regarded as glaciokarstic landforms. However, Coxon (1986, 1987a, 1987b) examined a large number of turloughs, including the 90 largest in Ireland all of which have a maximum area of inundation in excess of 10 ha. She concluded that "... in all instances where the nature of the

depression could be demonstrated, a bedrock hollow appeared to be present" and that "In a large number of turloughs, bedrock is exposed at several locations on the surrounding slopes, or was shown by augering to be near the surface, while augering in the depression indicated a considerable depth of unconsolidated sediments" (Coxon, 1986, p359). On this evidence, turloughs may be considered to be 'closed depressions of moderate dimensions' that are found in areas underlain by limestone and hence may be considered to be a type of doline. Some authors have alluded to a similarity with poljes, but Williams (1964) and Coxon (1986) both argue that turloughs and poljes have little in common beyond their periodic inundation, although the two authors differ in terms of which features the two landforms are considered to have, or not to have, in common.

In summary:

- poljes and turloughs are both periodically inundated;
- lacustrine sediments are deposited in both poljes and turloughs;
- the area of inundation in poljes is generally much larger than in turloughs; the size range for the 90 largest turloughs in Ireland is 10 - 650 ha, with a median of 30 ha (Coxon, 1987b);
- poljes are more clearly defined as landforms than turloughs, i. e. they have clearer topographic divides and there is a clear break of slope between the area of inundation and the sides of the polje, which are usually markedly steeper than those of turloughs;
- there appears to be a greater degree of tectonic influence on polje location than is the case with turloughs;
- turloughs are clearly associated with glaciation, whereas poljes are found in a wide range of climatic zones, including the tropics.

The formation of turloughs remains a matter for speculation. Three options were proposed by Coxon (1986). Firstly, turloughs may be hollows due to glacial erosion and deposition, and the associated groundwater flow lines may have developed post glacially. The location of the flow lines could have determined which glacial depressions became turloughs, or alternatively the development of the flow lines may have been linked with the filling and emptying of the turloughs. Secondly, the turloughs may be glacial hollows, lying along preglacial flow routes which survived glaciation but now have an inadequate capacity due to clogging with glacial deposits. Thirdly, glaciation may not have completely destroyed surface karstic features, and turloughs may thus be preglacial hollows modified by glaciation, with associated preglacial flow routes. Further evidence, particularly concerning the amount of glacial erosion which has occurred on the western lowlands, and concerning the nature of the bedrock floor of the turloughs, is required before it can be determined which of these models is closest to the truth, or whether more than one is true, and turloughs are polygenetic.

TURLOUGHs AND TIANKENGs

Turloughs have been recognised as special landforms by ecologists and groundwater hydrologists, although the term has not been widely used by karst scientists because to date turloughs have only been identified in a small geographical area. Similarly, the term tiankeng is not widely known because the majority of tiankengs occur in China, although examples have recently been recognised in other karst areas (Waltham, this volume). There does not appear to be a specific 'turlough forming process', but turloughs appear to be polygenetic landforms that are strongly associated with dissolution, karstic drainage and underground flow routes, and in most cases with glaciation. Like turloughs, there does not appear to be a specific 'tiankeng forming process' but, as argued in other papers in this volume, they appear to be polygenetic, resulting from a combination of focussed underground drainage, dissolution,



Figure 1. Turlough near Ballyshannon, County Donegal, Ireland. (Photo: Richard Watson)

collapse, and geology, notably bed thickness and structure. Tiankengs may be distinguished from other collapse dolines by their size and morphology and turloughs may be distinguished from poljes by their size and morphology. The two landforms lie at opposite ends of the doline spectrum, but it is appropriate that both terms should become established in the lexicon of karst geomorphology.

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Giant dolines of the Muller Plateau, Papua New Guinea

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Abstract: The Muller Plateau lies within the Southern Highlands of Papua New Guinea, and is distinguished by its giant dolines. Many of these have exceptionally large dimensions and a morphology comparable to that of the megadolines of the Nakanai Mountains on New Britain and the tiankengs of the South China karst. They are all caprock dolines. The geology, physical geography and hydrology of the Muller Plateau are compared with those of the Nakanai Mountains and the South China karst. Proposed mechanisms for the formation of three groups (Rogorepo, Mamo and Atea) of giant dolines on the Muller Plateau are discussed. The Muller Plateau giant dolines, like the megadolines and the tiankengs, formed during the Pleistocene. The Muller Plateau dolines have formed in an environment that has many similarities to the other giant dolines. However, it is unlikely that they will ever evolve to the magnificence of the Nakanai megadolines or the aesthetics of the Chinese tiankengs, as a controlling factor in their development is a siltstone caprock and impure interbeds within the Darai Limestone.

Key words: megadoline, New Guinea, karst, cave, chamber

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INTRODUCTION

Giant forms of karst features are rare and when found they are always subject to ranking for the record books. The Muller Plateau in the Southern Highlands of Papua New Guinea (Figure 1) has several giant dolines amongst its hundreds of smaller dolines. They are comparable to the tiankengs of South China and the megadolines in the Nakanai Mountains, New Britain, Papua New Guinea; these are referred to as megadolines in this paper, as that is the published name, though a strong case has been made to classify them as tiankengs (Waltham, this volume).

Both the Muller Plateau and the Nakanai Mountains lie in the tropics around 5°S, and their geology and physical geography have many common features. These are compared to those of the tiankengs in the South China karst. The Nakanai Mountains and South China contain the greatest number of giant dolines in the World (Waltham, this volume).

The Muller Plateau lies on the southwestern slopes of the Muller Range, above escarpments 600-1000 m high 10 km west of the Strickland Gorge (Figure 1). A number of the Muller Plateau dolines have been identified as collapse features (Caffyn, 1974; James et al, 1976), and are believed to have formed in a similar manner to collapse dolines (Waltham and Fookes, 2003). These may be separated into two groups: those in carbonate rocks and those in non-carbonate rocks. The latter are less common and are called caprock dolines; the Muller Plateau giant dolines fall within the second group, while most megadolines and the tiankengs are in the first group (Zhu and Waltham, this volume).

Comparative geology

The rocks of the Muller Plateau are a marine sequence 1400 m thick that includes the Darai Limestone (Francis, 1980). This limestone consists of Upper Oligocene to Middle Miocene algal and foraminiferal biomicrites. The overlying Lai Formation is almost entirely siltstones and mudstones, whereas the underlying Ieru Formation is mainly fine-grained clastic sediment (Francis, 1980). The Yalam limestones of the Nakanai Mountains are younger, from Lower Miocene to Lower Pliocene. They vary from a compact and massive limestone, to a porous coral algal limestone and a well-bedded bioclastic limestone similar to chalk in colour, porosity and permeability (Audra et al, 2001). Their thickness varies between 500 and 1000 m (Löffler 1977). A wide range of carbonate rocks, from Cambrian to Triassic, form the South China Karst (Yuan et al, 1998). They crop out as massive limestones, dolomites and dolomitic limestones, in a sequence up to 3000 m thick in Guizhou

and Guangxi (Waltham, 2003). They had been uplifted to become part of the Eurasian continent before the marine sediments of the Muller Plateau and the Nakanai Mountains were deposited.

Where the Darai Limestone has been exposed on the Muller Plateau by erosion of the Lai Formation, surface karst processes have led to a great variety of landscapes. In the Nakanai Mountains, the Yalam Limestone was covered by thick Pliocene volcano-sedimentary deposits (Audra et al., 2001). Since uplift these have been weathered and eroded, exposing the limestone and in places forming a poorly developed polygonal karst. In the catchments for the underground rivers, the thin beds of the volcanic cover act as a caprock limiting the penetration of seepage waters and collecting runoff (Audra and Hobléa, 2001). Erosion levels expose continuous limestone outcrops across large areas of the South China karst, and an impressive cone karst landscape has formed, though there are some areas covered karst with a thin and discontinuous caprock.

Both the New Britain limestone and the South China carbonates have been described as pure. In contrast, although some beds of the Darai Limestone are pure, there are numerous interbeds of impure limestone and calcareous clastic sediment (Francis, 1980). The limestone in China is strong and well lithified, while the Muller Plateau Darai Limestone varies in lithology between strong micrites and weaker, more chalky rock, and much of the Nakanai's Yalam Limestone is more comparable to a strong chalk. In all three areas, the limestones were deformed and uplifted in the late Tertiary and early Pleistocene Himalayan orogeny. As they were uplifted, they were folded, faulted and jointed - providing the fracture nets that allowed water penetration into the limestone and into major conduits.

Major surface rivers have cut into the three terrains, forming deep gorges and canyons. This rapid valley incision lowered the springs and deepened the vadose zones in the massifs by up to 1000 m. The deeply incised Strickland River and its tributaries such as the Yu Nali (*Yu = River*) are the main influences on the Muller Plateau karst (Figure 1). In all three areas, cave resurgences have become perched above major rivers, as the result of uplift and incision by the major surface rivers at greater rates than those of the smaller underground rivers. The Nakanai Mountains uplift is believed to be at the exceptionally rapid rate of 3 mm per year (Löffler, 1977). On mainland Papua New Guinea, it is slightly slower, at 2-3 mm per year (Gillieson and Spate, 1998). In South China, it has all but ceased (Yuan et al, 1998). However, all three areas still experience earthquakes, and the island of New Britain still has its active volcanoes (Audra, 2001a).

Comparative physical geography

Climate, vegetation and hydrology are all important as influences on the rates of cave development and surface denudation in these three karst terrains. The Muller Plateau dolines lie at elevations of 2000–3100 m, in a cool, highland, tropical climate (Löffler, 1977). Annual rainfall has been estimated at 3.5–4.5 m (James et al, 1980a); this could be a gross under-estimate, as the maximum recorded annual rainfall is 11 m at the Ok Tedi mine, 150 km to the northwest and at the same altitude as the Muller Plateau (Gillieson and Spate, 1998). The Nakanai Mountains have a hyper-humid, equatorial, mountain climate with an extremely high rainfall estimated to be between 10 and 12.5 m (Audra, 2001b). The rims of the megadolines that contain rivers are at altitudes of 200–600 m, where the rainfall is much lower (Audra et al, 2001). The South China tiankengs are in the subtropics, and have a warm to temperate climate; most tiankengs have rims at altitudes of 1000–1500 m (Zhu and Chen, this volume). On the Muller Plateau, the annual means and wide range of temperatures are comparable to those experienced in South China (Yuan et al, 1998). Variations in South China are controlled by latitude and season, but the only temperature controls on the Muller Plateau are diurnal and altitude effects. The Nakanai Mountains have the highest mean temperature and a lower annual range (Audra et al, 2001).

Vegetation on the Muller Plateau ranges from a mixed tropical rain forest, through moss forest, to open clearings that contain shrubs and grasslands. The Geleru clearing (Fig. 1) in the Atea catchment supported a small population until the 1960s, and its vegetation is therefore the result of slash and burn agriculture. Other clearings remote from habitation or hunting grounds also show evidence of fire (Pybus, 1974). The Nakanai Mountains are covered by primary tropical forest (Audra et al, 2001). In these tropical areas, full forest vegetation can grow even on the steepest slopes and rock is only visible in occasional bluffs and where landslips have removed the plant and soil cover. At present, the tiankengs in China lie in a mixture of agricultural land and subtropical forest. In the past, there would have been subtropical forests inter-dispersed with grassland. In all three areas, climate and vegetation are ideal for the carbon dioxide production that is essential for limestone solution.

Comparative denudation rates are $400 \text{ m}^3 \text{ km}^{-2} \text{ a}^{-1}$ for the Nakanai Mountains (Audra, 2001c), $200 \text{ m}^3 \text{ km}^{-2} \text{ a}^{-1}$ (James, 1980) for the Muller Plateau. No values are available for the South China

karst, they are quoted as high (Yuan et al, 1998; Zhu and Chen, this volume), but they are expected to be significantly lower than the tropical areas.

The development of a large cavern is an essential precursor to the creation of a giant collapse feature, and a subterranean river is a usual requirement for this. After collapse, the river has three further roles - to dissolve and remove carbonate breakdown, to mechanically erode and transport both carbonate and insoluble breakdown, and to continue to enlarge the cavity by basal sapping of the walls. The size of a subterranean river depends upon its catchment area, and the percentage of it that is on non-carbonate rocks controls its aggressivity.

On the Muller Plateau, the catchment for the Yu Atea is over 100 km^2 , almost all of it on the Ieru and Lai Formations (Francis, 1980). This produces an estimated low flow of $4 \text{ m}^3 \text{ s}^{-1}$; high flows exceed $30 \text{ m}^3 \text{ s}^{-1}$ at the Atea Doline (James and Martin, 1980). The catchments on the Nakanai are harder to characterize because the outcrop ratio of the insoluble caprocks to bare limestone has not been recorded. The catchment for Muruk cave is about 20 km^2 , and this produces a low flow of between 2 and $4 \text{ m}^3 \text{ s}^{-1}$ at the Berenice resurgence (Audra and Hoblea, 2001). The rivers flowing through the megadolines have much greater low flows, estimated at up to $20 \text{ m}^3 \text{ s}^{-1}$ (Audra et al, 2001). The river flowing through the Xiaozhai Tiankeng has a catchment of 280 km^2 (Zhu and Chen, this volume), composed of carbonates, sandstones and shales (Senior, 2003). The river has an average annual flow of $7\text{--}8 \text{ m}^3 \text{ s}^{-1}$ and has a maximum discharge of $174 \text{ m}^3 \text{ s}^{-1}$ (Zhao, 2001). These are accurate figures, as the water from this tiankeng is diverted to a hydroelectric power plant. The annual distribution of the river flows is also important. The Muller Plateau runoff is effectively constant throughout the year; it only requires the afternoon convective rains to raise the flow in the rivers because the soils and epikarst are permanently saturated (James and Martin, 1980). In the Nakanai Mountains and South China, the monsoon rains generate huge flows that are exceptionally destructive mechanical erosive agents (Audra et al, 2001; Senior, 2003).

The tiankengs in South China have floors surrounded or partially surrounded by vertical cliffs (Zhu and Chen, this volume). The cliffs may have pronounced ledges and breaks, leading to gentler slopes formed by the accumulation of wall breakdown and slope wash. Many tiankengs have a river across their floor or evidence of one flowing through their base; ideally, there are inlet and outlet caves in the tiankeng. Although many of the megadolines fit this description perfectly, there is a noticeable difference between these two giant collapse features. The tiankengs have large vertical cliffs of bare rock, while the megadolines have few bare cliffs but their walls are overhung or covered with vegetation (Audra et al, 2001). The giant dolines of the Muller Plateau only partially fit the tiankeng description, as they do not have rivers flowing across their floors.

THE MULLER PLATEAU

There are three notable groups of giant dolines on the Muller Plateau (Fig. 1), which are each distinguished by the details of their morphology and the mechanisms proposed for their formation.

The Rorogepo dolines

The giant closed depressions at Rorogepo form grassland clearings amongst the moss forest (Fig. 2). Since they have never been cultivated, it is probable that the grasslands are controlled by cold air drainage into the depressions and temperature inversions. The thinly bedded Darai Limestone that crops out in them has interbeds of impure limestone and calcareous clastic sediment. The Rorogepo depressions have rim diameters ranging from a few metres to over a kilometre; in many there are smaller depressions nested within the larger ones (White and Frank, 1980). It is unlikely that these are collapse features as they have gentle slopes and erratic shapes developed by the gradual removal of material by solution processes (Francis et al, 1980a). In the floor of one small doline, Uli Mindu is an unstable solution shaft 200 m deep that ends in a large rockfall chamber (Beck, 2003). Such enlargement at the base of deep shafts is common and results from wall breakdown. The process continues up the shaft until a doline forms inside a partial or complete ring of

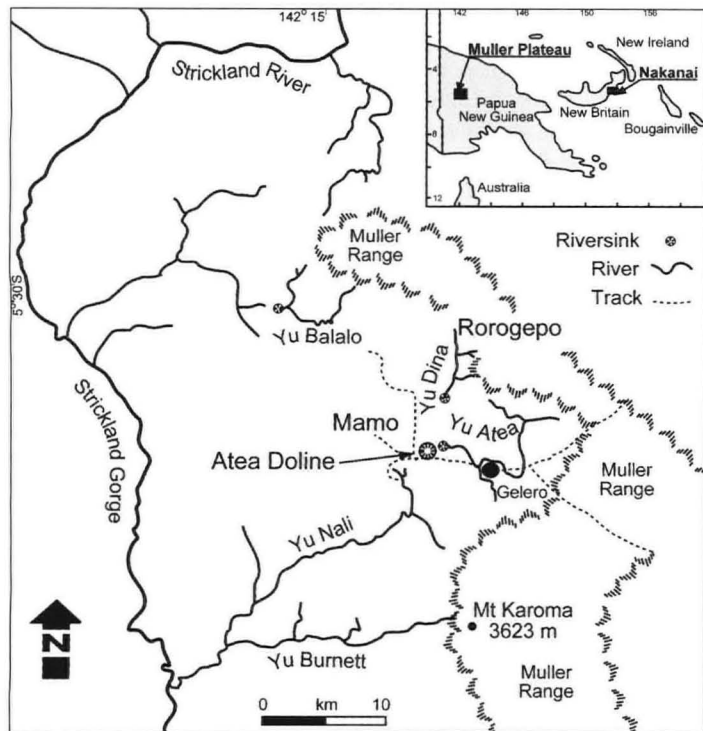


Figure 1. Locations, within Papua New Guinea, of the Muller Plateau in the Southern Highlands and the Nakanai Mountains in New Britain. (After Montgomery, 1974)

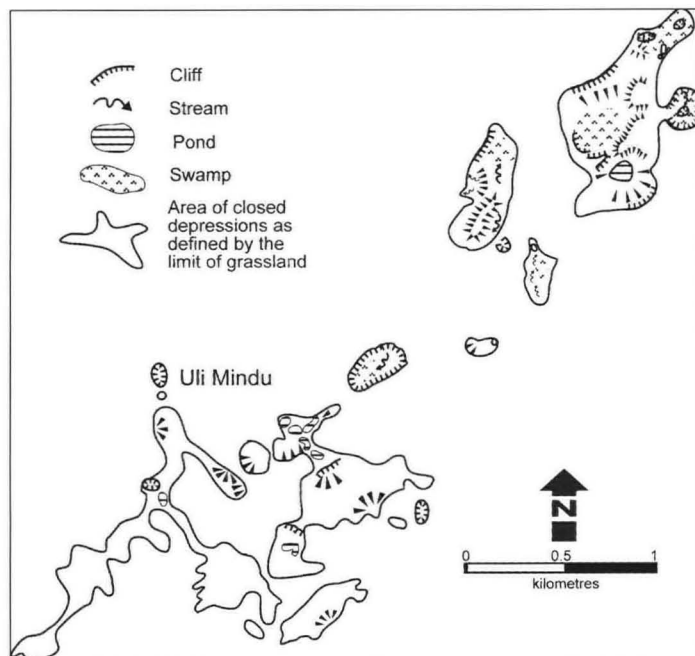


Figure 2. Dolines of Rorogepo. (After White and Frank, 1980)

cliffs. Some have volumes of around 1M m^3 and have the appearance of tiankengs (Fig. 3), but have clearly evolved from solution shafts.

The morphological similarity between solution and collapse dolines arises from the lithology of the local Darai Limestone. With relatively strong and competent units of pure limestone inter-bedded with weaker units of impure limestone or calcareous clastic sediment that are less permeable, seepage waters commonly issue from the contact between a pure limestone and the underlying less permeable bed. This gives rise to basal sapping of the competent units and consequent rockfalls. Exposed faces around shafts and dolines retreat by this method, and maintain their steepness over time. Under these circumstances, even dolines that are initially solutional evolve to have steep walls overlooking their own breakdown debris (Fig. 3).

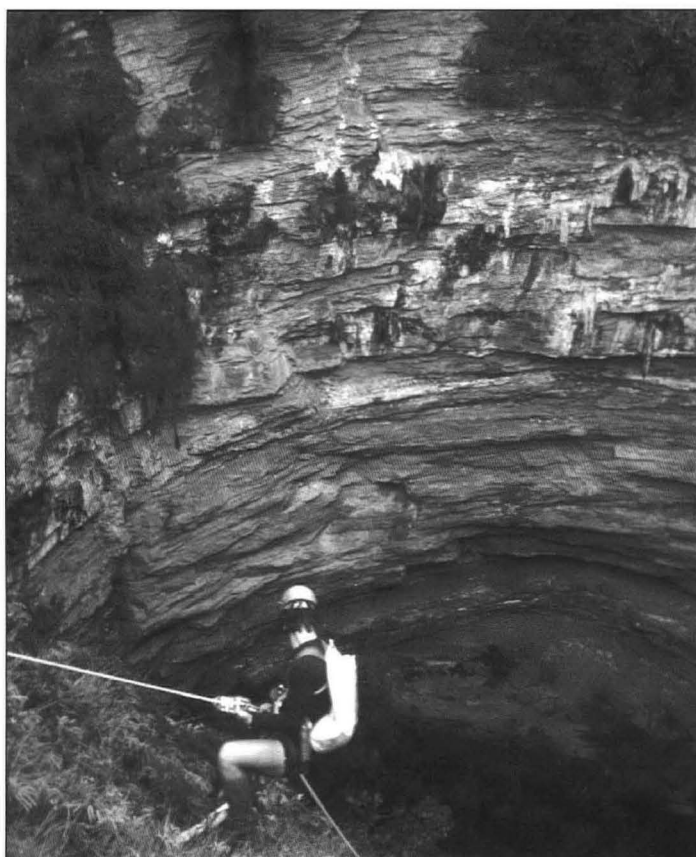


Figure 3. A Rorogepo doline. (All photos by Alan Warild)

The floors of the Rorogepo giant dolines are covered with fine sediments, and some have ephemeral lakes, indicating that the conduits draining them are immature or blocked by sediment. The horizontal caves in them are small.

The Mamo dolines

The 100 km^2 plateau of Mamo has been called a doline karst (Francis et al, 1980a). It contains more than a hundred large dolines. One doline 600 m across has been seen from the air (Löffler, 1977), but it has not been found by field workers and is thought to be a very large solutional depression of unknown depth. Numerous rivers reach the northern edge of Mamo and then sink into the Darai Limestone; without exception, the sinks are blocked by debris or sump. The resurgences of these rivers are believed to be 1000 m below the scarp on the southwest edge of Mamo (Fig. 4). These rivers possess sufficient aggressivity to create large caverns in the pure limestone beds of the Darai Limestone, beneath the siltstone cap of the Lai Formation that covers most of Mamo.

A few of the Mamo dolines have been explored around the Uliwapo clearing (James, 1974). The largest has a volume of 31M m^3 and also the dimension ratios necessary to be classed as a tiankeng (Zhu and Waltham, this volume). These are caprock dolines with steep, vertical and overhanging rock walls that require equipment for descent to their floors. In the largest dolines, there are no caves, but in the floor of one smaller doline of 3M m^3 , a cave with a large stream is blocked by an unstable rockfall after 40 m of horizontal passage.

It is suggested that the Yu Rongoma is forming by solution voids in the limestone of a size suitable to create the giant dolines that are partially in the cover rocks. The river has a base flow of about $1\text{ m}^3\text{ s}^{-1}$, and has much higher flows after heavy rain (James, 1974). However, even the high flows fail to remove the products of collapse as the voids stope upwards. The breakdown material from the siltstone and the Darai Limestone presents such an effective barrier that the river can no longer use its original route and out of necessity finds a new one. The new routes are immature, as input periodically exceeds reservoir capacity, and a lake forms at the Yu Rongoma sink in periods of continuous heavy rainfall (James, 1974). Such ponding further reduces the river's potential to remove the products of collapse by mechanical means. Each new route of the river beneath Mamo has the potential to form additional dolines; some lines of dolines have pronounced orientations, which are thought to be due to joint or fault control (Francis et al, 1980a).

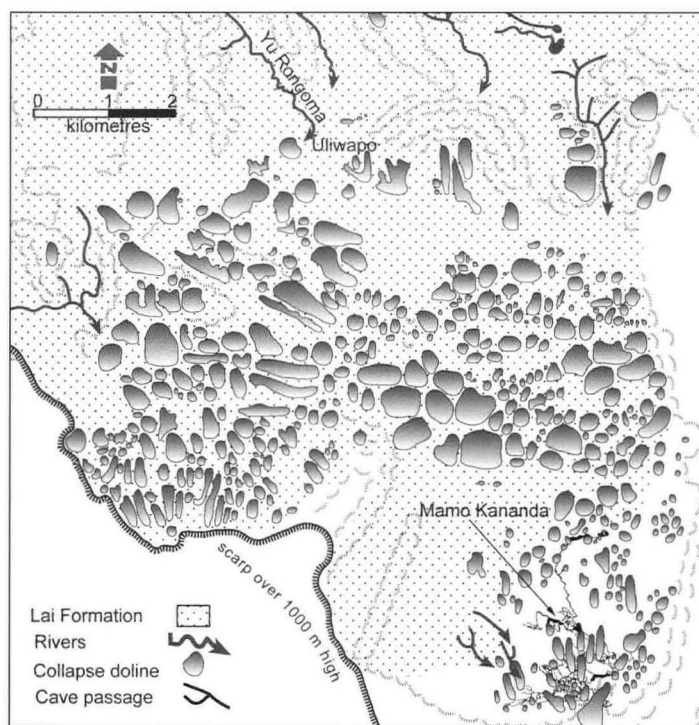


Figure 4. The hundreds of dolines on Mamo. (After Montgomery, 1974)



Figure 5. The Uli Malemuli doline.

There has been no further investigation of the most of the giant dolines on Mamo since the experiences of the 1973 expedition to the Muller Plateau led to an expectation that they would not contain caves. While the areas of the dolines can be accurately obtained from aerial photographs, their depths cannot, and caves are not always revealed. Some of the dolines have huge areas but it is thought that the depths of these are relatively small. Exceptionally high rainfall and tectonic activity in the region accelerate wall retreat. The result is that doline floors accumulate debris because there is no mechanism for removing the insoluble breakdown generated from the siltstone cap and the non-carbonate components of the Darai Limestone. It is possible that this vast array of caprock collapse dolines was formed by the rivers that now sink north of Mamo. It is likely that rivers in the past would have flowed further south and breached the 30-80 m of impermeable siltstone cap along faults and shear zones.

In the southeastern section of Mamo, one circular doline has a volume close to 1M m^3 (Fig. 5). It has a nearly level rim in siltstone (Fig. 6), and a large cave entrance opens from its floor into Uli Malemuli. The cave and doline together reach a depth of 420 m. The caprock doline formed by collapse into a void that was originally part of the cave. Several small streams now gather on the surrounding siltstone and fall as glistening curtains into it. The upper beds of the Darai Limestone on Mamo produce dolines with vertical



Figure 6. The view out from Uli Malemuli into the doline.

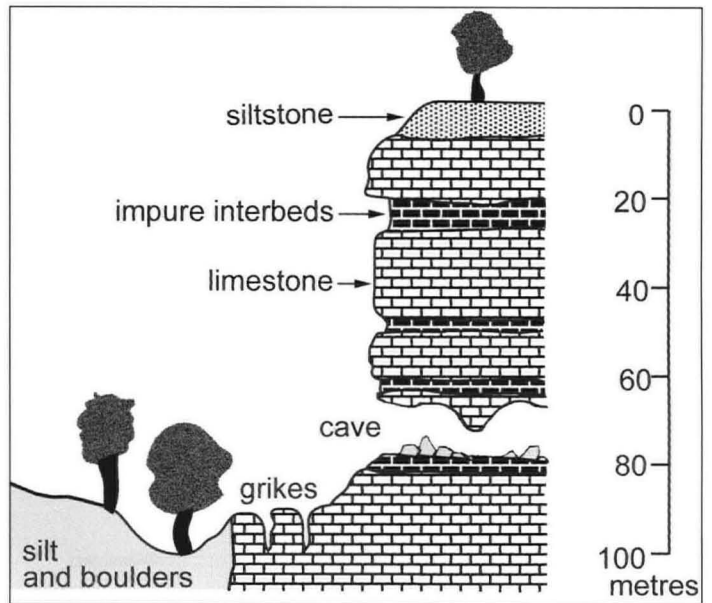


Figure 7. Profile through the wall of a Mamo doline. (After James et al, 1980b)

and overhanging walls, free from vegetation (Fig. 7). The pure limestone, friable siltstone and impure interbeds weather differentially: the limestone forms vertical faces, while the other beds crumble and retreat, forming overhangs above ledges covered with debris. Caves have formed in some pure limestone beds, and connect several dolines until terminated by wall collapse. The present silt and boulder floor often is 20 m below the most common level of the caves and may contain rock pinnacles between deep

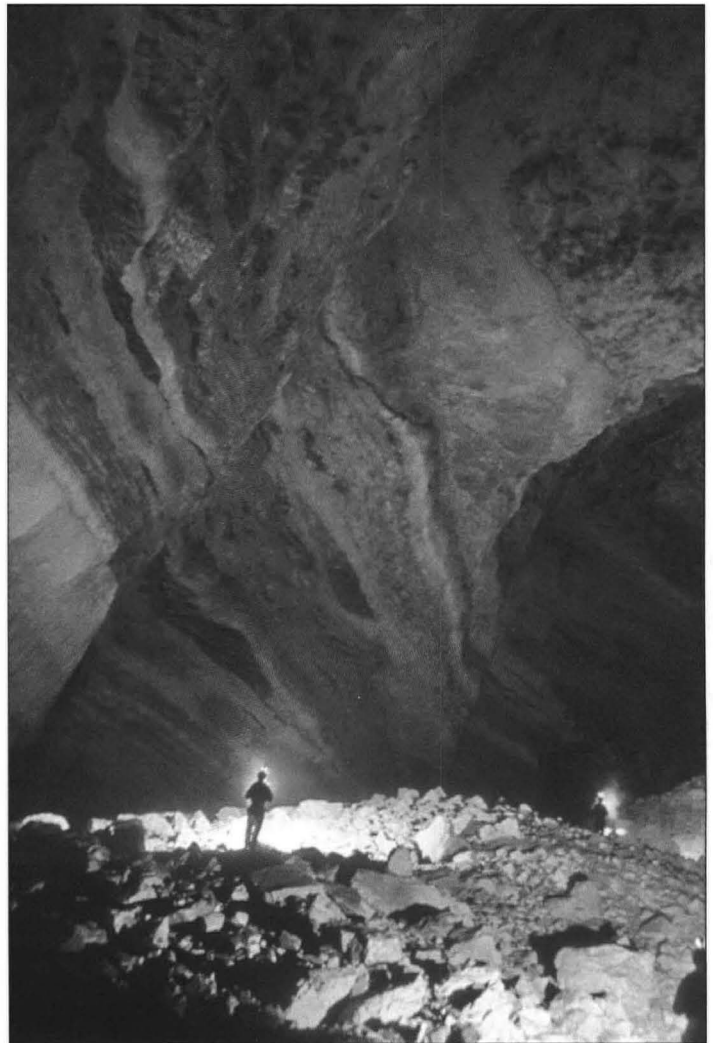


Figure 8. Space Oddity, the terminal chamber in Mamo Kananda.

grikes. With the high denudation rates on the Muller Plateau, the limestone is rapidly eroded as soon as it is exposed.

Where the Lai Formation has been stripped from the Darai Limestone in southeastern Mamo, a pyramid-and-doline karst has developed (James et al, 1980b). Here the dolines are much smaller than the caprock collapse dolines; they are formed by solution and are only slightly modified by collapse (Francis et al, 1980a). The 55 km of known passages in Mamo Kananda lie almost entirely beneath this pyramid-and-doline karst. The cave is characterized by extensive horizontal development at eight levels, each preferentially developed in the pure and more soluble limestone beds (James et al 1980b).

Mamo Kananda has three chambers with more than 1M m³ of air space, as evidence of the size of voids that can be generated beneath Mamo. The composition of the boulder piles on the chamber floors, and of the bedding exposed in the walls, shows that these chambers have formed by upward stoping through many beds of the Darai Limestone. The weak and friable impure limestone and clastic beds offer little resistance to the upward development, and the stoping is also assisted by cave passages in higher levels and by tectonic activity. The rivers that created the initial low-level voids no longer flow through the breakdown caverns in normal flow, but they invade the caverns in flood as their new routes to depth are immature or partially blocked. Space Oddity (Fig. 8) is a very large cavern at the lowest point reached in Mamo Kananda (525 m below the entrance). This is a classic dome chamber, but the walls show that even at this depth the Darai Limestone still contains impure and clastic beds, and its compacted floor debris demonstrate the impossibility of all but the largest rivers penetrating and removing the breakdown.

If these collapse chambers in Mamo Kananda stooped through to reach the surface, they will form giant dolines before they are further

enlarged by wall retreat. However, the siltstone caprock has already been stripped above them, and rapid surface lowering is taking place mostly by solution. Even if the chambers are breached to create dolines, these are unlikely to reach the depths of the Nakanai megadolines or the Chinese tiankengs, as breakdown will continue to accumulate and floors will rise. They have only limited potential to become deeper if the rivers exploit new routes directly below the breakdown chambers and undermine the existing floors.

The Atea dolines

The Atea Doline is the focus of the Atea area (Fig. 9). It is where the Yu Atea sinks into the cave of Atea Kananda, with its 35 km of known passages. It is one of the most beautiful river sinks in the world (Fig. 10). The Atea Doline was first interpreted as a collapse feature because of the near vertical walls and the presence of collapse blocks on the floor (Caffyn 1974, James et al., 1976). However, it was formed when the Yu Atea breached the Lai Formation and invaded older passages formed by the much smaller Yu Dina (Fig. 9); it has therefore been classed as a solution doline (Francis et al, 1980b). In reality, it is neither of these, as it is a river sink at the end of a blind valley. More than 100 m in total depth and width, it compares in size to tiankengs and megadolines, but it has a stepped profile that lacks the diagnostic ring cliffs of a tiankeng and is open on one side (Fig. 11). The steep cliffs of the Atea Doline are a feature of basal sapping of pure limestone units lying over less permeable interbeds. Scars from recent rock falls are well developed on its southern wall.

The Yu Atea has flows and abrasive sediment loads both large enough to drive considerable mechanical erosion. The Darai Limestone interbeds provide fine quartz sand for this process, and the Yu Atea brings in additional quartz sand from the Ieru Formation (Gillieson, 1980). Chemical solution potential of the Yu Atea waters is also high, with the biomass of the tropical rain forests providing copious amounts of carbon dioxide to make its waters aggressive (James 1980). Despite this, the impure limestones and clastic beds in the upper Darai Limestone are resistant to solution; exposed surfaces develop insoluble clayey rinds after calcium carbonate is leached out. The insoluble residues also coat the pure limestone and inhibit its solution by the Yu Atea. This inhibition is so effective that the cave river carries (within experimental error) the same concentrations of dissolved calcium carbonate as it enters the Atea Kananda and as it leaves the Atea Resurgence (James 1980). This suggests that mechanical erosion dominates in the Yu Atea conduits, and is the major force for their enlargement.

The Yu Atea now sinks at the northern end of the Atea Gorge with the mostly abandoned gorge still taking flood flows (Fig. 9). The sinking waters resurge in the Atea Doline at the Atea Outflow Caves (Fig. 11) on top of a thick mudstone that forms a substantial ledge around the doline. The main flow of the Yu Atea emerges from the largest outflow cave, in which it rises from immature wall fissures beside a large collapse zone. This collapse has diverted some of the flow to form the other outflow caves, and the reduction in size of the main conduit forces the flood flows of the Yu Atea through the Atea Gorge. This is another example of the products of collapse of the upper Darai Limestone beds not being removed by rivers with very large flows.

On entering the Atea cave, the Atea river has cut chambers and shafts that drop 30 m to the Ship Canal, which is perched on a bed of mudstone 30 m thick. Flow slows in the canal, and insoluble residues coat the floor, walls and roof. The same materials have consolidated the breakdown in the Holocaust so effectively that the Yu Atea is forced back into one of its distributaries, where it now cuts down through the mudstone bed to sumps below the Penstock (Fig. 9). The large-scale collapses that have formed the breakdown chambers of Aftermath, Holocaust and Winchester, and also the Silver Hammer Room, all lie in the hinge zone of the Mamo Syncline (Fig 9), probably because the strike joints are there more closely spaced. As in Mamo, the breakdown piles are huge, and if their chambers stooped through to the surface they will form giant dolines.

The Yu Dina is believed to have formed about half the known passages in Atea Kananda when it sank in the dry valley north of the

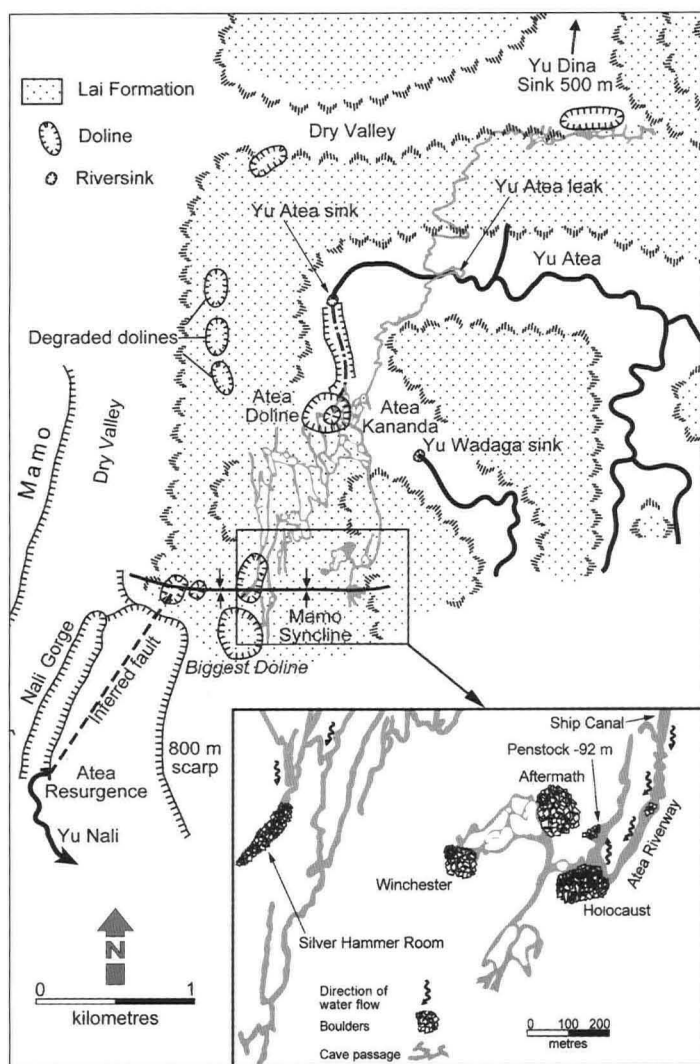


Figure 9. Surface features in the Atea Doline area and their relationship to cave passages in Atea Kananda. (After Francis et al, 1980b)



Figure 10. Aerial view of the Atea Doline.

Atea Doline and abandoned its surface course round to the west (Francis et al, 1980b). One of its courses south appears to have lain beneath the degraded dolines just west of the Atea Doline (Fig. 9). These dolines now have the bowl-shaped morphology of solution dolines, but have degraded from initial caprock dolines with steeper sides. Most of the Yu Dina passages are choked by sediment or collapse before they reach the Mamo Syncline. The far western passage ends in the Silver Hammer Room, a large breakdown chamber directly below a giant caprock doline on the axis of the Mamo Syncline. Despite being smaller than the Yu Atea, the Yu Dina was capable of forming a solution void large enough to initiate upward stoping, but it had insufficient erosive power to remove the breakdown debris and was forced to find a new route through the Mamo Syncline. Just south of the Silver Hammer Room and its overlying doline, another caprock doline near the Himbiraga dry valley, on the southern limb of the Mamo Syncline (Fig. 9), was once described as the biggest doline in the world (James, 1974). About 400 m long and 200 m across, it is well over 100 m deep, thereby matching the dimensions of tiankeng as defined by Zhu and Waltham (this volume); though its perimeter cliffs are broken and it has no river flowing through it.

The current sink of the Yu Dina is at the Dina Fault, where it can retreat no further upstream as it drains off the non-carbonates of the Ieru Formation (Fig. 12). Its postulated route to the Nali is too deep in the limestone for its caverns to stope upwards to reach the surface; great depth below the surface accounts for the large collapse chambers in Muruk Cave, not forming new megadolines in the Nakanai Mountains (Audra, 2001).

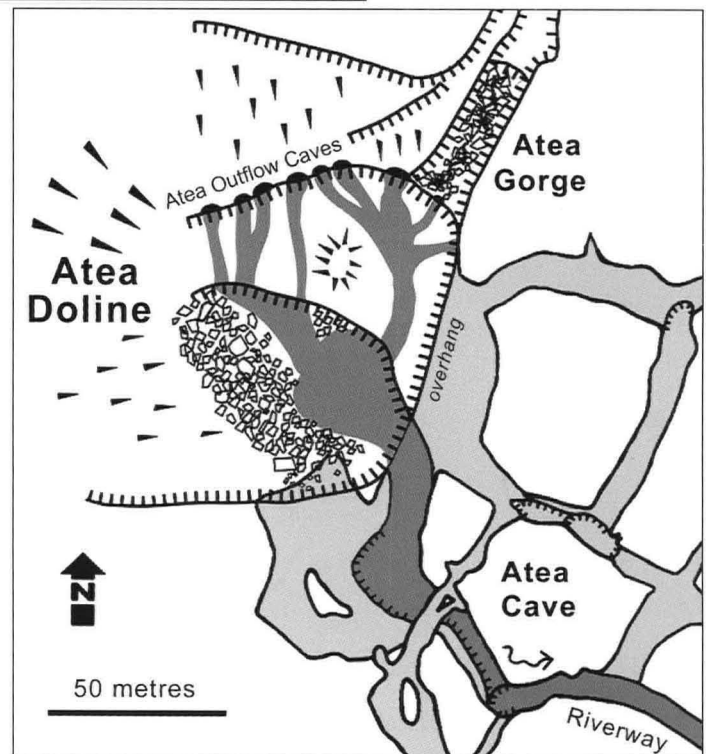


Figure 11. Morphology of the Atea Doline. (After Montgomery et al., 1980)

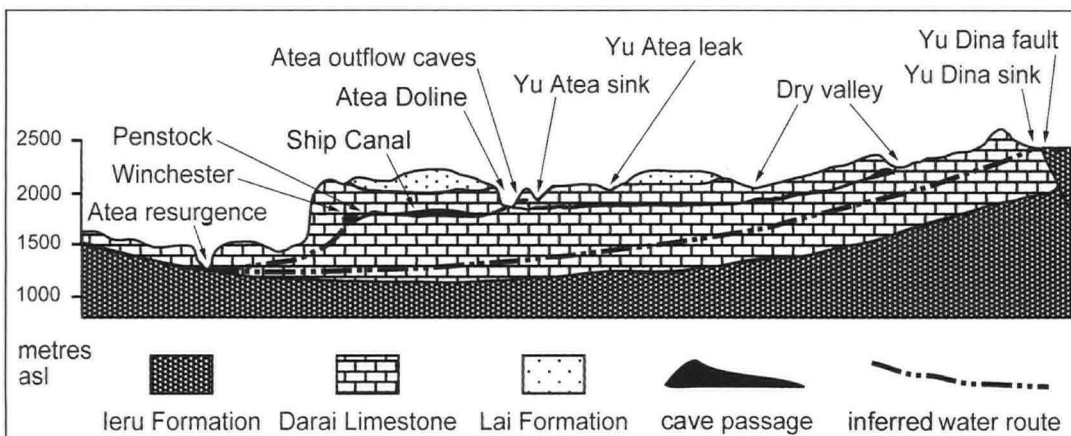


Figure 12. Profile through the Muller Plateau in the Atea area. (After Francis et al, 1980b)

The Yu Atea is already forming a new sink at Yu Atea Leak (Fig. 9) as the siltstone cap is removed from limestone that contains an existing stream cave. Evidence from Rorogepo and Mamo indicates that the number of potential stream and seepage sinks increase when the Darai Limestone is exposed. The result is that the underground conduits fragment, and dolines created by collapse or solution are smaller. Hence, as the Yu Atea retreats headward it is unlikely to develop giant dolines. Downstream of its known cave, the course of the Yu Atea appears to lie so deep below the surface, and with such a steep gradient, that future development of giant dolines is again unlikely.

THE MULLER GIANT DOLINES IN CONTEXT

The giant dolines are the largest karst features on the Muller Plateau, as are the megadolines in the Nakanai Mountains and the tiankengs in South China. In common with the other two areas, they have formed after rapid uplift in places where there is continuing tectonic activity. China's tiankengs are thought to have been formed mainly formed in the late Pleistocene (Zhu and Chen, this volume). Consideration of both mechanical and solution erosion rates, and the chalky nature of the host limestone also place Nakanai's megadolines in the late Pleistocene (Audra et al, 2001). Opinions are that the Muller Plateau was established in its present form about a million years ago (Francis et al, 1980a), and this means that the Muller dolines have also developed during the Pleistocene. However, it is impossible to place them more accurately within this time frame, as it is believed that some will have been formed sequentially by the same underground rivers.

Classification of dolines on the Muller Plateau is complicated because the solution and collapse dolines have very similar appearance. It is also understood that no giant doline is entirely formed by collapse or solution; the name merely implies that one process dominates. Despite this, it is possible to be confident that all the giant dolines of Mamo and Atea are caprock dolines. The Nakanai megadolines and the Chinese tiankengs are largely collapse dolines, with a proportion of caprock dolines. The Muller Plateau dolines are distinguished by lying high above the active cave rivers, and the Mamo sector is remarkable for its high density of giant dolines.

The relative amounts of mechanical erosion in the three regions depend on river size and abrasive load; South China may well rank first in both of these. In terms of the limestone geology and its ability to support mature karst, the Muller Plateau is formed on the impure sequences of the Darai Limestone that appear to have properties in between those of the ancient, hard, compact and pure carbonates of South China and the friable and porous Yalam Limestone of the Nakanai. The purity of the limestone is directly related to its solubility, and the Darai Limestone has numerous interbeds that resist solution. In South China and the Nakanai Mountains, chemical corrosion enhances mechanical erosion. In contrast, on the Muller Plateau chemical corrosion is limited, and in many cases not available, for removal of collapse material.

The quality of the rock also affects the scale of karst features. Although many of the common karst landforms are found both on the Muller and in the Nakanai, they are poorly developed and are generally covered in vegetation. Young, weak and porous limestones may not be expected to support large karst features (Yuan et al. 1998). It is therefore surprising that the giant dolines are found both in the Nakanai and on the Muller Plateau. Their development on the Muller Plateau could have been aided by the presence of a caprock. Perhaps, the veneer of volcano-sedimentary deposits on the Yalam limestones on the Nakanai has had a greater role in the development of the megadolines than simply channeling runoff into the conduits to feed their enormous rivers. These are the rivers, which transform the megadolines from just depressions filled with tropical forest into magnificent and awesome sites.

The tiankengs of South China, with their vertical cliffs of bare rock are without doubt among the largest, most impressive and aesthetically pleasing karst landforms in the world. The giant dolines of the Nakanai and the Muller stand close behind them, and are equally remarkable as features of geomorphological significance.

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Cave un-roofing as a large-scale geomorphic process

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Abstract: A morphogenetic approach appears to be the most sensible in defining the tiankeng as a typological category. Tiankengs are giant collapse dolines formed over large river caves, with continuous precipitous perimeter and a diameter-to-depth ratio between 0.5 and 2. The term bears an evolutionary meaning, referring to the youthful stage of open collapse doline development, and the relationship of tiankengs to large underground rivers. The latter criterion separates tiankengs from other types of giant collapse features, such as caprock collapses over evaporites or large collapses over hydrothermal cavities. The South China karst offers evidence that un-roofing of caves is a large-scale geomorphic process playing an important role in the formation of cone and tower karst. It is probably the major process in the origin of large depressions, gorges and valleys in tropical karst, although other geomorphic processes contribute to shaping and maturation of a landscape and eventually obscure the origin in unroofed caves. Many saddles between hills and towers in fengcong and fenglin karst may owe their origin to cave un-roofing.

Keywords: tiankeng, limestone gorges, karst collapse, cave un-roofing, fengcong, fenglin

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An extensive field excursion in the South China karst, for Chinese and international karst scientists within the Tiankeng Investigation Project during October 2005, had the objective of evaluating the validity of the tiankeng term as a distinctive typological category of giant dolines. The fieldwork also provided an excellent opportunity to appreciate fengcong and fenglin karst. Based on observations made during the excursion, this paper first discusses how the typological distinction of tiankeng may better be established, and then discusses the role of cave un-roofing in the formation of tropical karst.

THE TIANKENG AS A TYPOLOGICAL CATEGORY

Alternative methodological approaches may be used to define tiankeng as a typological category of karst geomorphology. These are considered with reference to the characterization of tiankengs in China provided by Zhu & Chen (this volume).

Morphological approach

A morphological approach uses characteristics of shape and dimensions as principal criteria for delineating tiankengs as a type. Genetic considerations are subordinate, used only to distinguish between sub-types of tiankengs. Chinese researchers have generally followed this approach. They have stressed morphological and morphometric criteria in delineating a tiankeng as a type of giant doline, and have distinguished collapse tiankengs and erosional tiankengs as sub-types.

The principal morphological and morphometrical characteristics of tiankengs are:

- Vertical or sub-vertical walls, giving a pit-like profile;
- Large diameter and depth (the minimum limit is arbitrarily set at 100 m for both dimensions);
- Continuous precipitous perimeter;
- Small diameter/depth ratio (generally between 0.5 and 2).

The use of morphological criteria alone does not seem to be adequate to define a tiankeng as a typological category within karst geomorphology, as this would lead to the blending of features of different origins.

Genetic approach

A genetic approach stresses the origin and development of the features, and the processes and conditions essential for them to form. Morphological considerations remain relevant, as they are used to

broadly delineate a family of forms to assess. However, morphological criteria within this approach are not decisive, but are subordinate to genetic considerations. As geomorphological features evolve and change through time, the genetic approach should account for evolutionary changes and variations in the morphology.

The studies by Chinese workers (and observations during the 2005 fieldwork) strongly suggest that most tiankengs are collapse features that have formed over large underground river passages. They form where some favourable speleogenetic conditions (sites of lateral and/or vertical expansion of a river passage) coincide with geological weaknesses (structural or lithological disruptions). The formation of tiankengs may involve various breakdown mechanisms and processes (including upward stoping by slab and block breakdown, lateral expansion of an initial opening through face retreat, and un-roofing of a cavity by subaerial weathering).

The established Chinese usage of the tiankeng term implies vertical and sub-vertical walls as an attribute of this feature, but the genetic approach requires a feature to be viewed in the evolutionary perspective. For most collapse dolines, vertical or steep walls characterise the youthful stage. Their evolution, through maturation to degradation, involves the smoothing of profiles, increasing the diameter, and decreasing the depth, hence increasing the diameter/depth ratio (Fig.1). A roughly circular perimeter, that is initially continuously precipitous, is breached on one or more sides,

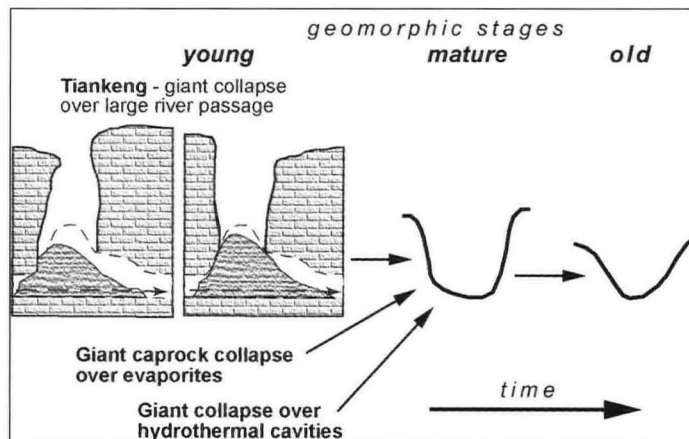


Figure 1. The place of a tiankeng within the morphogenetic typology of giant collapse dolines.

commonly along large cave passages or surface gulleys intercepted by the collapse (Fig. 2). A study of radar topography models (SRTM) of the South China karst (Fig.3) suggests that fengcong topography is characterized by the presence of numerous giant dolines, including those with gentle slopes and breached sides, most of which can be regarded as degraded tiankengs if the term is defined under a genetic approach.

The simple genetic approach does not allow inclusion of large erosional features (the erosional tiankengs of Chinese workers) to the tiankeng category. These are a kind of karst shaft with abnormally large diameter, formed mainly by dissolutional and erosional action of sinking streams (commonly of allogenic drainage). The presence of a large underground river and its trunk cave passage is not a prerequisite for erosional shafts to form. Hence, their origin is radically different from common tiankengs, which are principally collapse features.

Morphogenetic approach

A morphogenetic approach to defining tiankengs considers equally the genetic and morphological criteria and views them in relation to each other.

Tiankengs are defined as giant collapse dolines (the minimum limit is arbitrary set at 100m for both depth and width) formed over large river passages (chambers), which have continuous precipitous perimeter walls and a diameter-to-depth ratio ranging between 0.5 and 2. The morphological characteristics used in the definition are

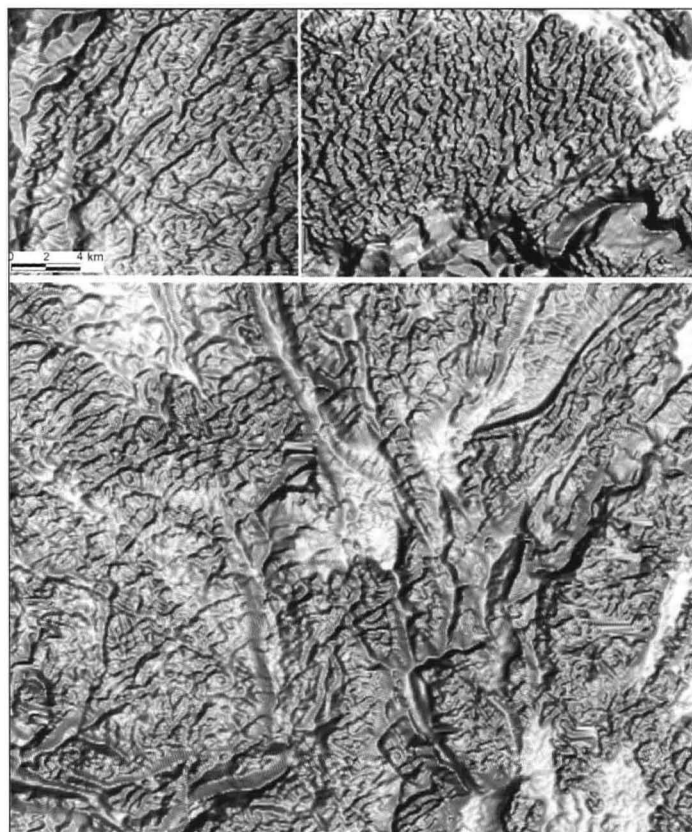


Figure 3. Samples of typical fengcong karst areas in South China, represented by digital topography models based on SRTM data. Giant dolines of the tiankeng scale are numerous, constituting a notable component of the landscape. Many of them, although smoothed to a degree, still retain their distinctive closed perimeters, and are so isolated in the topography that their collapse origins are apparent. Other dolines have merged to create valleys, or have broken at their sides to create amphitheatres onto adjacent lowland. Collapse and un-roofing forms, re-worked to a variable degree, reveal patterns that may best be interpreted in terms of disintegration of the structurally guided underground karst.

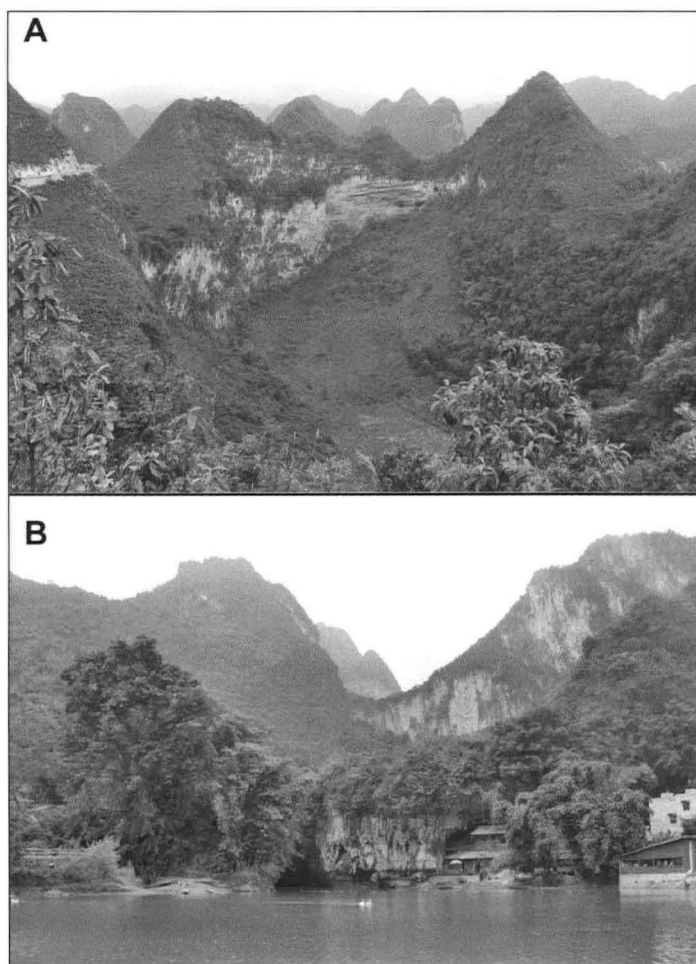


Figure 2. Degrading collapse dolines. Degradation is by destruction of cliffs and accumulation of colluvium, and by breaching of the perimeter due to progressive un-roofing of connecting cave passages or surface fluvial processes. **A** : a degrading tiankeng in the Leye karst, Guangxi. **B** : degraded collapse dolines (karst windows) aligned to the course of a low-gradient underground river at Sanmenhai Dong, Guangxi; the area between the cliffs in the foreground and the middle-ground is occupied by two collapses that expose fragments of the cave river; further cave un-roofing and merging of collapses will create a valley.

inherent to young collapse dolines. Therefore the term "tiankeng" bears an evolutionary meaning, referring to the youthful stage of open collapse doline development (Fig. 1).

This approach allows establishing tiankengs as an evolutionary subtype (stage) of giant collapse dolines (mega-dolines). Further geomorphic evolution of tiankengs leads to their degradation, so that older forms lose the distinctive morphological characteristics of tiankengs and should better be generically termed as giant collapse dolines.

Within the morphogenetic approach, two characteristics of tiankengs are of primary importance:

1. Gigantism of tiankengs. Tiankengs are giant collapse dolines. Setting up the lower limit for depth and diameter is arbitrary but necessary, as it is gigantism that relates tiankengs to specific conditions of formation and separates them from other types of collapse dolines.
2. Relation to large underground rivers. Tiankengs are collapse features formed over large underground river passages. This characteristic is linked with gigantism and refers to the specific mechanisms of creating a large underground void that can serve as a receptacle for a large mass of breakdown material. Moreover, dissolutional removal of material by an underground river is an important factor for massive breakdown development, the upward propagation of the breakdown structure and its eventual opening to the ground surface.

Both the gigantism and the large underground rivers tie tiankengs to humid tropical environments or to situations in other climates where allogenic streams are swallowed into karst to produce large underground river passages. The genetic criterion

separates tiankengs from other giant collapse features, including caprock collapses over evaporates (*e.g.* in Canada and Russia) and large collapses over hydrothermal cavities in arid regions formed (*e.g.* in Oman), which do not classify as tiankengs.

LIMESTONE GORGES

Gorges with vertical walls, or slot canyons, are common landforms in many limestone karst areas. Although their formation at some sites has been attributed to cave roof collapse, due to the presence of obvious remnants of cave morphological features, karst geomorphologists generally tend to avoid recognizing this mechanism as being of primary importance in gorge development. Instead, the primary process behind vertically walled gorges is believed to be surface fluvial entrenchment; the gorge walls do not flare out to valley slopes because their degradation is limited by infiltration and reduced runoff (Jennings, 1971).

During the 2005 Tiankeng Investigation Project, two remarkable limestone gorges were observed in the Chongqing karst, and both offered unambiguous evidence of the formation due to roof collapse of major cave river passages. The evidence included the presence of fragments of former cave roofs surviving as natural bridges in the otherwise open sections of the gorges, and abrupt terminations in front of major trunk cave passages at upstream and/or downstream ends of the gorges.

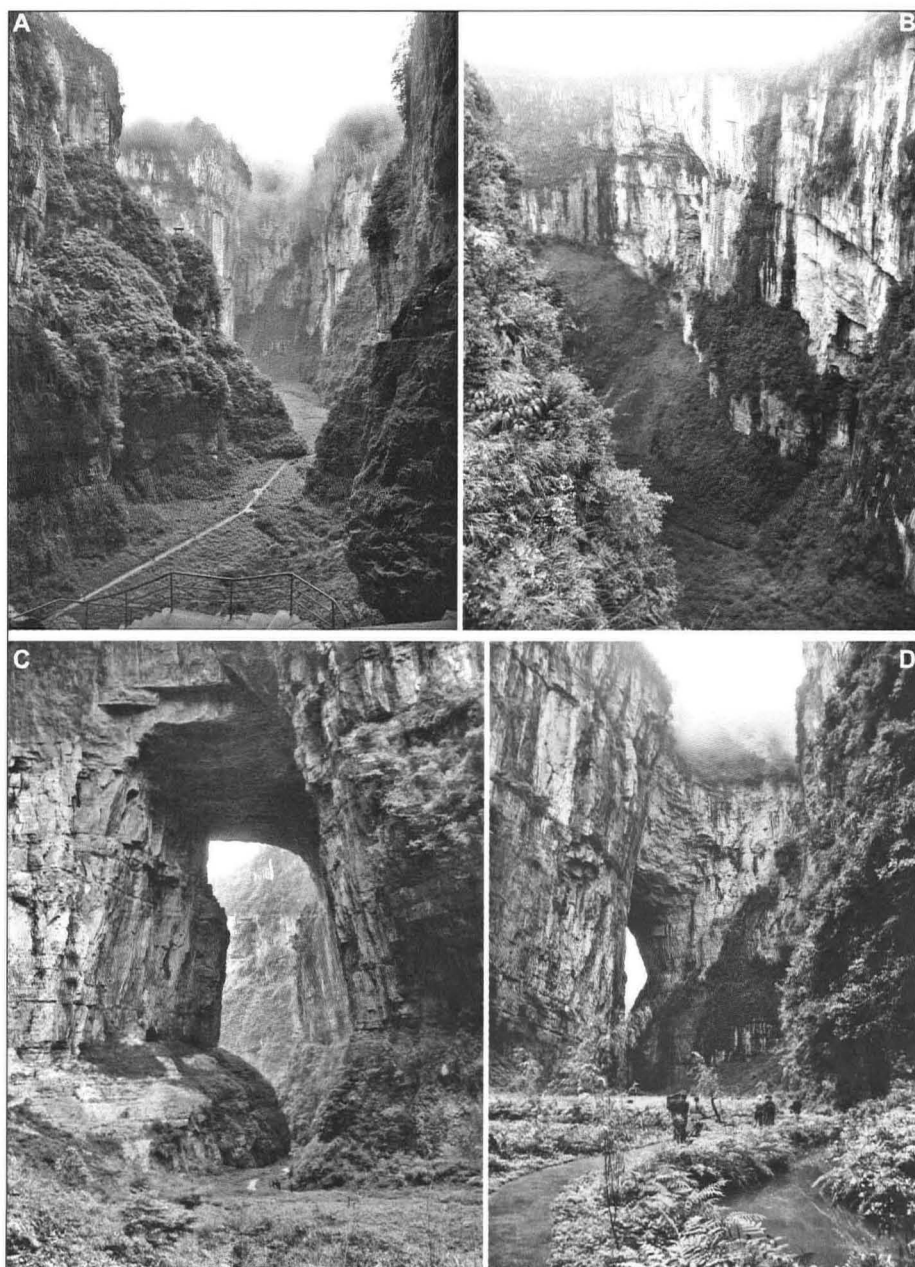
The Sanqiao (Three Bridges) site is a perfect example of gorge formation by cave un-roofing (Fig.4A). It has several closely spaced

tiankengs aligned on the course of a river that was formerly subterranean. The tiankengs are separated by massive natural bridges, that are remnants of the trunk cave passage. Evolution of the tiankengs continues by their elongation along the river, which will eventually breach the bridges and merge the tiankengs (Fig.4, C-D).

Tianjing Gorge (also know as the Great Crack, Fig. 4B) has its downstream end continuing into a trunk cave passage through to the Xiaozhai Tiankeng. Within the gorge, a remnant bridge illustrates the mechanism of roof retreat, by which the gorge continues to extend. Limestone in the face of the bridge is exposed to weathering at the end of the gorge, so that the remnant of cave roof retreats while the gorge advances along the passage (Fig. 5A). Where the roof thickness above major cave passages is not too great, such lateral roof cutting is probably the main mechanism of cave un-roofing and gorge propagation, after collapses at the weakest sections have established initial openings (tiankengs). The process of face weathering includes dissolution, erosion, crumbling, slab and block breakdown. The same was observed on one of the bridges in the Sanqiao site (Fig. 5B).

These examples strongly support the contention that gorges have been formed due to un-roofing of caves, and that tiankengs were precursors to the gorge formation. The un-roofing starts by a collapse and continues through lateral roof retreat. Further massive collapses along the course of a trunk passage are certainly possible, progressively fragmenting the cave and creating more fronts for lateral retreat.

Figure 4. Limestone gorges formed by un-roofing of trunk cave river passages. **A** : Sanqiao (Three Bridges). **B** : Tianjing Gorge (Great Crack). **C** and **D** : karst bridges, the remnants of the cave roof, separating open sections of gorge at Sanqiao.



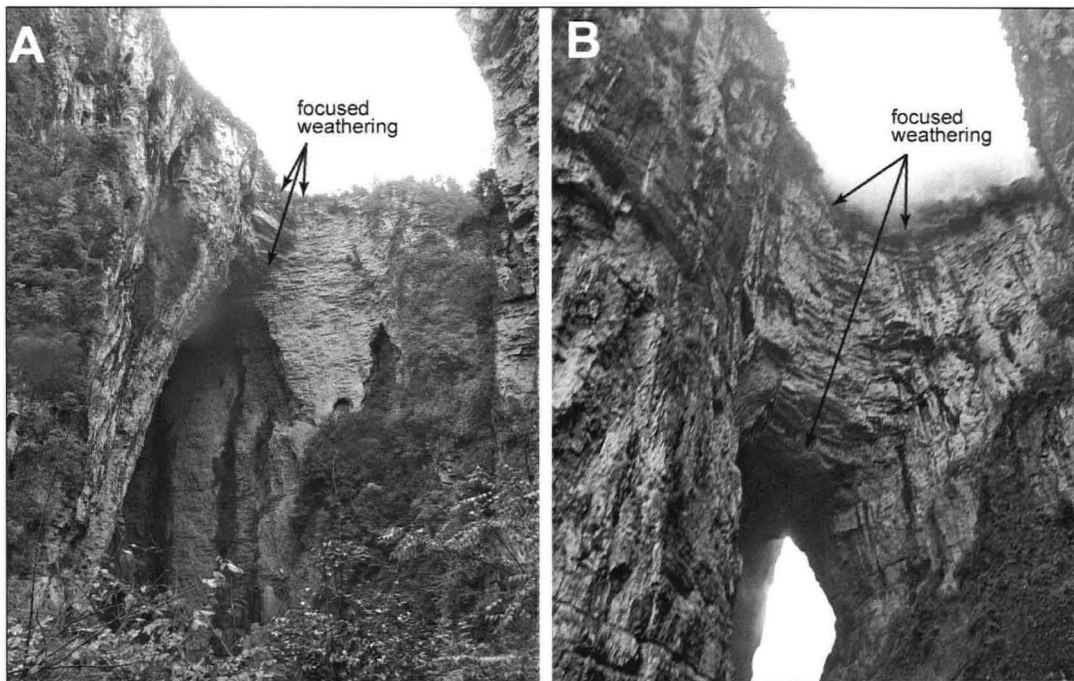


Figure 5. Focused weathering at the terminations of gorges that continue into cave passages. **A** : within the Tianjing Gorge. **B** : within the Sanqiao site.

UN-ROOFING OF CAVES

During the last decade considerable attention has been given by many researchers to so-called unroofed (denuded) caves. It was long ago appreciated that lowering of the karst surface due to ongoing denudation inevitably results in uncovering and destruction of caves, but recent works in Slovenia drew specific attention to unroofed caves (Mihevc, 1996; Mihevc et al, 1998). Unroofed caves are recognized as particular surface karst forms, partially transformed by surface processes. However, the wider role of cave un-roofing within karst geomorphology is not yet clarified. Broadly speaking, karst collapses, including tiankengs, are variants of cave un-roofing, as is the formation of limestone gorges through collapse and lateral roof retreat.

The role of cave un-roofing in tropical karst

Within the Guangxi karst, an area of typical fengcong stands above a common bedrock base, which rises from a corrosion plain at base-level (Fig. 6). A river flows from the plain into a trunk cave passage that is progressively losing its roof. The cave un-roofing, and the localised retreat of the limestone hill is one of the geomorphic processes that cuts the massif to base level. Other cave passages, when unroofed, create lows in the denuding fengcong topography. It is likely that the gentle valley above the cave entrance had been formed by un-roofing of a trunk passage within the ancient high-level of the same multi-phase cave system. It is equally likely that un-roofing of other, older passages of this paleo-cave system contributed to the formation of the present landscape now seen as a typical fengcong karst. It is suggested that cave un-roofing plays a major role in the formation of tropical karst.

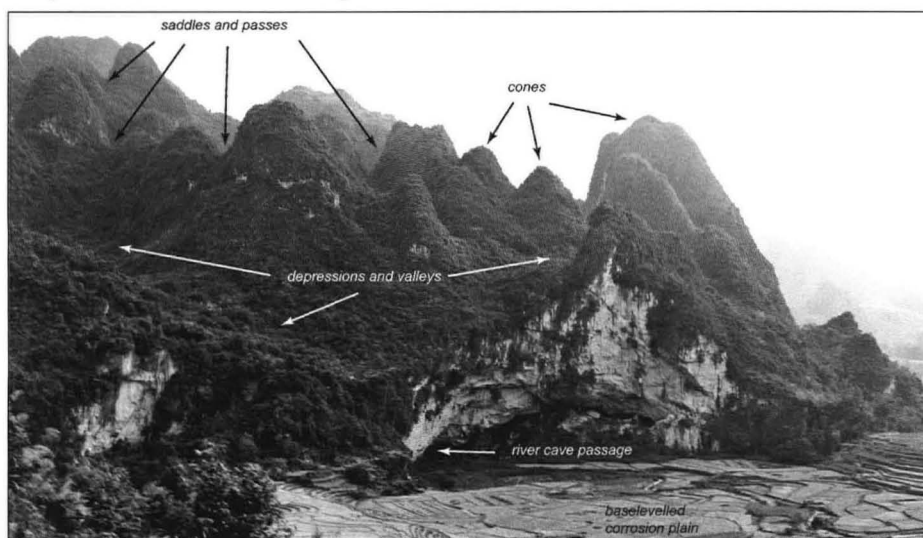


Figure 6. Fengcong karst with a large underground river beside a bedrock plain in Guangxi.

Cone and tower karst landscapes (fengcong and fenglin) are essentially residual karst morphologies, resulting from long-lasting intense karstification in humid tropical conditions. The formation of these landscapes has been viewed mainly from the perspective of surface geomorphic processes. It is commonly accepted that preferential near-surface dissolution is the primary mechanism involved, with surface collapse playing only a minor role (Day, 2004). The cones and towers are considered as erosional remnants, while the intervening depressions and lowlands are the focus of current karstic dissolution and fluvial geomorphic activity.

The morphology of cone and tower karst is extremely variable. One of the main causes of this variability is a diversity of regional tectonic evolution and base-level history. Tectonic uplift and base-level lowering cause rejuvenation of mature landscapes, and the re-organisation and complication of their geomorphic systems; in the case of karst, this extends to both surface and underground components. In karst, rejuvenation underground is a prerequisite for rejuvenation of the surface topography (Ford & Williams, 1989: p438). Multiple phases of uplift and base-level shifts, alternating with prolonged periods of stability, may add considerable complexity to the geomorphic system (Ford and Williams, 1989: Fig. 9.34).

Collapse features are indicators of rejuvenation of karst landscape. Tiankengs are fresh landforms, in which the collapse origin is readily recognizable. The same applies to gorges which have remnants of cave roof (bridges) or which are directly continued by cave passages. In mature landscapes, such as typical fengcong karst, the collapse origin of the forms is not so obvious from their morphology, and it can be only inferred from oblique evidence.

There are several lines of evidence that support the important role of cave un-roofing in the formation of fengcong and fenglin karst terrains:

- Un-roofing of caves is an inevitable consequence of ultimate karst development. Any void in the rock will be unroofed in the course of karst denudation. When unroofed, elements of cave morphology integrate into the surface topography. Caves are therefore precursors of negative landforms in the future topography.
- Dimensions of cave passages in tropical cone karst are great enough to play an important role in surface karst topography when caves are unroofed. This is directly evidenced by tiankengs and gorges, which are freshly unroofed caves (Fig.4). Numerous cave remnants in mature tropical karst suggest that dimensions of the caves are comparable with those of major elements of the cone karst morphology (Fig. 7). Cave explorations made during last two decades, by the China Cave Project and many other groups, suggest that typical dimensions of trunk passages are many tens of metres in width and height but in many places they exceed 100 m.
- The number of cave passages in tropical cone karst is great enough to play an important role in surface karst topography when underground systems are denuded. The potential of this may be inferred from the 2800 underground rivers, with a total length estimated at about 14,000 km, within the 150,000 km² of cone karst in South China (Zhu & Chen, this volume). The total length of substantial passages in cave systems (including abandoned passages in upper levels) should be at least several times greater. This suggests that elements of cave morphology will inevitably constitute important and common elements of surface topography when integrated into cone karst landscapes.
- There are many caves remnants, including karst bridges, arches, truncated passages and unroofed cave gorges, that are incorporated into modern karst landscapes, many of which are mature.
- Recognition of the role of cave un-roofing in the formation of cone karst morphology is impeded by the problems of interpretation of mature landscapes, in which unroofed remnants of cave passages are so greatly reworked by surface processes that their origins are obscured.

In most karst terrains, the depressions and lowlands between the cones and towers are mainly interpreted as being formed by focused karstic dissolution and fluvial geomorphic activity. In the light of the above arguments, an alternative interpretation is that a considerable proportion of them have originated due to the un-roofing of caves.

Depressions

Bearing in mind the proven collapse origin of tiankengs and their geomorphic evolution by degradation), many, if not most, large dolines recognizable in fengcong karst could be interpreted as degraded tiankengs. Digital topography models of sample mature fengcong karst terrains in Guangxi reveal numerous large depressions and blind valleys, which could have evolved from tiankengs (Fig. 3). The interpretation that most large depressions in mature fengcong karst are degraded tiankengs (or otherwise originated as collapse features) is also supported by some observed densities of normal tiankengs in areas experiencing rejuvenation; in the Leye karst of Guangxi, the Dashiwei group consists of 26 tiankengs. This indicates that surface collapse could be the prime origin of large depressions in other fengcong karst areas that have evolved into mature karst landscapes.

Saddles between cones

Integral features of the fengcong karst are saddles (or passes) between adjacent cones (Fig.6). Although research specifically addressing their nature appears to be unpublished, they are tacitly understood, within the conventional geomorphological thinking, as being the result of some sort of surface fluvial activity, perhaps relicts of a fluvial paleo-drainage pattern, or of selective denudation along structurally weakened zones. Their cross-sections are commonly V-shaped or U-shaped, allowing various interpretations regarding shaping processes. In longitudinal profiles, most saddles

are just crests between adjacent depressions, although some are passes retaining fragments of horizontal or inclined floor.

While not completely rejecting other possibilities, it appears that the saddles and passes between cones could be relicts of unroofed cave passages. Their plan pattern and altitude distribution seem to generally conform to an imaginable pattern of mature branch-work cave systems that existed on higher levels, since removed by denudation; there is scope for specifically designed morphometric analysis to demonstrate this more soundly. In most cases, cross sections and the relative arrangement of the saddles fits to this explanation much better than to subaerial fluvial origins. Some cross-sections suggest that they are well preserved remnants of passage profiles (Fig.8), especially where they include hanging walls (Fig.9).

Traditional decorative arts in southern China can be very instructive for karst geomorphologists. Karst landscapes are depicted in artwork in many ways and techniques, and some essential features of landscapes are often captured and represented there with great expressive power (Fig. 10).

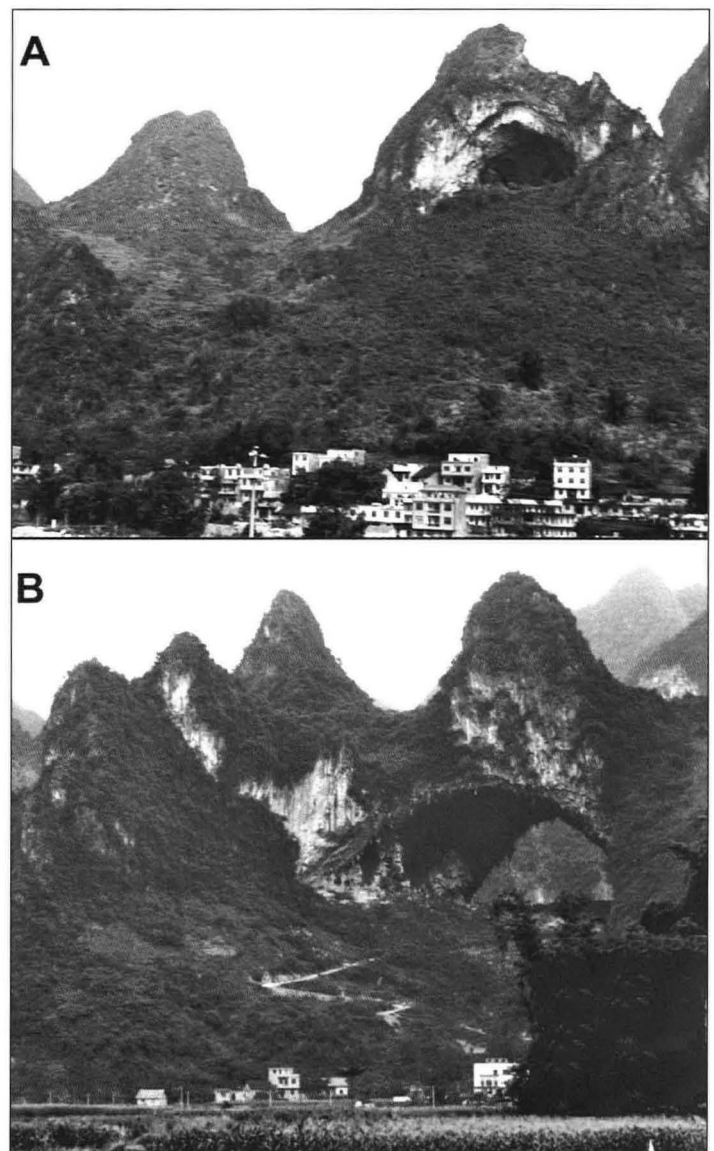


Figure 7. Truncated remnants of abandoned cave passages in the karst of Guangxi. **A** : un-roofing of the cave in the hill on the right will dismember the hill and create a new saddle between two smaller hills, but it is not clear if the existing saddle in the centre originated by un-roofing a cave; a remnant of an older saddle lies in the top of the hill, just above the cave entrance, and was formed by destruction of a passage at the higher level, now completely denuded. **B** : breaching of this dramatic karst bridge will complete the formation of a surface valley - the result of un-roofing a large cave passage.

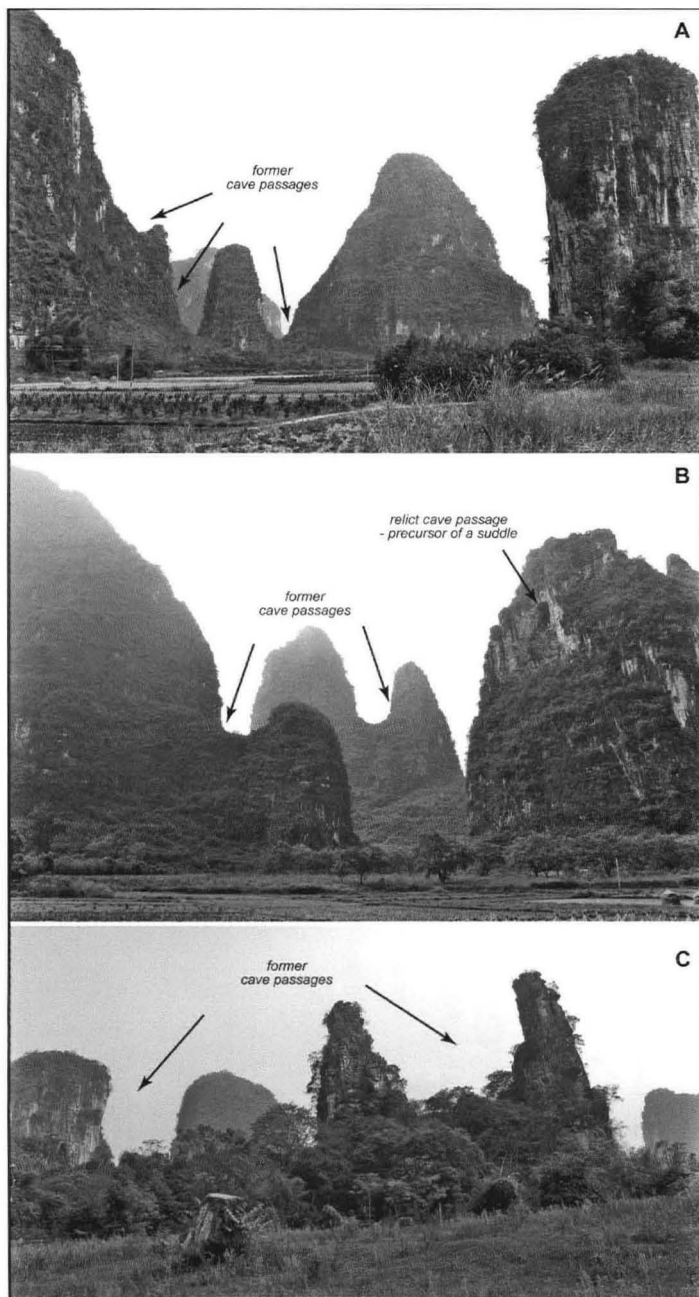


Figure 8. Saddles and passes in the fenglin karst south of Guilin. Their shapes and positions in the topography suggest that these forms may be remnants of almost completely destroyed cave morphologies. When eventually unroofed, a fossil cave in a hill on the right of the photo B will create a new saddle that further dismembers the hill.

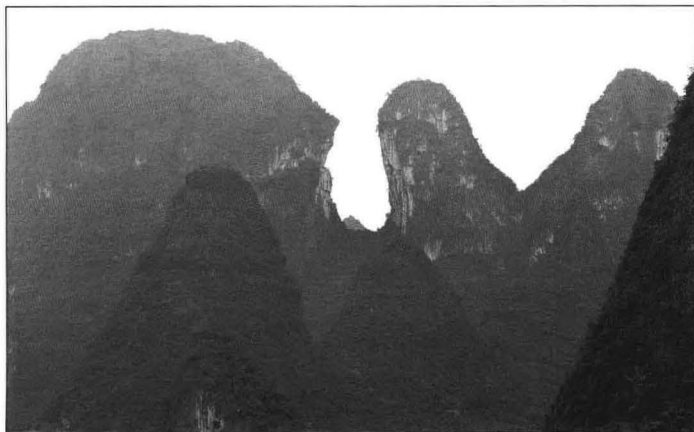


Figure 9. Fengcong karst in Guangxi: a saddle in the centre, with hanging walls, is a perfect illustration of its origin by un-roofing of a cave passage.



Figure 10. Chinese vases, depicting fengcong and fenglin karst. Fragments of unroofed passages and degraded tiangkengs can be recognised in these landscapes.

CONCLUSIONS

A morphogenetic approach is suggested to define tiangkeng as a typological category. Tiangkengs are giant collapse dolines formed over large river caves, with continuous precipitous perimeter and a diameter-to-depth ratio between 0.5 and 2.0. The term bears an evolutionary meaning, referring to the youthful stage of collapse doline development. Both the large size and the association with large underground rivers tie tiangkengs largely to humid tropical environments. This criterion also separates tiangkengs from other types of giant collapse features, such as caprock collapses over evaporates or large collapses over hydrothermal cavities.

It is suggested that cave un-roofing through surface collapse may be a large-scale mechanism that plays a significant, probably major, role in the formation of fengcong and fenglin karst terrains. It is probably the major mechanism of origin of large depressions (most of which evolved from tiangkengs), gorges and valleys, though other geomorphic processes certainly contribute to shaping and maturation of the landscapes and eventually obscure any origins as unroofed caves. Many saddles between hills and towers in fengcong and fenglin karst may owe their origin to cave un-roofing. This view of the important role of cave un-roofing in tropical karst morphogenesis is strongly supported by multiple evidence from various relicts of former caves integrated into the karst topography and recognizable even in mature landscapes.

Acknowledgement of the important and large-scale role of cave un-roofing in the formation of fengcong and fenglin karst opens new possibilities for morphometric analysis of such terrains and for reconstruction of their geomorphic evolution.

Acknowledgements

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Some large dolines in the Dinaric karst

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Abstract: The main characteristics of the Dinaric karst are all kind of depressions, not only poljes and dolines, but also collapse dolines and similar forms. Some examples of such forms of large dimensions are located on the higher karst plateaus (Pokljuka, Jelovica, Snežnik in Slovenia), on the contact karst (Škocjanske Jame), on the levels above poljes (Crveno Jezero above the Imotsko Polje), and behind large karst springs (Unška Koliševka above Malni springs). Slovene terms for karst depressions are defined.

Key words: karst geomorphology, depression, collapse doline, Dinaric karst.

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Karst depressions are the most characteristic features of the Dinaric karst, which covers the region between the Friuli plain in the northwest and the Albanian mountains in the southeast. These include are not only dolines, uvalas and poljes, but also collapse dolines and other depressions that are similar to collapse dolines (Kranjc, 2004). In practice, it is often difficult to distinguish a real collapse doline from other types of karst depression. It is even more difficult in the case of the older features, which have been modified by corrosion and other surface processes, and where the primary origin is no longer clear.

On the Kras plateau (from where the term *karst* originates), a typical example of an active collapse doline that has a river across its floor is Velika Dolina (Great Doline) (Fig. 1). It is situated very close behind the ponor where the Reka River disappears into the caves of Škocjanske Jame (Kranjc, 1997, 2004). The doline mouth measures 170 x 300 m and the depth is 155 m. There are more collapse dolines on the Kras plateau; some are larger than Velika Dolina, but they do not reach the underground.

THE KONTA AND DRAGA DOLINE TYPES

There are many large and deep depressions on the higher Dinaric and Pre-Alpine plateaus. Some of these could have a collapse origin, or collapse process at least played an important role in their genesis. One important type of depression is known as a *konta*; this is a local name, but it does appear in the Slovene karst terminology (Gams, 1973). A *konta* is a closed karst depression, like a doline, that has been remodelled during Pleistocene glaciation. Thus it is viewed among glaciokarstic landforms, or as a polygenetic karst depression of multiple origins. It is difficult to decide if the original depression was a solution or a collapse doline. On the floor of a *konta*, thick unconsolidated sediment (normally of glacial till) has accumulated, and creates a local aquifer, so that small springs occur. The combination of good soil and reliable water is the basis for the economic use of the *konta* in farming. A good example is the *konta* of Kranjska Planina on the Pokljuka plateau, which is used as a summer mountain pasture (Fig. 2).

Similar large depressions appear also on the lower Dinaric plateaus. These are not considered as glaciokarstic landforms because there was no overall glaciation on these plateaus, with the exception of some small-scale, local ice. This type of depression is locally known as a *dol* or a *draga*. It is again not clear if the original form was a solution doline or if it is a polygenetic form as an intensively remodelled collapse doline. Although these plateaus were not glaciated during the Pleistocene, the climate then was sharp, and frost shattering was more intensive. A good example of such a depression is the Smrekova Draga (Spruce Tree Doline) on the plateau of Trnovski Gozd. Its rim stands at an altitude of 1250-1400 m (Rojsek, 1995). It is about 1500 m in diameter, reaching a depth of 150-300 m. There are no rock walls that can be evidence of a collapse origin. The southern slopes reach the highest and are very steep, while the northern slopes are more gentle. The approximate volume is 18M m³. During the last Pleistocene glaciation, a small glacier from the nearby mountain of Golak reached the *draga*, and left till on its floor. According to Habič (1968), ice should have filled the whole depression at the peak of the glaciation, remodelling and deepening it by about 100 m, by mechanical and chemical

processes. Some of these large Dinaric depressions have steep rocky slopes, and there are entrances to cave or shafts on the floors of others. Whether these are or are not collapse dolines, such forms and features are not typical of normal solution dolines.

HYDROLOGY OF THE COLLAPSE DOLINES

Velika dolina (Fig. 1) is an active collapse doline in a hydrological sense, as a river flows across its floor, within the cave system of Škocjanske Jame. Typically, the bottom of a collapse doline is filled with boulders, breakdown debris and other mechanical weathering products. Only in some cases is it possible to find a connection to the underground water course. Downstream of Škocjanske Jame there is the collapse doline of Risnik (Lynx Doline). In plan this measures 540 x 360 m, while its depth is 74 m. The cave passages carrying the Reka River lie 160 m beneath the doline floor (Mihevc, 2001). Another great collapse doline, Unška Koliševka (Doline of Unec), lies immediately behind the karst springs of Malni, not far from Postojna. The doline's maximum depth is 119 m and the stream feeding the Malni springs passes through 33 m beneath its floor.

The collapse doline of Crveno Jezero (Red Lake), near the town of Imotski, Dalmatia, Croatia, is a special case (Bahun, 2000). Its maximum depth is 528 m, and it is filled with water 287 m deep (Fig. 3). It had been thought that the water level in Crveno Jezero corresponds to the regional piezometric water level and that small fissures provided the only effective connection between the water of the collapse doline and the host aquifer (Kunaver, 1959). However, recent diving explorations have found large openings in the



Figure 1. Škocjanske Jame: the collapse dolines of Velika Dolina and Mala Dolina, and Škocjan village. (Photo: Škocjanske Jame Regional Park)





Figure 2. Kranjska Planina konta, a glaciokarstic depression used for summer pasture.

submerged walls of the doline and cave entrances at its floor (Garašić, 2000). These conduits allowing water to flow in and out, and through the doline.

The topographic locations of collapse dolines does relate to patterns of underground water flow. Many of them are on the karst plateaus, on reasonably levelled surfaces. Dolines on the high plateaus are high above the piezometric levels, and high above the main underground streams. Consequently most of these great depressions do not have the characteristics (or at least do not have enough characteristics) to be classified among the collapse dolines (that form by collapse into cave passages). Their collapse origins remain open to debate.

Collapse dolines that lie relatively close to underground streams are situated either close behind karst springs (such as Unška Koliševka above the Malni springs) or immediately downstream of ponor caves (such as Velika Dolina at Škocjanske Jame). They are situated also on surfaces where the underground streams are relatively near the surface (such as Risnik on the Kras, and Crveno Jezero above the margin of the Imotski polje). It appears that the larger collapse dolines only develop where there is a large underground river.

DIMENSIONS OF SOME COLLAPSE DOLINES

Smrekova Draga, on the plateau of Trnovski Gozd, has a volume of 18M m^3 , and is probably the greatest such depression in Slovenia. But according to the Slovene karst terminology it is a konta, which is a glaciokarstic depression and is not a collapse doline.

Volumes of collapse dolines on the Dinaric karst around Logatec, north of Postojna, have been calculated (Šušteršič, 1973). The highest value was 2.75M m^3 , for Laška Kukava (Doline of Laze), but these results are not fully reliable, and may be underestimated by about 30%. They are therefore much smaller than the great Chinese tiankengs, of which Xiaozhai, Haolong and Dashiwei have volumes of 119, 110 and 67M m^3 respectively (Zhu & Chen, this volume).

On the Kras plateau the greatest collapse dolines are Senik (Hay Barn) near the village of Nabrežina, (Aurisina in Italian), and Veliki Dol (Great Doline) near the village of Avber. Senik measures 770 x

650 m across its rim, and has a mean maximum depth of 50 m ; it has a volume of 9.89M m^3 or 11.2M m^3 , depending upon the definition of the rim. Veliki Dol, near Avber, is an elongated depression of $600\text{ x }350\text{ m}$, with a mean maximum depth of 70 m ; its volume is calculated as 7.18M m^3 . In the caves of Škocjanske Jame, Velika Dolina and Mala Dolina, together with the two smaller collapse dolines of Sapendol and Lisičina, have a combined volume of 6.2M m^3 . Further out in the Kras, the largest collapse doline is Radvanj (9M m^3), followed by Globočak (4.6M m^3), Bukovnik (1.5M m^3) and Risnik (1.5M m^3) (Mihevc 2001).

There are no published data on the volume of Crveno Jezero. A rough estimation can be calculated from the depth of 520 m , the dimensions of the upper rim of $450\text{ x }400\text{ m}$, and the diameters at water level of $210\text{ x }180\text{ m}$. This gives a value of at least 25M m^3 , though figures of 30M m^3 have been quoted.

TERMINOLOGY

When using English, the Slovenes also use the international term collapse doline, irrespective of the type of a collapse doline or whether there is a special term for it that is used in the Slovene language. According to the Slovene Karst Terminology (Gams, 1973), the language has 11 synonyms for a collapse doline: *dol*, *dolina*, *draga*, *koliševka*, *koliševka*, *konta*, *koševlec*, *kukava*, *udorna dolina*, *udorna vrtača*, and *udornica*.

The terms *dol* and *dolina* are very clear. In the largest sense *dol* means down, as opposed to up that is a hill or mountain. *Dolina* means a valley, covering all the types of valleys, from broad river valleys to the small close depressions on karst. The expressions *udorna dolina*, *udorna vrtača*, and *udornica* originated from *udor*; this means collapse. The origin and meaning of the other terms is not so clear. In colloquial language some of these terms do mean collapse doline in the strict sense of the word, while the others cover the large palette from doline and collapse doline to uvala and polje.

These comments on the Slovene language must also apply in the other languages of people living on karst. There are many words for the same phenomenon, and on the other hand the same term can mean a set of different phenomena. A good example is the word *jama*: in Slovene, this means a horizontal cave, while in the Croatian and Serbian languages it means a vertical shaft.

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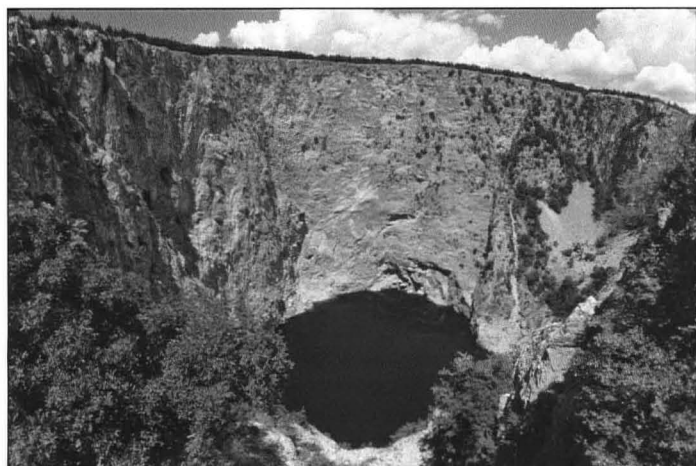


Figure 3. Crveno Jezero collapse doline. (Photo: Tony Waltham)

Hydraulic processes in the origin of tiankengs

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Abstract: Tiankengs are formed most commonly by the collapse of bedrock into underlying caves that contain active rivers. The collapse propagates itself by blocking and diverting the underground streams, so that hydraulic gradients become steeper and the solutional and erosional capacities are enhanced. Most of the volume of a tiankeng is produced by removal of mass by the cave streams. A large and fluctuating discharge is most favorable. As diversion passages form and enlarge, they foster further collapse and diversion. Stress release around the collapse encourages the opening of new fractures with trends that differ from regional fracture patterns. These processes account for the large scale of tiankengs in comparison to the original cave passages.

Keywords: Karst, doline, collapse, hydraulic

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Tiankengs are large karst depressions with nearly vertical walls and a mean depth and diameter typically more than 100 m each (Zhu and Zhang, 1995; Zhu and Chen, 2005). Their type area is in south-central China, where the largest and most abundant tiankengs are located (Fig. 1). Most tiankengs contain active cave streams at their bases, or show evidence that similar streams were present in the recent geologic past (Fig. 2; Senior, 1995). Although other origins are possible, collapse into cave streams must be considered the leading process of tiankeng development. This paper investigates the pertinent physical and chemical processes and provides several field examples.

FIELD OBSERVATIONS

Two active field examples from the karst of southern Indiana, USA, are used here to illustrate the processes that appear to produce tiankengs. This karst area is developed on early Carboniferous limestones and dolomites with a mean dip of about 0.3° to the southwest. The carbonate rocks have been dissected to a maximum of about 50 m by through-flowing rivers, to form an extensive karst plain typified by closely clustered dolines. Both of the Indiana examples are small relative to tiankengs, but they provide easy access for viewing the essential processes.

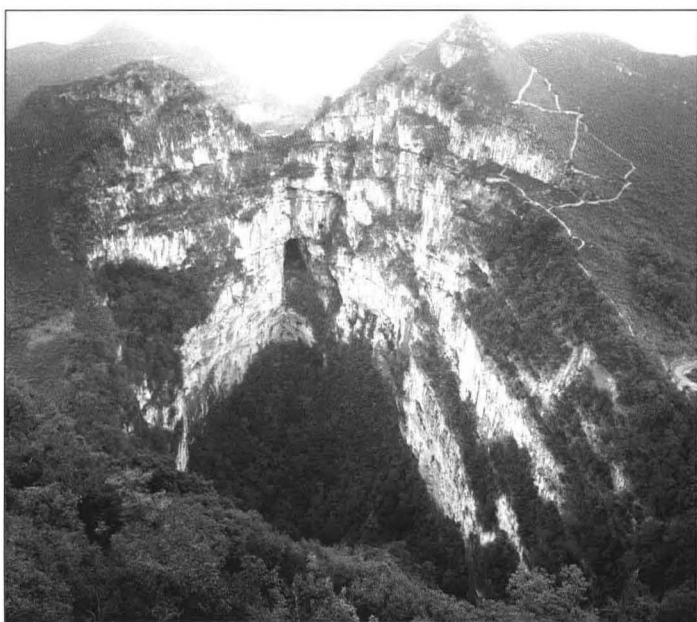


Figure 1. Dashiwei Tiankeng, Guangxi, China, is up to 613 m deep and has an opening 600 x 420 m.

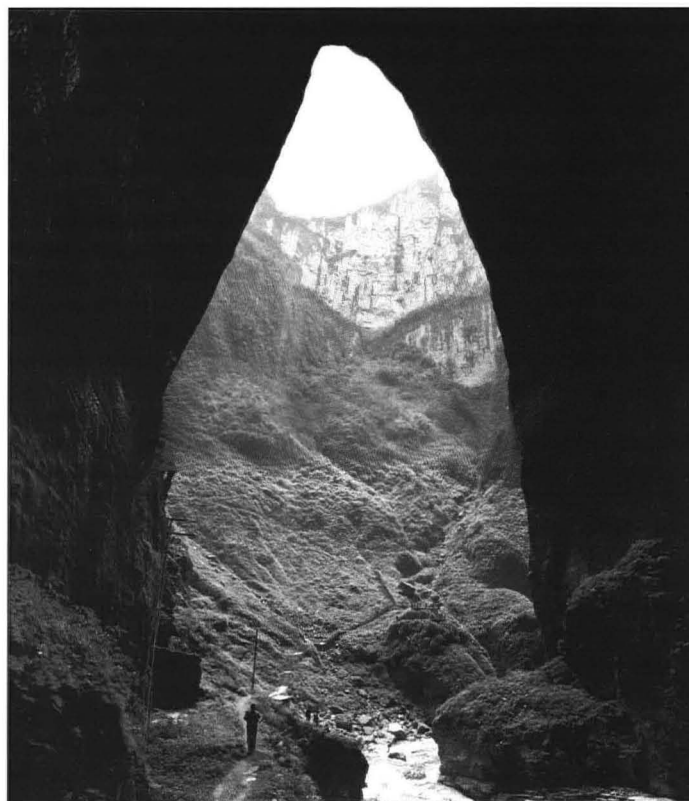


Figure 2. The downstream end of the river cave Di Feng Dong, at the base of Xiaozhai Tiankeng, Chongqing, China. The stream flow shown here is at moderate flow but represents only what is left after withdrawal of water for a hydroelectric plant. Xiaozhai is probably the world's largest tiankeng, with a volume 1.6 times greater than that of Dashiwei Tiankeng.

Wesley Chapel Gulf

Lost River, with a drainage area of roughly 400 km², is the largest stream that lies entirely within the southern Indiana karst (Malott, 1932; Bassett, 1976). The downstream half of the basin consists mainly of subsurface drainage that is partly accessible through cave entrances. Exploration and dye tracing show that the present underground paths of the water deviate considerably from the former bed of the river, which is now dry (Fig. 3).

Wesley Chapel Gulf is the largest karst depression in the basin (Fig. 4). Its walls are nearly vertical along most of its perimeter. The depression is broad, with an area of 3.4 hectares (about 300 m x 100 m), but it has only about 10 m of relief from its alluviated floor to its highest rim. No one would mistake this shallow depression for a tiankeng, but it shares many of the physical characteristics of actively forming tiankengs.

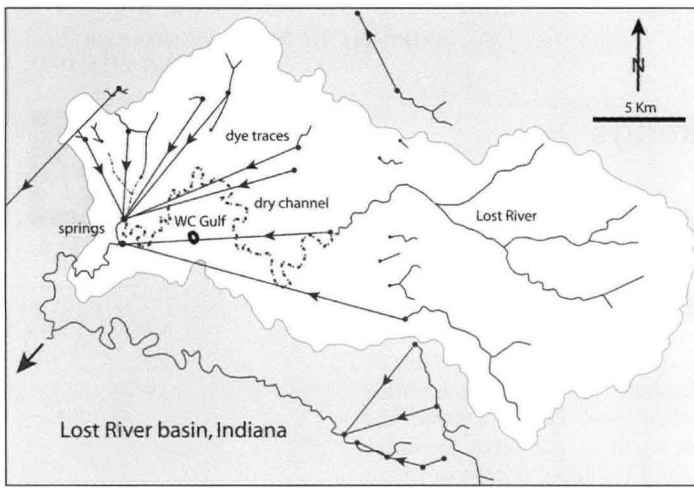


Figure 3. Map of the Lost River basin of southern Indiana, USA, showing the location of Wesley Chapel Gulf (WC) in relation to surface drainage and dye traces (modified from Bassett, 1976).

Three caves are accessible from entrances around the walls of the Gulf. Recent discoveries from another entrance nearby have so far accounted for more than 30 km of mapped passages, all of which lie no more than 20-30 m below the land surface. This system extends westward from Wesley Chapel Gulf for several kilometres. The Gulf and surrounding caves are located near the contact of two thin-bedded limestones, the cherty St. Louis Limestone and the overlying purer Ste. Genevieve Limestone. Collapse blocks are typically thin slabs.

The discharge through and around Wesley Chapel Gulf varies from about 0.3 to 4 m³/sec (extrapolated from data by Bassett, 1976). During low flow, water drains around and beneath the Gulf without appearing at the surface. During high flow the Gulf is flooded, and that is the source of the thick alluvium that covers its rather flat floor. The Gulf therefore has the geomorphic character of a polje, but without the size or the structural guidance that is typical of poljes. As cave development progresses, the Gulf widens by collapse around its perimeter. This collapse in turn forces the water to seek alternate routes, which perpetuates the tendency for further collapse. The entire Lost River Cave consists of multiple routes for

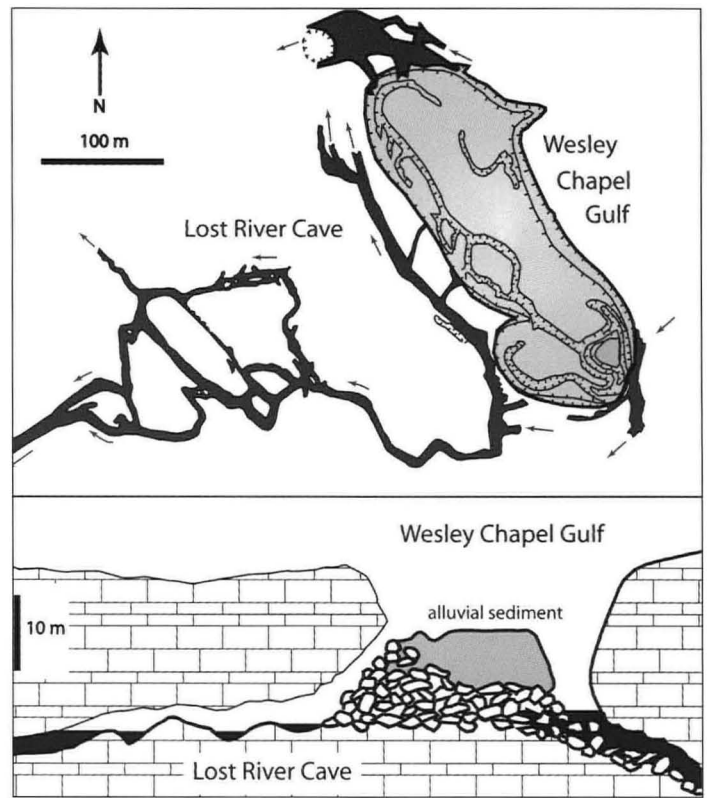


Figure 4. Map and profile of Wesley Chapel Gulf and related caves, from surveys by Malott (1932), updated by R.L. Powell, Indiana Geological Survey.

water with many overflow passages formed by periodic floodwaters. Accessible cave passages are generally less than 10 m in width and height (Fig. 5), and it is clear that collapse of a single passage could not produce a depression as broad as Wesley Chapel Gulf.

Blue Spring Cave

The processes that operate at Wesley Chapel Gulf are even more clearly revealed at Blue Spring Cave, 18-20 km to the north (Fig. 6). This cave is a large dendritic stream system with a total of 34 km of

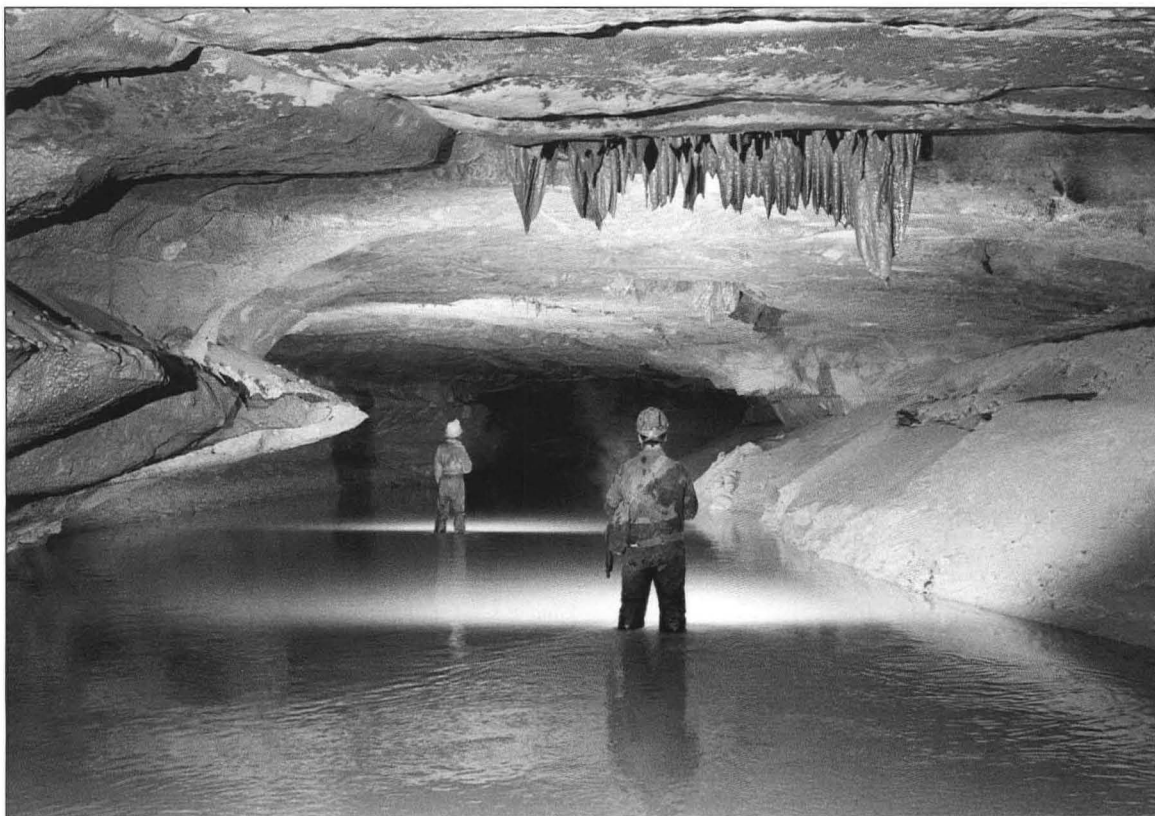


Figure 5. One of the main stream passages in Lost River Cave in low flow.

mapped passages. It is located mainly in the massive, prominently jointed Salem Limestone, which produces large collapse blocks instead of thin slabs. It is overlain by the thin-bedded, cherty and shaly lower strata of the St. Louis Limestone. The main stream has a maximum discharge of more than $10 \text{ m}^3/\text{sec}$ and a minimum of only about $0.1 \text{ m}^3/\text{sec}$ (measurements by the authors). The cave drains an area of about 30 km^2 .

As the cave enlarged, the main stream passage collapsed at a junction with a major tributary, to form a large compound doline (Fig. 7). The main passage in this area has a width and height of about 10 m, and the land surface lies an average of 20-25 m above the passage ceiling. The collapse material has a low enough permeability that it eventually forced both the main stream and its tributary to develop alternate routes around it. The sequence of collapse and diversion is clearer than at Wesley Chapel Gulf, but the surface depression is much smaller and has no flat floor.

The diversion routes now form a labyrinth of passages, known as the Maze, which has a total length of about 1.5 km (Fig. 8). Nearly all of these passages are joint-guided fissures in the Salem Limestone. The total relief in the Maze is about 20 m, about half of which lies below the present water table. Its passages have irregular ceiling heights and contain pools up to 10 m deep. Today the entire combined flow of the main cave stream and its tributary passes through the Maze. Its passages are small enough that water fills them entirely during severe floods, so they continue to grow and multiply.

The orientation of solution facets (scallops) in the walls of the Maze show that some of the water has traveled through the breakdown as well as around it on both sides. Water from the main stream now bypasses the collapse around the northeastern side, while water from the tributary follows southwesterly bypass routes. The passage pattern shows that originally most of the flow from the main stream also drained around the southwestern side. The collapse and diversion appears to date from the late Pleistocene at least 100,000 years ago. This estimate is based on dating of correlative passages in other caves, including Mammoth Cave, Kentucky, 175 km south in an extension of the same karst (Granger et al, 2001).

As shown in Figure 7, the deepest dolines overlie the collapse in the main cave passage, but many of the shallower ones seem to show no relation to the passages beneath. The thin-bedded St. Louis Limestone tends to provide lateral paths for vadose water, in preference to vertical paths. Many dolines in the St. Louis are enlarged by the removal of material to points where the water is able to descend vertically into the underlying Salem Limestone. Also, some dolines have formed over secondary collapse zones in and around the Maze.

The Salem Limestone contains two prominent joint sets with average trends about 10° counterclockwise from east-west and north-south. These trends are roughly parallel to the regional dip and strike. The local dip direction and angle vary throughout the cave but have no apparent effect on the joint patterns. The overall passage orientation in the cave follows the same pattern as the joints. More than half of the passage length is guided by the dip-oriented joints, and a much smaller percentage follows the strike-oriented joints. These trends are shown in the rose diagram of individual passage segments, obtained from the survey data for the entire cave and weighted by length (Fig. 9). However, if only the passages in the Maze are considered, a different pattern emerges. In the Maze, much of the passage length has the same trends as those in the rest of the cave, but even greater lengths are oriented at angles about $15\text{--}25^\circ$ to either side of the dip-oriented trend. As a result, many passage segments in the Maze intersect at acute and obtuse angles.

There are two possibilities for the difference in passage trends between the Maze and the rest of the cave. It is most likely that stresses in the vicinity of the collapse have produced additional joints with trends that are not present elsewhere. A less plausible explanation is that the diversion passages simply follow existing joints that were not utilized by the main passages until they could be enlarged by stress release around the collapse. The "new" joints are roughly radial and tangential to the main collapse zone, which suggests that the directions of most of the Maze passages are related to stress patterns produced directly by the collapse. Development of

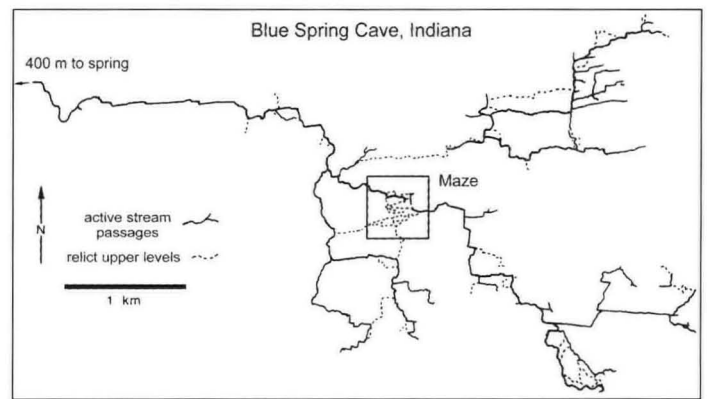


Figure 6. Map of Blue Spring Cave, Indiana. The shaded area shows the location of a maze of diversion passages around an extensive collapse zone. (Map by A. Palmer, D. Chase, M. Palmer, T. Hall and others.)

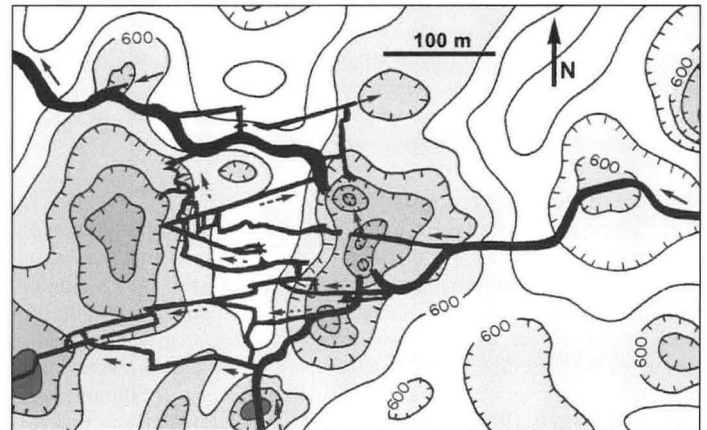


Figure 7. Map of the Maze, Blue Spring Cave, and its relation to compound dolines at the surface. Cave passages are delineated with black lines. The shaded areas are depressions and the dark gray areas are doline ponds. Arrows indicate flow directions in the cave. The main stream enters from the right and exits at upper left. The major tributary enters from the bottom of the map. The major collapse is located beneath the line of deepest dolines in the middle of the map. Contours are in feet, at intervals of 10 feet ($\approx 3 \text{ m}$).

new joints can be important in aiding the diversion of cave streams around collapse zones. If similar stresses are present around the collapses that form tiankengs, the resulting fractures may help to define some of the vertical walls of these depressions.

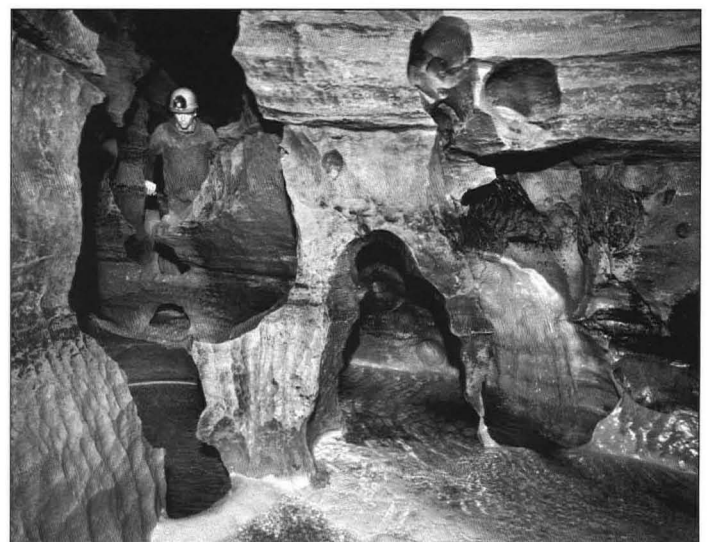


Figure 8. A passage in the Maze of Blue Spring Cave during low flow.

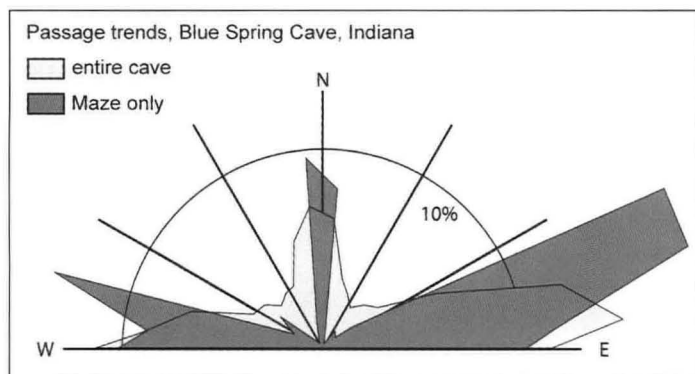


Figure 9. Rose diagram comparing passage trends in the Maze with those in the entire Blue Spring Cave. The lengths in each sector are summations of the lengths for each passage segment in the survey data.

GENETIC PROCESSES

The dolines described above have an origin that involves not only bedrock collapse, but also hydraulic processes, dissolution, and erosion. Most of these processes can be quantified, which helps to support the concepts and also to show that the observations of small dolines apply as well at the huge scale of tiankengs.

Nature of bedrock collapse

The largest tiankengs have a much greater volume than any known cave room. To account for the large mass of material that has been removed from a tiankeng, much more than collapse into a single cave passage is required. Collapse of a cave produces a jumble of rock that occupies about 20-40% more volume than the original opening. As the collapse propagates upward, the blocks eventually fill the available space so that further collapse is greatly diminished or halted entirely (Šušteršič, 1984). In the breakdown pile in Figure 10, note the loose packing of the upper blocks and the proximity of the intact ceiling above them. If only a few ceiling blocks fall into a cave, there is no change in overall cross-sectional area. Space is neither created nor filled, but is simply redistributed. There is greater resistance to underground stream flow because the openings are smaller than the original passage. If bedrock collapse is the only active process, even if it extends all the way to the surface, any resulting karst depression is smaller than the original collapsed cave.

If the collapse continues and the cave ceiling migrates upward, eventually the top of the breakdown pile may become inaccessible even to floodwaters. As a result, the only space available for the stream flow is the lower sections of the breakdown pile. This part of the pile has the lowest permeability, because small breakdown fragments tend to filter down between the larger blocks and fill much of the space. Shaly beds tend to crumble into small chips that can clog the openings between blocks of more competent bedrock. Sediment and soil from the surface may contribute to the pore filling. If material is removed from the bottom of the pile by erosion and dissolution, much of the space is re-filled by material subsiding from above. The size of the surface depression depends almost entirely on the volume of material carried away by the cave stream.

Hydraulic processes

As collapse material accumulates in a cave, the hydraulic efficiency is reduced considerably. A steeper hydraulic gradient is required to transmit water through a collapse zone than through the original unobstructed passage, and therefore the water tends to pond at the upstream side of the obstruction to provide the necessary gradient.

The amount of hydraulic head that is lost across a constriction in a water-filled cave passage is illustrated in Figure 11. In this figure the constriction is simplified to a single narrow tube that interrupts the main passage. The total head loss through the narrow tube is shown in relation to the discharge and to the ratio of passage diameters. The hydraulic gradient in the unobstructed passage is very small compared to that in the narrow tube. The total head loss (Δh) across the constriction is shown on the left axis of the graph. This is how high the water would have to rise at the upstream end of the constriction to allow the water to pass through. But since the entire passage is already water-filled, Δh would be represented as pressure head, which is the height to which water would rise in a well that penetrates the cave passage.

For example, if the passage diameter constricts from 2 m to 0.5 m, $d_1/d_2 = 4$. If the discharge (Q) = 3 cubic metres per second, the head would rise almost 30 m higher at the upstream end of the constriction than at the downstream end. Such steep gradients are only intermittent, as they are likely to occur only during large floods. It is during those times that the water would be most likely to form bypass routes through the network of joints and partings around the constriction.



Figure 10. Collapse at a passage intersection in Mammoth Cave, Kentucky. The strata are similar in age and character to those in Lost River Cave.

The head loss caused by the constriction is composed of several parts: the *line loss*, which is the head difference that is necessary to move the water through the narrow tube, and the *local losses*, which represent the head consumed by changes in velocity (either magnitude or flow direction). Local losses occur at any convergence, divergence, bend, obstruction, or junction. The line loss is computed by

$$\Delta h_{\text{line}} = (v^2 f L) / (2 d g)$$

where v = mean flow velocity, f = friction factor, L = flow distance, d = passage diameter, and g = gravitational field strength. Any compatible system of units may be used. The friction factor (f), which has no units, is about 0.03-0.05 in a typical cave passage. Reports of field measurements in caves often cite f values as high as 100, but these include all the local losses, including those caused by breakdown. This equation can be modified for non-circular cross sections, but the details are unnecessary here.

Local head losses are all proportional to v^2 . They must be computed with the aid of experimental coefficients, which can be found in most books on fluid mechanics. Local head losses can also be estimated from changes in momentum, which means that any change in velocity (due either to variations in cross-sectional area or to curvature of flow) will contribute to the local head loss. Local head losses in Figure 11 are caused only by convergence of water into the narrow tube and divergence at the end of the tube. During high flow, these may exceed the line loss. No coefficients are available for cave breakdown, but the concept of head loss by itself is sufficient for geological interpretation. When one considers the many constrictions, enlargements, branches, and curves that the water must negotiate in a breakdown pile, it is obvious that the head loss will be much greater than that shown in Figure 11.

Because all head losses increase with the square of the flow velocity, hydraulic gradients are steepest during floods, especially in constrictions where the cross-sectional area is small. During low flow, a cave stream may be able to pass easily through a breakdown pile. But during floods, when the discharge is at least hundreds of times greater, the water will pond severely on the upstream side of the breakdown pile. This imposes a high pressure on the surrounding bedrock, and a steep hydraulic gradient across the boulder pile and any openings that bypass it. Enlargement of diversion passages around the breakdown is most rapid at these times.

Dissolution rates

When water ponds upstream from a collapse or other passage constriction, considerable pressure can build up (Fig. 11). Aggressive water from the cave is forced into all available openings in the surrounding bedrock, which rapidly forms a network of enlarged fissures. Because of the steep hydraulic gradient, there is a tendency for many of these openings to bypass the constriction.

Consider the system of bypass routes where Q = discharge (cm^3/sec), b = long dimension of the fissure cross section (cm), and L = fissure length (cm). Most such fissures are short, with fairly large initial widths. A fissure in limestone with $Q/bL > 0.001$ cm/sec will enlarge at the maximum possible rate allowed by the water chemistry (Palmer, 1991). All fissures that exceed this value will enlarge at roughly equal rates. For reference, consider a typical fissure where $b = 100$ cm and $L = 10,000$ cm. A discharge (Q) of 1 L/sec is needed for it to reach the maximum enlargement rate. This may not be achieved during low flow, but during periodic floods a large number of fissures could sustain this amount of discharge. The result is a maze of interconnecting passages in which all fissures enlarge at roughly uniform rates of about 0.001-0.1 cm/yr, depending on the water chemistry. The amount of annual growth also depends on how long the floodwater conditions persist during the year. Even where new passages are not formed, the stream will dissolve the breakdown blocks and allow more to come down from above. For further discussion, see Palmer (1991, 2002).

To achieve high dissolution rates at and around the collapse zone, cave water must arrive while still considerably undersaturated with the local carbonate minerals. Field measurements show that the degrees of calcite and dolomite saturation almost invariably decrease with increasing discharge (see example in Fig. 12). In many cave streams the low-flow water is supersaturated, owing to loss of

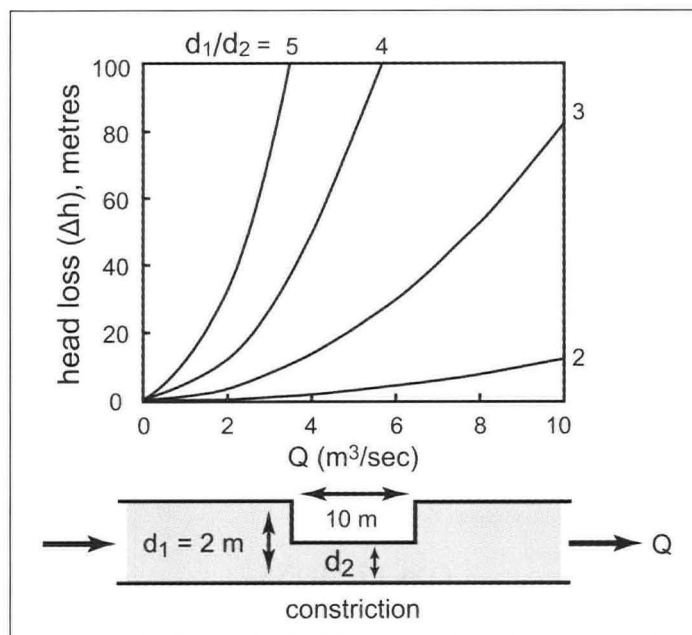


Figure 11. Head loss across a constriction in a cave passage, in relation to discharge and ratio of passage diameters.

carbon dioxide to the surface through cave entrances and smaller openings. Even in these caves, the water becomes aggressive during floods and retains low saturation levels for long distances into the aquifer (Palmer, 2002).

The negative slope of SI vs. stage in Figure 12 is typical of cave streams. From this relationship it is possible to show that the dissolution rate varies with at least the second power of the flow velocity. However, this single field example does not apply everywhere. Nevertheless, the impact of periodic flooding on dissolution rate is clear.

Erosion rates

The erosive force (F) on an object exposed to a turbulent stream = $C_d \rho v^2 A/2$, where ρ = water density, v = water velocity, A = cross-sectional area of the object perpendicular to the flow, and C_d = drag coefficient (experimental). For a typical rectangular breakdown block with a flat side facing into the flow, $C_d \sim 1.2$. The dependence of F on v^2 is similar to that of head loss in turbulent flow.

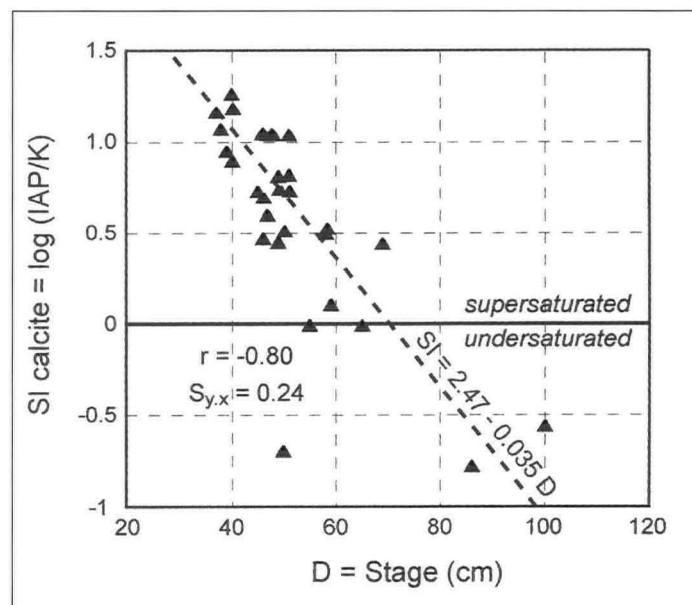


Figure 12. Saturation index (SI) vs. flow stage in a sinking stream entering Mystery Cave, Minnesota, USA (calculated from data by S R Grow). Aggressiveness toward calcite (negative SI) is greatest during the highest flow. IAP = ion activity product, $(\text{Ca}^{2+})(\text{CO}_3^{2-})$, and K = equilibrium constant (solubility product) for calcite.

As shown by small scallop lengths, flow velocities of several metres per second are common in cave passages during floods (see Curl, 1974). A scallop length of one centimetre (a typical minimum in most passages) indicates a flow velocity of roughly 3.5 m/sec. The effective weight of a limestone block immersed in water is about 62% of its weight in air. The drag force exerted by water moving at 3.5 m/sec (about 1200 newtons) would equal the effective weight of an immersed cube of limestone of about 45 cm on each side. It is likely that this force could move the block even uphill (depending on its position relative to other blocks). Figure 13 shows blocks of sandstone more than a cubic metre in volume that have been lifted up steep slopes by floodwaters.

During low flow the drag force is a tiny fraction of what it is during floods, and little erosion can take place. The resistance of a block to erosion is also greater if it is not totally immersed in water, or if it is weighed down by other blocks. Thus, in a breakdown pile, mechanical removal of the debris in a collapse pile takes place mainly during the greatest floods.

CONCLUSIONS

A tiangkeng evolves in several stages: (1) underground diversion of a large surface river to form a cave; (2) localized collapse of the main stream passage; (3) increasing hydraulic gradients and flow velocities through the collapse material; (4) accelerated dissolution

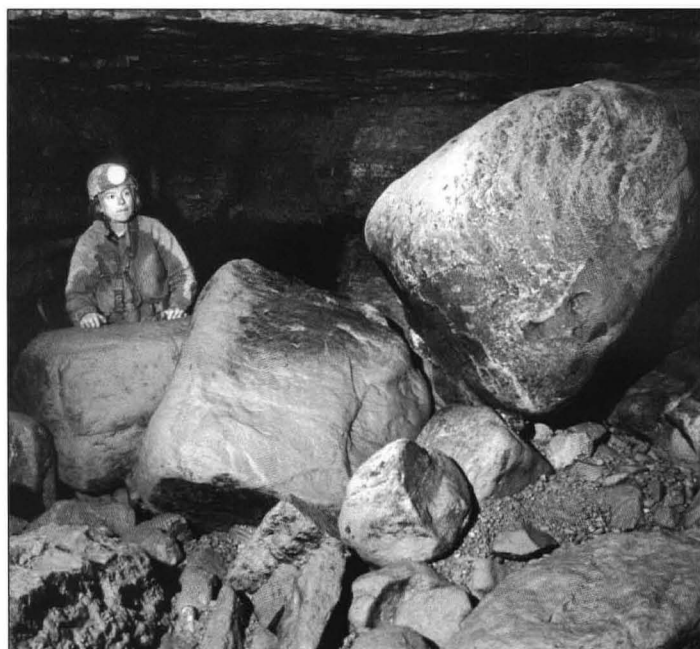


Figure 13. Sandstone boulders carried uphill by floodwaters in Lockridge Aqua Cave, Virginia, USA.

and erosion of the collapse material, especially during floods; (5) development of floodwater bypass routes; and (6) additional collapse, not only where breakdown blocks have been removed by dissolution, but also into the growing network of diversion passages. Stage 6 leads back to stage 3 in a continuing loop.

Even where the cave at the base of a tiangkeng shows no evidence for multiple branches, it is likely that most of the area directly beneath the depression has been affected by development of diversion channels and collapse into them. These processes probably account for the large floor areas of tiangkengs.

The origin of diversion passages is aided by the opening of fractures, both old and new, as the result of stress release during collapse. New fractures can form that have trends different from those elsewhere in the region.

When a cave stream is obstructed by collapse, the hydraulic head at the upstream end rises with the square of the flow velocity. The erosive force increases in the same way. Dissolution rates in cave streams also vary strongly with velocity. All of these processes are therefore highly sensitive to discharge. The large volume of a tiangkeng therefore depends strongly on the accelerated dissolution and erosion during floods.

Acknowledgements

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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 second 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 m³.

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).



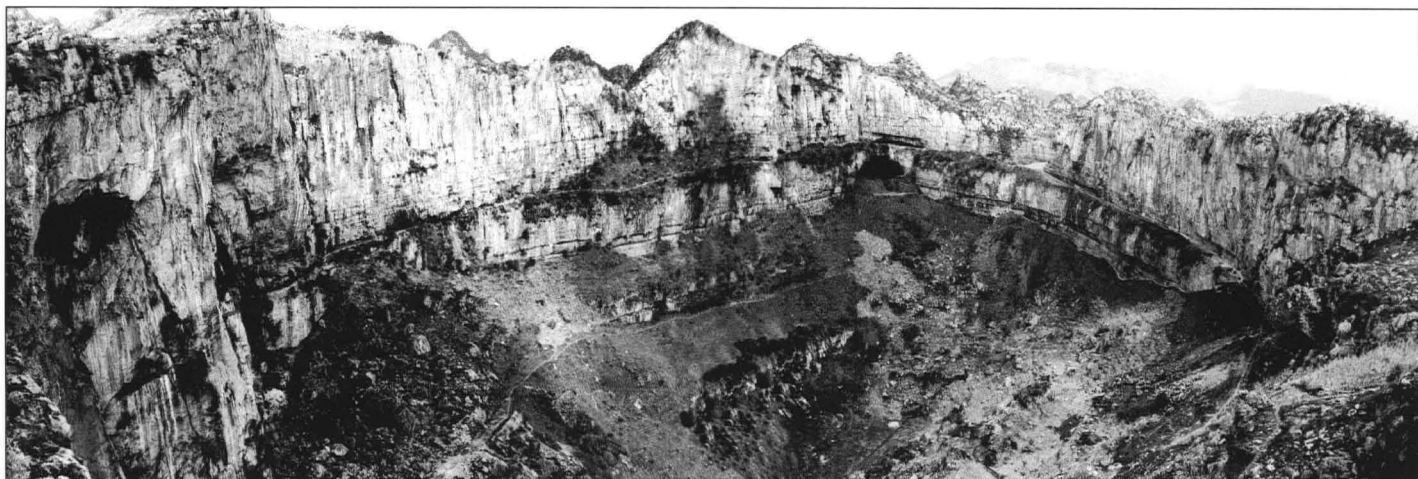


Figure 2. Looking east along the length of the Xiaoyanwan tiankeng; on the lower slopes, note the bedrock ribs on the north side (left) contrasting with the debris ramp on the south side (right) (Photo: Zue Xuewen).

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.

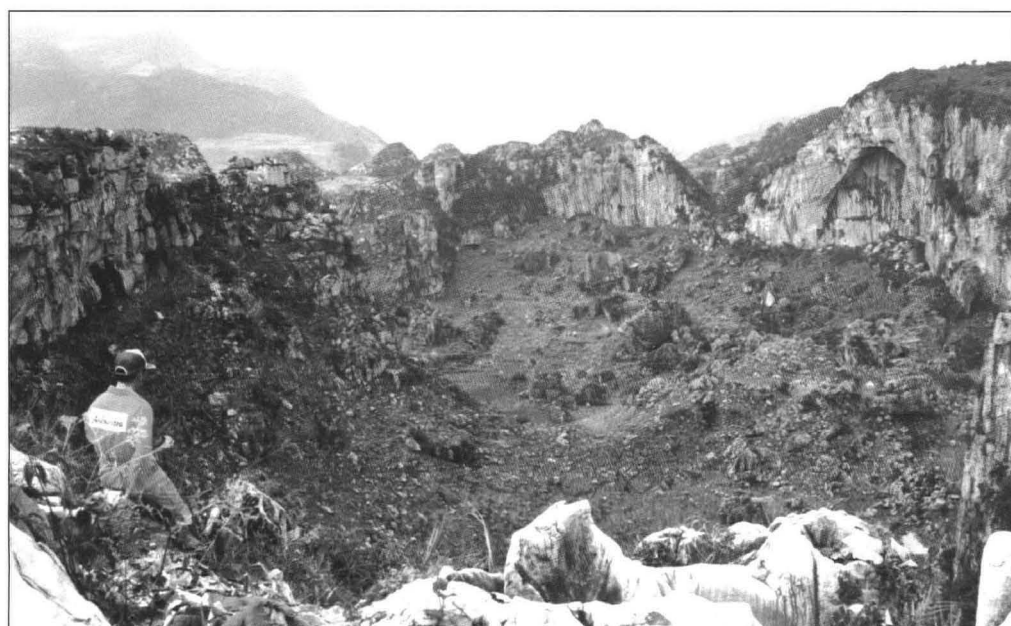


Figure 4. The degraded tiankeng of Dayanwan, seen from its eastern rim, with the edge of its deep internal doline visible in the foreground (Photo: Zhu Xuewen).

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.

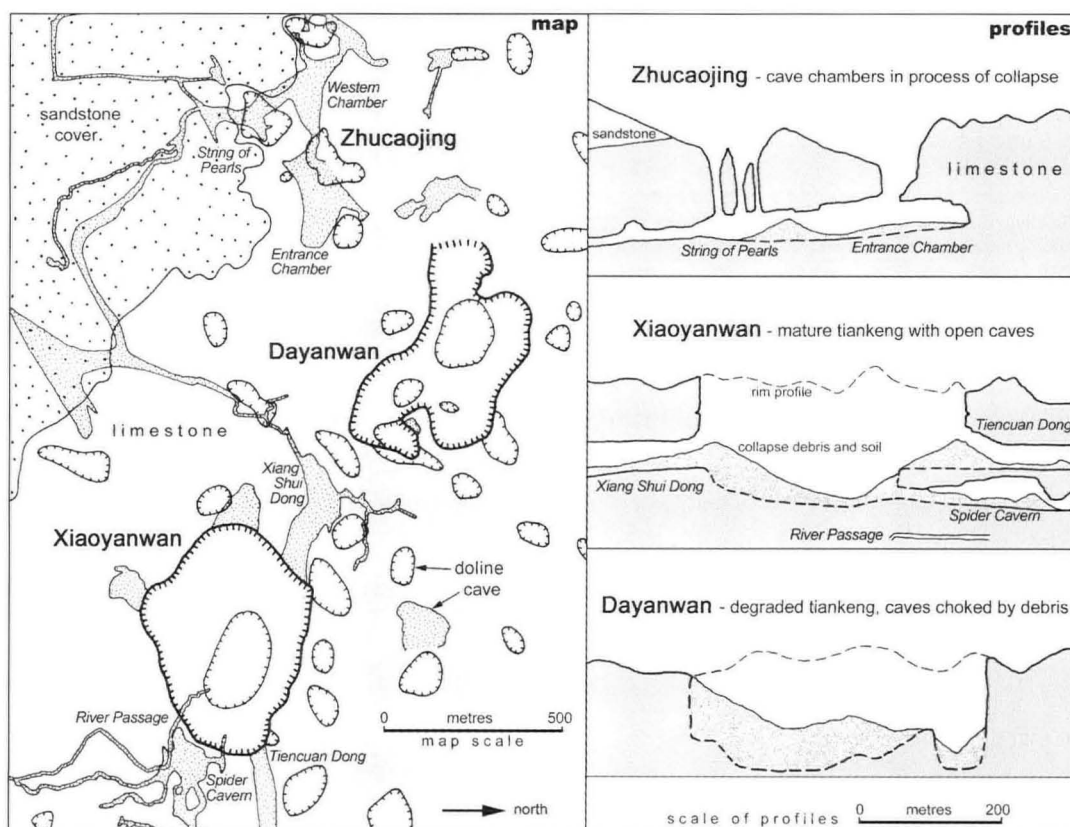
EVOLUTION OF THE TIANKENGs

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 Zhujaoling 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.

Acknowledgements

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Size scales for closed depression landforms: the place of tiankengs

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Abstract: Development of large collapse structures in karstic terrain requires an interaction between mechanical instability and chemical removal of collapsed rock. Upward migration of pre-existing voids can choke out if there is no mechanism for the efficient removal of fallen blocks. Rates of dissolution, size of initial cavity, and overlying bedrock characteristics determine the size of the final surface landform. Collapse features range in scale from small sinkholes to hundreds of meters in such features as the Golondrinas collapse pit in Mexico. Tiankengs are interpreted as end members on a continuous scale.

Keywords: collapse, doline, tiankeng

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Tiankengs, or giant dolines, are closed depressions formed mainly by mechanical collapse of limestone beds coupled with dissolutional removal of collapsed blocks. Collapse plays an important role in most karst processes but is generally considered to be secondary to dissolutional processes. The objective in the present paper is to compare collapse and dissolutional processes and the way in which the resulting landforms scale with size. Ultimately, it is shown how tiankeng fit into the family of closed depression landforms. The problem is approached by taking a very broad look at closed depression features of all types and gradually focusing in on the specific features of interest.

CLOSED DEPRESSION LANDFORMS

Scaling Parameters

To describe closed depression landforms, the only basic measurement needed is a length scale. The physical dimensions of closed depressions, depth and width, are the most commonly used. The width scale length varies over about four orders of magnitude. The smallest depressions that can be recognized as distinct karst features have dimensions of about one metre. The largest are the Dinaric poljes with dimensions of tens of kilometres. The range of the depth scale is about three orders of magnitude. There are recognizable depressions with depths of less than one metre. The maximum depths are less than 1000 m (excluding entire cave systems, where the accumulated depth may exceed 2000 m).

The area of closed depressions has been used as a scaling parameter. Various definitions of area have been proposed. Area can be defined as the area lying within the highest closed contour on a map of the depression feature. As recharge inputs to karst aquifers, the entire catchment draining into the closed depression is a useful concept (White and White, 1979). Drainage divides can be mapped between closely spaced depressions in polygonal karst (Williams, 1972). Volume would also be useful, but volume is less easily extracted from maps and other data sources. In the present discussion, only length measurements are considered.

To further differentiate between categories of landforms, it is helpful to define various dimensionless aspect ratios. Most closed depressions have length/width ratios on the order of unity although some are elongate. Very high values would describe solutionally widened fractures of various sorts. These are not considered in this discussion. The depth/width ratio is the most useful. Depressions with depth/width ratios in the range of unity or less are usually classified as dolines (or the roughly equivalent term *sinkhole*, that is widely used in the United States, especially in the hydrogeological and engineering literature). Features with depth/width ratios much greater than unity are considered to be pits or shafts.

For the present discussion, a third aspect ratio is needed, the ratio of the diameter at the top of the depression to the diameter at the bottom of the depression (Fig. 1). The usual dolines are bowl-shaped – wide at the top and narrow at the bottom. Many pits and shafts maintain a more or less uniform width from top to bottom. However, depressions formed by collapse of underlying cave chambers tend to bell out with depth so that the bottom is wider than the top. There is also a reversal of curvature. Dolines tend to be concave upward; collapse chamber structures tend to be concave downward.

Processes

Closed depressions result from the operation of some combination of three processes: dissolution of the bedrock, collapse of underlying cavities, and the piping or suffosion of unconsolidated soils. The latter is the most important process from the viewpoint of land use hazards. When the engineering literature or the popular press speaks of sinkholes, they are usually referring to soil piping and suffosional features. For present discussion, we are concerned only with the dissolution and mechanical collapse processes.

The processes at work in the development of large closed depressions are:

- Dissolution by vertically-moving water
- Mechanical stoping.
- Dissolution by horizontally moving water.
- Horizontal mechanical transport, mainly by flood waters.

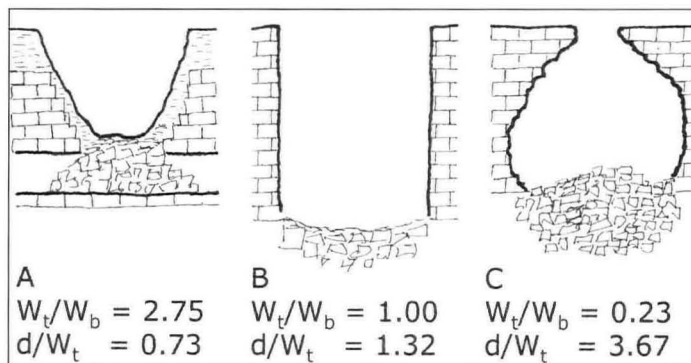


Figure 1. Sketch showing top width/bottom width aspect ratios, W_t/W_b , and depth/width ratios, d/W_t , for closed depression features resulting primarily from collapse. (A) Collapse doline; weathering and slumping of walls and later soil mantling produces a bowl-shaped profile often indistinguishable from a solution doline. (B) Vertical walled doline or stoping shaft: stable wall rock and vertical fractures preserve the vertical profile. (C) Breakout dome that has intersected the land surface: internal profile reflects the original stress arch.

Chemically undersaturated water moving vertically along fractures, and especially along fracture intersections, can enlarge them into a variety of chimneys, pits and shafts. Where the active agent is a fast-moving film of water clinging to the walls, the result is a shaft with near-vertical walls, including the vertical shafts of eastern United States (Pohl, 1955; Brucker et al., 1972). Large volumes of rapidly moving water introduce splashing and mechanical erosion to produce the more rugged and irregular vertical features such as, for example, the deep shafts of alpine caves in Europe or those found in the high plateaus of Mexico.

Mechanical stoping is the result of mechanical failure of the ceiling of pre-existing cavities. The intrinsic mechanical strength of overlying beds and the existence of fractures are the main parameters. Because stoping depends on mechanical properties of the rock and not chemical properties, a stoping shaft initiated in a cavity in soluble rock can extend upward into non-soluble rocks. An example is Dante's Descent in the Coconino Plateau, Arizona, USA, where an initial cavity of the Mississippian Redwall Limestone has migrated upward through layers of sandstone and lava flows to produce a shaft 100 m deep and open at the surface (Fig. 2). Another example is the Big Hole, near Braidwood, NSW, Australia (Jennings, 1966) where stoping was through layers of sandstone.

Vertical mass movement, whether in solution or by stoping, is not sufficient for the development of closed depression features. There must also be lateral transport to carry the removed material away – ultimately to deposit it in a surface stream. For the dissolved load, transport is by flow in conduits draining toward springs. Mechanically stoped blocks that fall into an active stream are eventually dissolved and carried away in solution. However, insoluble materials can also be carried horizontally if there is sufficient stream power in the horizontally moving water. Flood flow is especially important.

If there is an initial cavity of volume V_c , falling blocks due to stoping will fill the cavity and the void will migrate upward (Fig. 3). However, the bulk density of the accumulating rubble pile will be less than that of the original solid bedrock, so the void space will become smaller as it migrates upward. If there is no removal of the rubble at the base, simple mass balance arguments show that the volume of the shaft, V_s , is

$$V_s = \frac{1-\theta}{\theta} V_c$$

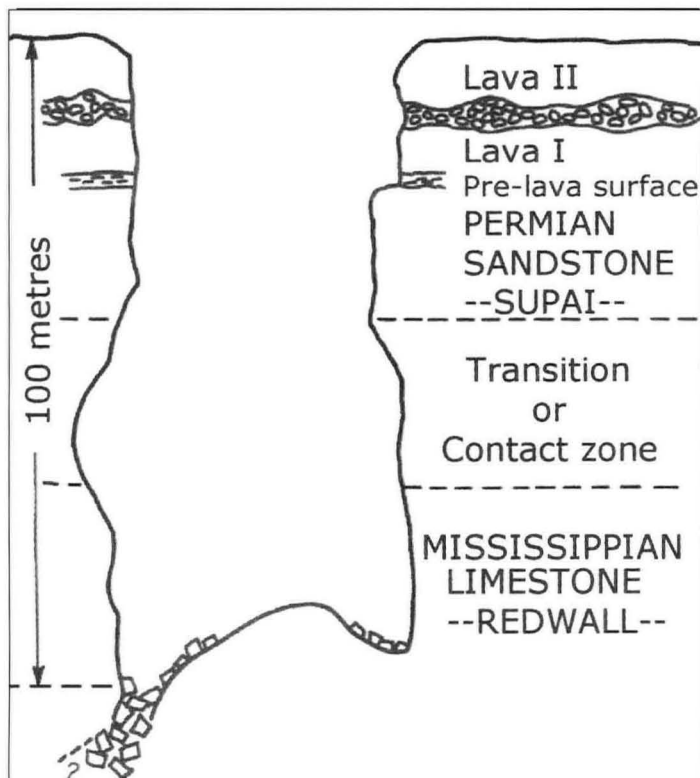


Figure 2. Dante's Descent, a shaft stoped through non-carbonate beds.

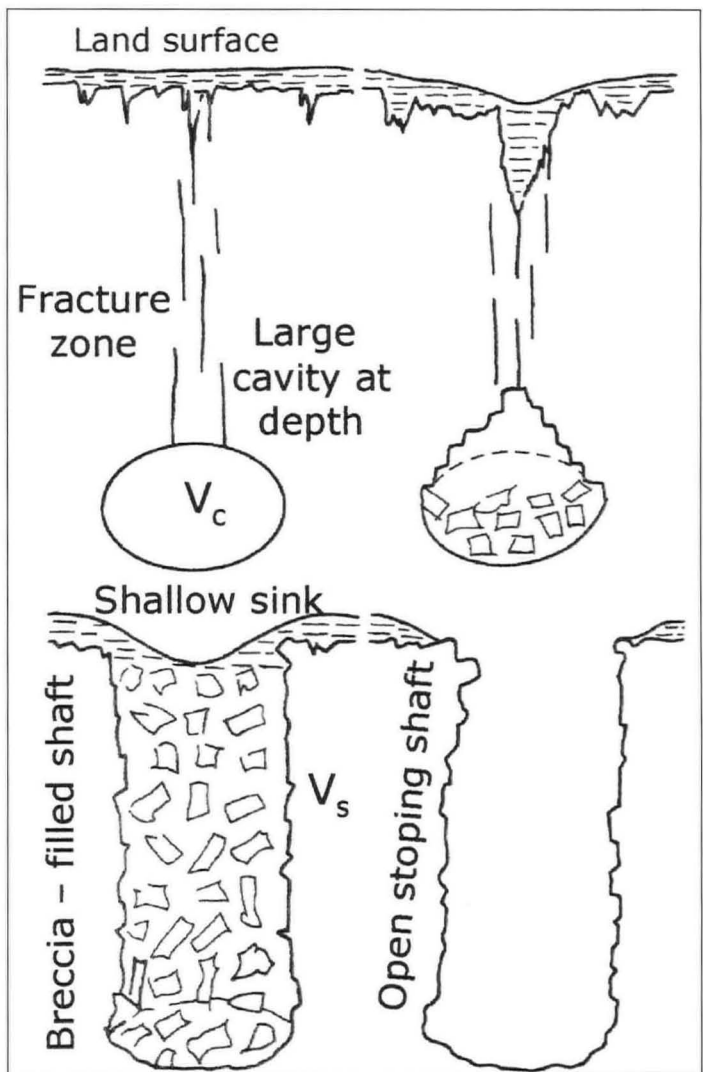


Figure 3. Sketch showing the development of a stoping shaft with and without removal of accumulated rubble.

Here θ is the bulk porosity of the rubble pile. Depending on the volume of the original cavity and its depth below the surface, there may be a residual shaft that reaches the surface, or the incipient shaft may choke and fill before it reaches the surface. This process is identical to that of mine subsidence which produces anthropogenic sinkholes entirely in clastic rocks. If there is continuous and effective horizontal transport, there is no limit to how far the stoping shaft can migrate.

Dissolution and collapse are not mutually exclusive processes. Most closed depression features are the result of both. It is possible to separate features based on the dominance of one process over the other (Fig. 4).

Geological constraints

Processes that produce closed depression features by either chemical dissolution or by mechanical stoping must operate within constraints imposed by the geologic setting. Included among these constraints are:

- Thickness of carbonate rocks
- Depth to water table, commonly defined by regional base levels
- Large scale structure – folds and faults
- The fracture system
- Lithological characteristics of the carbonate rocks

The thickness of carbonate rock is a self-evident constraint on dissolution processes. Solution dolines and solution shafts will have their depths limited by the available thickness of soluble rock. Soluble rock thickness is less constraining on collapse dolines and stoping shafts which may migrate upward through non-carbonate rock.

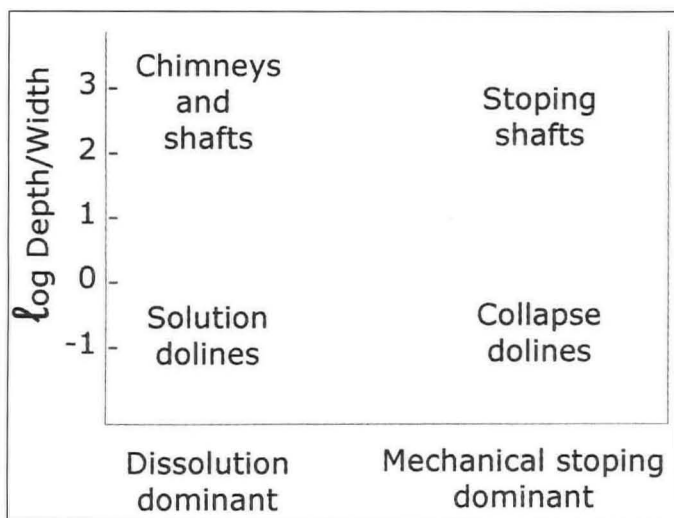


Figure 4. Categories of closed depression features based on process. Only the depth/width aspect ratio is used but a size scale, perpendicular to the axes, would be needed to complete the figure.

Closed depression features are usually considered to be primarily phenomena of the vadose zone. With this constraint, deep air-filled depressions are only possible in regions with deep water tables, exactly the conditions at the sites of the Chinese tiankengs. The horizontal transport system at the base of large collapse structures may be a free surface stream, but it could also be a conduit in the phreatic zone. There exist water-filled closed depression features such as the cenotes of the Yucatan Peninsula in eastern Mexico, which may have originated as vadose zone features, before being flooded by post-Pleistocene sea level rise. An exceptional feature is Zacatón in Tamaulipas, Mexico (Gary, 2002). This is a shaft, 350 m deep and around 100 m across, comparable in size to the tiankeng, but entirely water-filled.

Large scale structures, mainly folds and faults, create the setting in which karst development can take place. Very deep shafts can develop in relatively thin limestones if the limestone beds happen to be nearly vertical. For the interpretation of specific features, the local fracture system and the details of bed thickness and bed lithology are the most important geological parameters.

The entries on the list of geological constraints are, in effect, independent variables. To produce extremely large and optimally developed features of any category, all of the variables must be optimized. The tiankengs, as giant collapse structures, have developed under near optimum conditions. Limit some of these conditions, especially thickness of carbonate rock and depth to base level, and there appear features with most of the characteristics of the tiankeng, but on a very small scale. The feature shown in Figure 5 is a common collapse doline, also known as a karst window. Vertical fracturing has produced the vertical walls. There is a competent underground stream to dissolve away the collapse blocks, but the feature is on a scale of 10 m instead of hundreds of metres.

MECHANICAL INSTABILITY AND STOPPING

The breakdown process

The term *breakdown* is often used for both a material and a process. Breakdown, the material, consists of piles of rock fragments found in caves and at the base of closed depressions resulting from the mechanical failure of the roof. Breakdown, the process, is the assortment of mechanical, geologic, and hydrologic processes that can lead to roof failure. The mechanical analysis of roof stability is generally based on brittle fracture of fixed or cantilever beams (White and White, 1969; 2000). Account can also be taken of inelastic creep caused by microfracturing within the beds (Tharp, 1994). For the most part, a cave ceiling is either stable or isn't. Any beds with a thickness less than the critical value for a particular passage width will fall soon after the cave is drained. The ongoing breakdown process requires some mechanism by which a stable ceiling becomes unstable. Such mechanisms include dissolutional widening of ceiling fractures so that fixed beams are converted into

cantilever beams, dissolutional removal of previously existing breakdown that may be propping up the ceiling, and any further widening of the passage. Further details of the geologic mechanisms triggering breakdown are given by Waltham (2002) and Osborne (2002).

Role of fractures and bed thickness

Roof collapse in thin-bedded limestones tends to be bed-by-bed. A stress arch develops over the cavity. If bed thicknesses are less than the critical thickness required by the width of the cavity, beds will fracture and collapse. If the overlying limestone strata are sufficiently thick, the beds will fail with each succeeding bed extending farther inward than the bed immediately below it. By this means, the collapse migrates upward until the process terminates at the stress arch. The end result is a dome-shaped chamber. If, however, the stress arch intersects the land surface, the breakdown dome will break through at the surface, producing an open pit which bells out the bottom (Fig. 1c). Breakdown chambers or breakout domes vary in size from a few metres to several hundred metres and are common in many caves.

There are two competing processes here, and the time relations between them are not always clear. The breakout dome is migrating upward by continuous spalling of the beds, while at the same time the overlying land surface is lowering by erosion and denudation. Although the evidence is not conclusive, it appears that most of the existing breakout domes reach a stable configuration quickly and early in the cave's history. It is the lowering of the land surface that much later intersects the stress arch and thus triggers the final collapse that results in an open pit. Two examples from America are shown in Figure 6. Another would be the large chamber of Maoqi Dong, in the Leye karst, with its skylight hole on the ridge above.

Regions with thickly bedded or poorly bedded limestones respond differently to stresses caused by the development of large cave passages. Massive limestones tend to be more stable and will



Figure 5. Smulton Sink, Centre County, Pennsylvania, USA, a typical collapse doline.

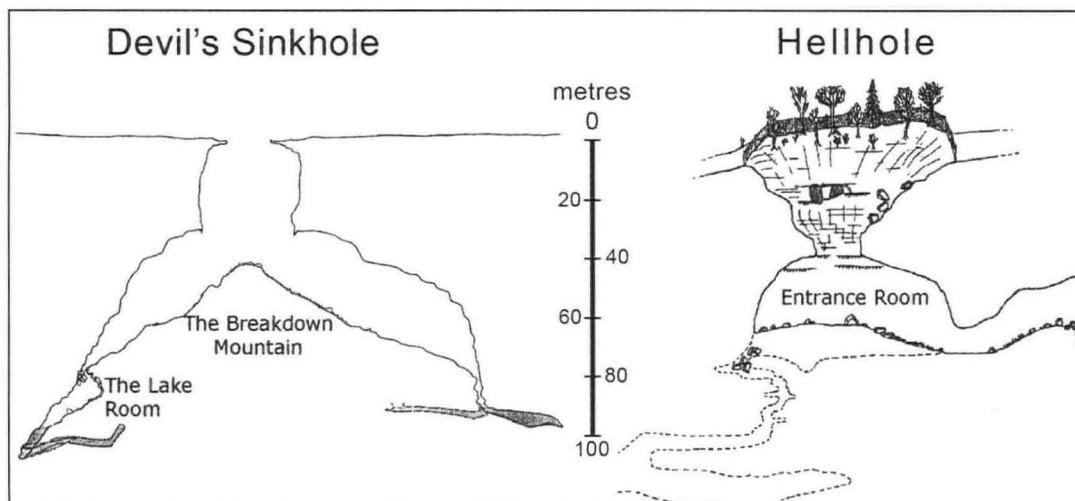


Figure 6. Profile maps of breakout domes that have intersected the land surface: Devil's Sinkhole, Texas, USA (from Elliott and Veni, 1994), and Hellhole Cave, West Virginia, USA (from Dasher, 2001).

support much larger cave passages. Breakdown, when it occurs, is more likely to be triggered by large vertical fractures rather than by separation along bedding plane partings. It is apparent that vertical fractures are a dominant controlling factor in the tiankeng. Figure 7 shows large vertical fractures in the wall of the Xiaozhai Tiankeng. Near-planar fracture surfaces can be seen in the walls of most tiankengs. It seems clear that tectonic processes that fracture the massive limestone beds are a major factor responsible for the occurrence of many tiankengs in southern China. Further evidence is provided by the karst towers, many of which also show extensive vertical fracturing (Fig. 8).

Pre-existing cavities vs continuous lateral transport

Cave roof collapse is a dominant process in the final dying stages of a cave's life cycle. As the land surface lowers, the epikarst punctures cave roofs, weakening beds, and initiating collapse. However, the truncation and decay phase of the cave life cycle can be stretched over hundreds of thousands of years. On a human time scale, cave roof collapses are rare although there are many cave passages that end in terminal breakdowns. Deep seated collapse in the absence of fracture control is even more rare. It seems unlikely that collapse alone could be responsible for large closed depression structures. Lateral transport is necessary.

SOME LARGE COLLAPSE STRUCTURES

A question to be addressed is whether the Chinese tiankengs are unique karst features, in the sense that the conditions that formed them did not occur elsewhere in the world, or whether there are

similar features elsewhere. If identical features do not exist, perhaps there are features that share a common theme with the tiankeng. Some possibilities are presented.

Icy Cove

The largest solution/collapse structure in the Appalachian Mountains of eastern United States is Icy Cove, in the Cumberland Plateau of Tennessee. The Cumberland Plateau is capped with a massive conglomeratic sandstone of Pennsylvanian age. Underlying this, and cropping out on the valley walls, is a sequence of Mississippian limestones, with a total thickness of about 160 m. Icy Cove was initiated by deep dissolution in the limestone which then stoped upward, undermining the clastic rocks above. Collapse of the clastic beds produced a closed depression 150 m deep with a rim-to-rim diameter of 1-2 km (Fig. 9). The depression is rimmed with sandstone cliffs with steep lower slopes and a relatively flat floor.

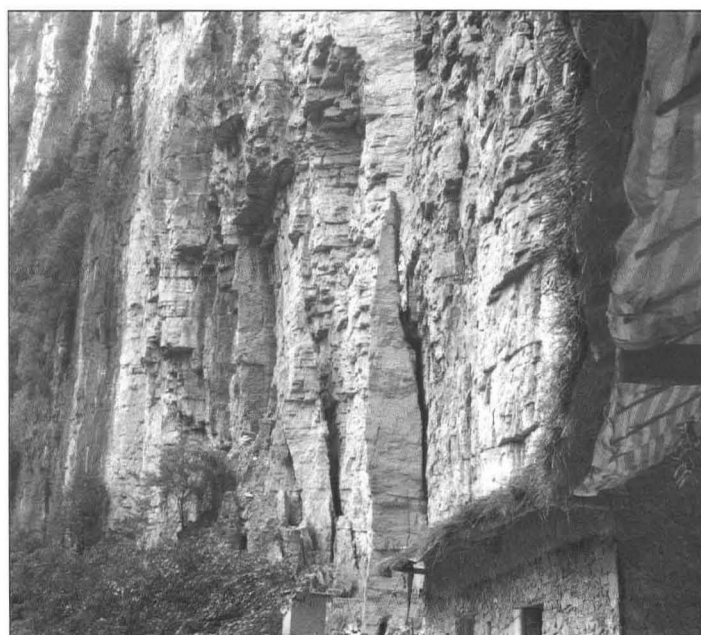


Figure 7. Vertical fractures on the wall of Xiaozhai Tiankeng, Chongqing.

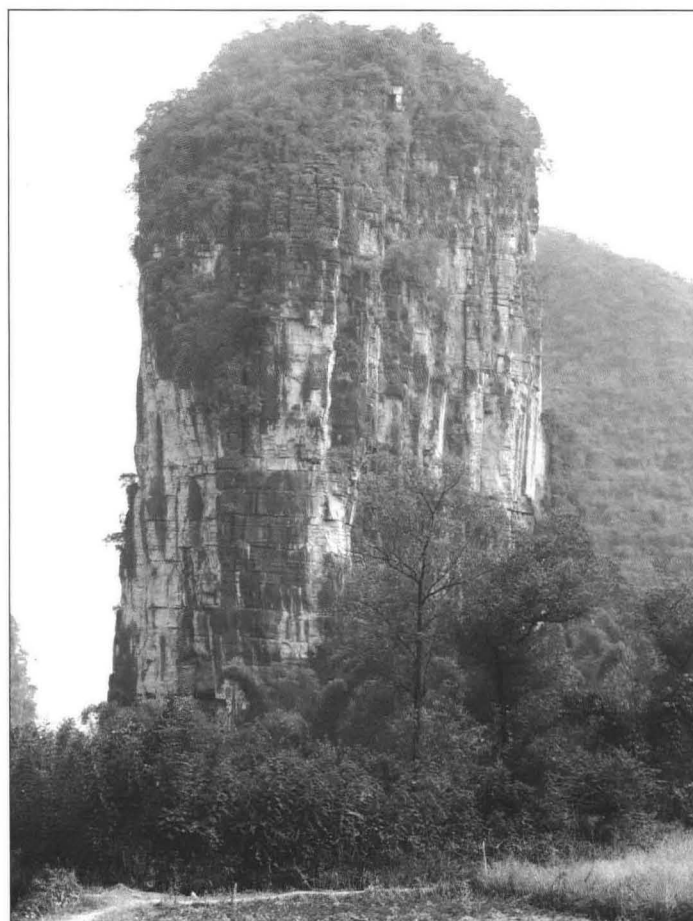


Figure 8. Well-developed vertical fractures on a karst tower near Yangshuo.

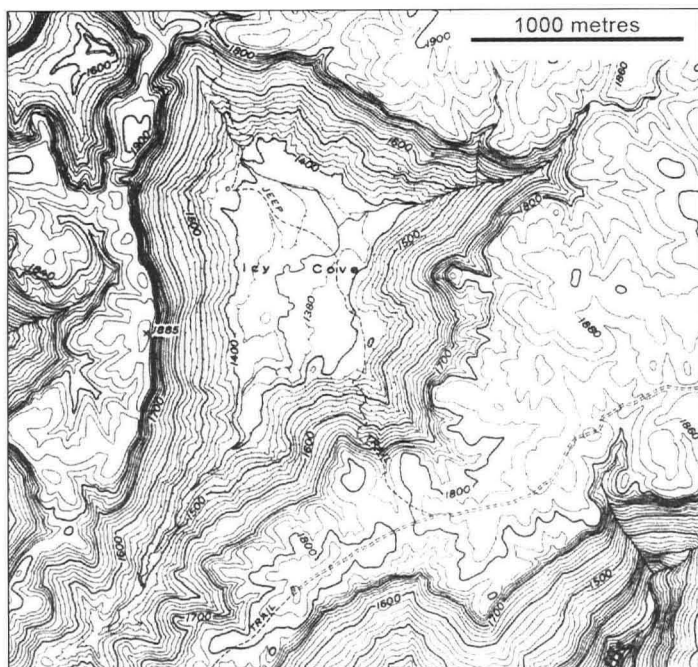


Figure 9. Icy Cove, Cumberland Plateau, Tennessee, USA; contour interval is 20 feet (6 m) (map extracted from U.S. Geological Survey).

Tres Pueblos Sinkhole

The Rio Camuy rises on volcanic rocks in central Puerto Rico, flows northward, and then sinks at the contact with the Tertiary Lares Limestone. Underground, the river flows through the large gallery of the Rio Camuy Cave System (Gurnee and Gurnee, 1974). About half way between sink and resurgence is the Tres Pueblos Sinkhole, a collapse doline, 140 m in diameter and 120 m deep (Fig. 10). The river skirts the bottom of the doline. The Tres Pueblos doline would fit the classification of a normal tiankeng (Zhu & Chen, this volume). It is a collapse depression with near-vertical walls and with an active underground river to carry away fallen blocks.

The Sótanos of Mexico

Zhu and Chen (this volume) note the sótanos of Mexico as possible tiankeng. Sótano means *cellar* or *basement* in Spanish but is also used as a general term for a pit by the local residents in the mountainous part of Mexico. There are three sótanos that have the 300 m depth comparable to a large tiankeng: Sótano de las Golondrinas, Hoya de las Guaguas, and one simply called El Sótano. There are many other pits on a smaller scale.

Figure 10. The Tres Pueblos Sink, Rio Camuy Cave System, Puerto Rico (map from Gurnee, 1964; image from Monroe, 1976).

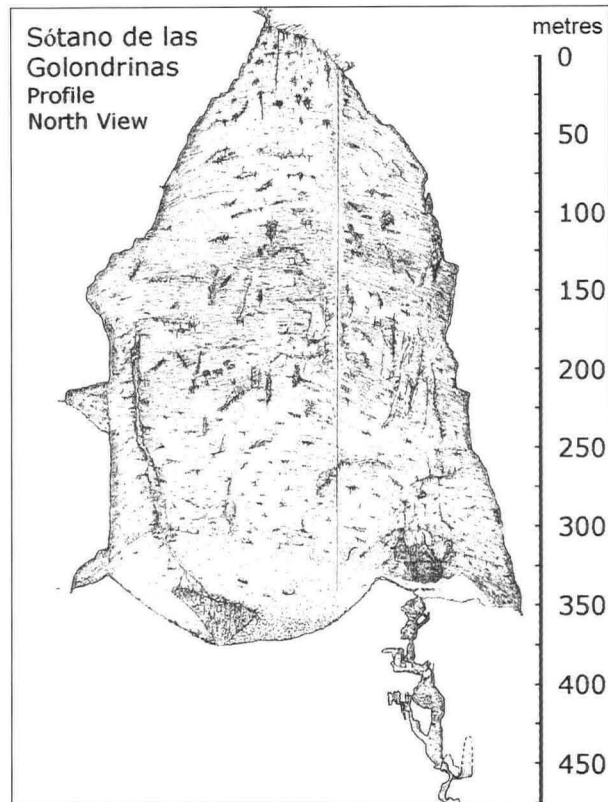
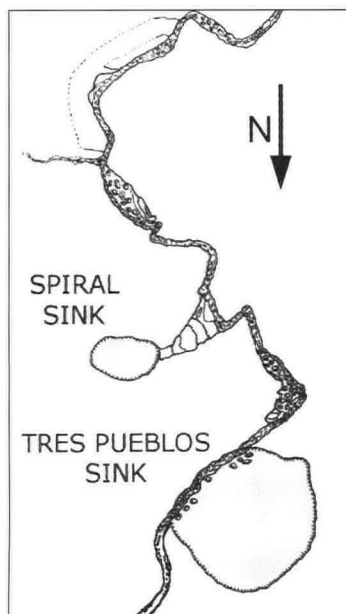


Figure 11. Perspective profile of Sótano de las Golondrinas, San Luis Potosi, Mexico (from Sprouse and Fant, 2002).

Sótano de las Golondrinas is the best known of the big Mexican pits (Raines, 1968; Sprouse and Fant, 2002). The entrance is on a hillside so the depth of the pit varies from 332 to 376 meters depending on the location of measurement. The pit is somewhat bottle-shaped (Fig. 11) with top dimensions of 49 x 62 m but with floor dimensions of 305 x 440 m. A narrow shaft near one wall can be descended for an additional 100 m, implying that the rubble pile occupying the floor is at least that thick.

Hoya de las Guaguas is an elongate pit developed along a major fracture (Fig. 12). It is in two sections. The open upper section is about 200 m deep, but then there is an offset, and the pit continues to a depth of 430 m. The pit walls bell out where they have expanded by serial breakdown through parallel fractures, but they are vertical at the ends of the main fracture. Hoya de las Guaguas may be an example of a major collapse structure in the making. If the off-set lower chamber were to stope its way to the surface, the result would be a large, deep, open pit with dimensions comparable to El Sótano.



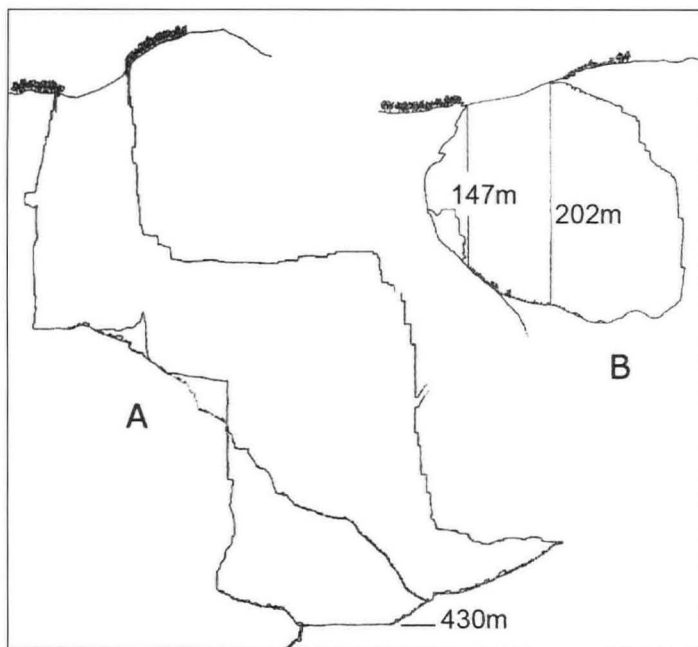


Figure 12. Profiles of Hoya de las Guaguas, San Luis Potosi, Mexico. (A) is along the fracture direction. (B) is perpendicular to the fracture and shows only the upper half of the pit (adapted from Ralph, 1979).

El Sótano is a simple closed depression feature 440 m deep. It too is developed along a fault or major fracture so that the pit is elongate with the dominant fracture appearing on the map (Fig. 13). The walls are nearly vertical with a more gently sloping floor. Of all the Mexican pits, El Sótano may be closest to resembling the Chinese tiankeng.

There are many pits of various shapes and depths described in the literature on Mexico caves. What cannot be determined from published maps is the relative contribution of vertical dissolution and collapse. Data for five more of the largest pits have been added to data for the three above in Table 1. This entire set of eight closed depression features appear to be primarily collapse structures, whereas many of the other pits recorded in Mexico are primarily dissolution features. A common aspect of the chosen set of closed depressions is that none of them gives access to underground streams. However, by inference, the streams should either be somewhere deep below the bottom of the shaft, or at least have been there in the past, because otherwise it is difficult to account for the volume of material removed. In this sense the Mexican pits are

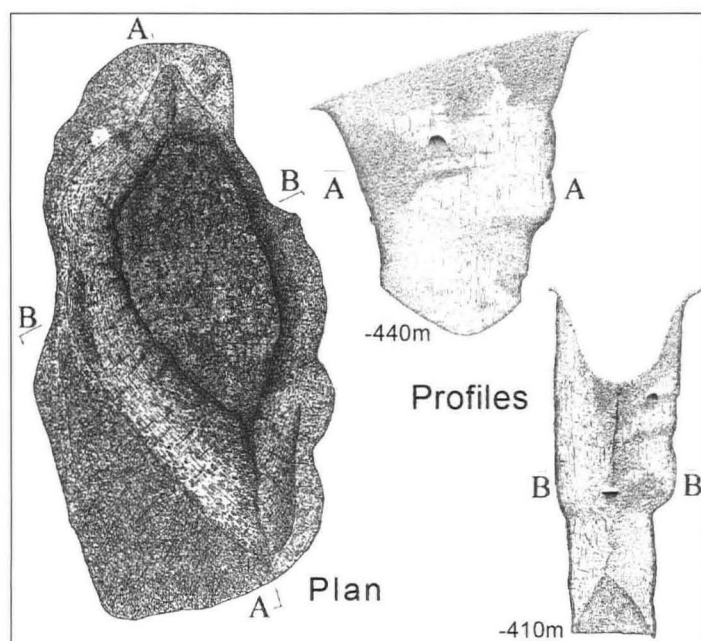


Figure 13. Map and profiles of El Sótano, Mexico (from Bittinger, 1979).

name	depth (m)	depth/width ¹	top/bottom ²
Sótano de las Golondrinas	350	5.83	0.20
Hoya de las Guaguas ³	202	2.53	0.35
	430	5.38	0.23
El Sótano	440	1.44	1.39
Sótano de las Guacamayos	140	1.12	0.84
Sótano de la Porra	110	5.00	0.58
Sótano de la Huasteca	130	3.71	0.35
Sótano de la Linja	80	2.35	0.29
Sótano de las Quilas	110	1.07	0.88

Notes

¹ Ratio of depth of pit to its maximum width at the top

² Ratio of maximum width at the top to maximum width at the bottom

³ First row refers to the upper pit; second row to total drop of the pit

Table 1. Depth and aspect ratios for some large Mexican pits.

immature, because the removal of the collapse rubble is incomplete. Likewise, each pit tends to be formed on one major fracture (or fault), with less development of cross fractures. As a result, the pits tend to be elongate along the master fracture. These smaller pits have many of the morphological features of the tiankeng but do not meet the minimum size criteria.

The aspect ratios tabulated in Table 1 illustrate the difficulties in categorizing closed depression features. Dolines are usually taken as bowl-shaped (wider at the top than at the bottom) and relatively shallow (with depths comparable to or less than their widths). In terms of the aspect ratios, d/W_t should be ≤ 1 . Closed depression features with d/W_t much greater than unity would be considered pits or shafts. None of the features in Table 1 has d/W_t less than unity, and many have values ranging up to 5. The W_t/W_b ratio gives a numerical measure of the overall profile of the closed depression (Fig. 1). With one exception, these ratios for the features listed in Table 1 are less than unity, meaning that these closed depressions bell out at the bottom and thus have shapes quite different from the usual dolines which would have W_t/W_b ratios substantially greater than unity.

SCALING LAWS FOR CLOSED DEPRESSIONS

The frequency of occurrence of closed depressions of any given depth falls off exponentially with depth. This has been demonstrated for a series of large populations of closed depressions (Fig. 14). All of the populations shown can be fitted to an equation of the form

$$N = N_0 e^{-Kd}$$

In this equation, N is the number of dolines of any given depth, N_0 is a fitting parameter, and K is a parameter with units of $(\text{metres})^{-1}$ characterizing the distribution. The Appalachian data set contains more than 5000 dolines including dolines in Mississippian limestone, in Ordovician limestone and in Ordovician dolomite. They all fit the same distribution function with the same numerical value of K , showing that the distribution of doline depths is relatively insensitive to carbonate rock lithology. However, different geographic settings, mainly a matter of local relief, produce different values of K . Lauritzen (2005) has introduced a half-depth defined as

$$z_{1/2} = \ln \frac{2}{K}$$

and has developed a diffusion model for the continuing denudation of the karst surface. When he constructs a plot similar to Figure 14, but with depth normalized to the half-depth defined above, all distributions fall on the same straight line. Overall, these results show that closed depressions have a geometrical similarity that extends across both geology and distance scales.

Although the data are much more sparse, closed depression diameters also appears to be distributed on a decaying exponential

(White and White, 1987). The exponential distribution is not followed by all closed depressions. Impact craters, for example, are fractal and are distributed on a power law function rather than an exponential function.

We can now consider closed depression features with d/W_i ratios much greater than one. Again the data set is sparse. Troester et al. (1984) found an exponential distribution for pit depths in Alabama. Minton (2005) has tabulated the depths of the 50 deepest pits in Mexico. These range from 170 to 410 m and include the deep pits that are listed in Table 1. Those for which the pit is an entrance drop are plotted in Figure 15. There is considerable scatter because of the small data set but again the distribution is exponential. These data span the depth ranges of all but the largest of the Chinese tiangkengs.

TIANKENGs AMONG CLOSED DEPRESSIONS

Following the above rather convoluted discussion, an attempt can now be made to place the tiangkeng into the overall scheme of closed depression features. From a geological point of view, tiangkengs are vertical-walled collapse structures, closely associated with extensive vertical fracturing, and with a substantial cave river system required for lateral transport. From a consideration of the size distribution of closed depression features, tiangkengs are not uniquely different from other collapse features, albeit at the extreme end of the size scale.

Leaving aside geology and looking only at geometry, the distinction between dolines and tiangkeng is given by the aspect ratio W_t/W_b which should be in the range of unity. The exact numerical value at the boundary is not defined. Likewise, the aspect ratio d/W_i distinguishes both dolines and tiangkengs from pits and shafts, but the exact numerical value at the boundary is not defined. Finally, there must be a scale factor, of which the depth is a good candidate, that defines the minimum size for a feature to be considered a tiangkeng. By these criteria, only a few of the Mexican closed depressions would be tiangkengs. El Sótano certainly would be, and Sótano de las Guacamayas and Sótano de las Quilas could be. The others tend to bell out at the bottom, with W_t/W_b aspect ratios substantially less than unity. These pits, including Sótano de las Golondrinas would be immature tiangkengs according to the given criteria. However, the bottle shape of Sótano de las Golondrinas is an end member of another group of features, the breakout chambers

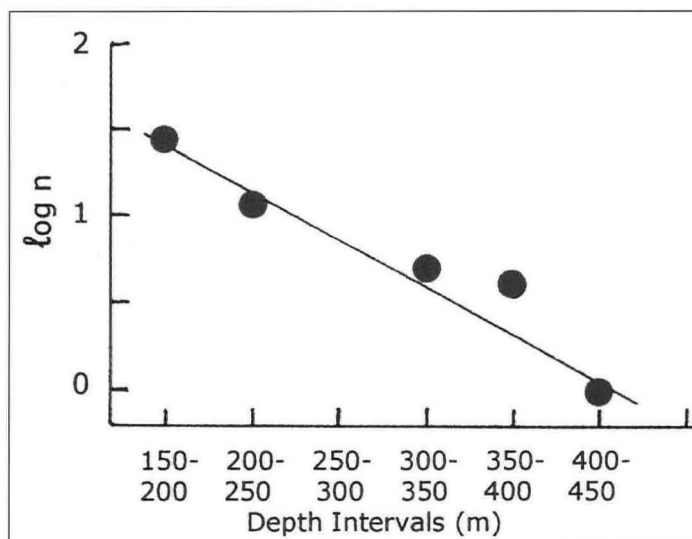


Figure 15. Depth distribution of the deepest entrance pits in Mexico (data from Minton, 2005).

with skylights. There is not, in the karst geomorphological literature, a specific term for this latter shape of pit or closed depression.

Acknowledgements

We are immensely grateful to Professor Zhu Xuewen and his colleagues for arranging an outstanding opportunity to view the tiangkeng landforms first hand. We thank the Chinese local officials for their excellent hospitality. Finally, we extend our appreciation to our colleagues on the investigating team for a very enjoyable excursion.

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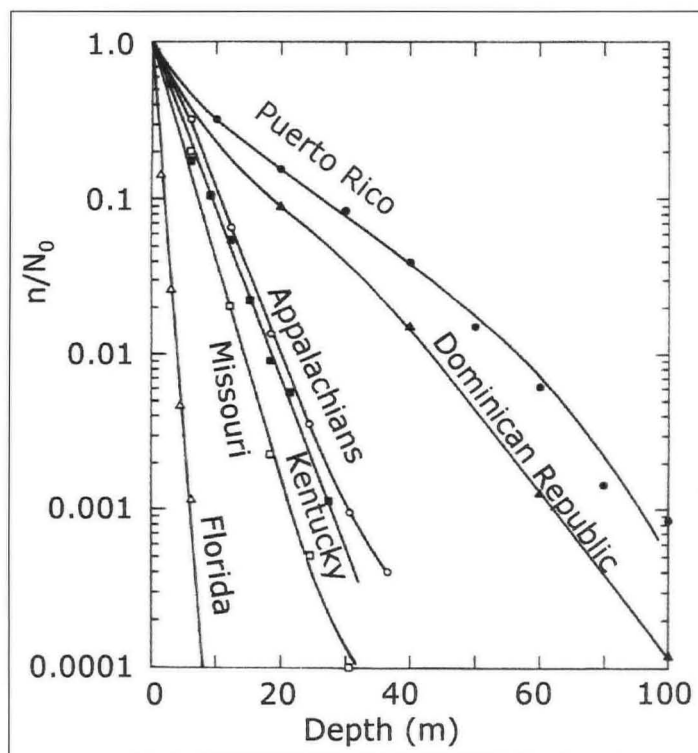


Figure 14. Distribution by depth of various populations of closed depressions (from Troester et al., 1984).

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Forum

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KARSTOLOGIA 2003/41

ABSTRACTS

Travertine deposits of St-Antonin (Bouches-du-Rhône, France): lithostratigraphy, palaeobotany and Holocene palaeoenvironments.

Les travertins de Saint-Antonin: séquence géobotanique et climato-anthropique holocène (Bouches-du-Rhône, France), pp.1–14.

Jean-Louis Guendon, Adam A Ali, Paul Roiron, Jean-Frédéric Terral, André D'Anna, Fernando Diaz Del Olmo and Rafael Baena Escudero

Travertines are carbonate deposits formed generally during temperate climatic periods. The travertine of Saint-Antonin was formed during the Holocene in accordance with this model. They usually present a succession of travertinous units and detrital sedimentary levels containing, respectively, leaf impressions and charcoal; snail shells and archaeological material have also been preserved, essentially in detrital levels. Two kinds of plant remains (leaf imprints and charred wood) have been sampled and analysed, allowing the reconstruction of vegetation dynamics based on a well-defined sedimentary sequence. Our results were compared with those of previous malacological, archaeological studies and climatic changes. The Preboreal and Boreal sequence, characterised by travertine units with detrital deposits, is dominated by a riverside vegetation (*Populus alba*, *Salix* sp., *Phragmites communis*) associated with some pubescent oak growing in the plateau. After this first period, detrital levels and hygrophilous species decrease. Correlatively travertinous facies and leaf impressions of mesophilous forest species increase (*Quercus pubescens*, *Acer monspessulanum*). They suggest the existence of homeostatic conditions, such as regular river flow, dense vegetation and few disturbances during deposition. The Middle Atlantic period shows optimal travertinisation and maintenance of forest environment. But this period is characterised by the beginning of the *Quercus pubescens* regression and the dominance of *Acer monspessulanum*. From the Atlantic to the first part of the Subboreal, important detrital sedimentary levels disturb the deposition of carbonate. They contain reworked archaeological material dating to the Neolithic. Vegetation seems to have been profoundly affected by intensive human exploitation. This process has broken up the forested area into different plant communities and favoured the dominance of heliophilous and thermophilous species (*Pinus halepensis*, *Rubus ulmifolius* and *Juniperus* sp.).

Measurement of torrential flows (Doria, Prealps of Savoy, France) by dilution of a food colouring (E110: yellow orange sunset)

Le jaugeage de débits torrentiels par dilution d'un colorant alimentaire (E110 : jaune orangé sunset). Application à l'exurgence de la Doria (Massif des Bauges, France), pp.15–22.

Bernard Fanget, Hamid Najib and Michel Mietton

The aim of this study is the measurement of torrential flows by dilution of a yellow orange food colouring (E110). Field measurements are realised in the Doria River, a mountain torrent in the Savoy Prealps. A gauge station, installed ten years ago, is

calibrated periodically by mechanical and chemical measurements. Moreover, the comparison of the concomitant mechanical and chemical methods allows the statistical validation of the proposed technique. The main advantages of this method are the lack of toxicity and the colour, comparable to the one of aquatic organic matter, and the low detection limit. This method allows high flow measurement values when using a suitable tank and adjutage.

Retreat rate of a marble side slope (Island Diego de Almagro, Chilean Patagonia).

Vitesse de recul d'un escarpement lapiazé (Ile Diego de Almagro, Patagonie, Chili), pp.23–26.

Mårten Veress, Gábor Toth, Zoltán Zentai and István Czöpek

Our research group measured the dissolution-related slope regression velocity of a marble's side slope on one of the marble stripes on the island of Diego de Almagro. Using the time of ice melting and the width of rim bordering the edge of the sidewall the velocity of regression is 0.4 to 0.5mm per year. This regression velocity exceeds by an order of magnitude the velocity of denudation caused by dissolution on the marble surface. Due to this fact, the marble stripes of the island become narrower to a greater degree than they become shorter.

Morphological observations in the Maramoye pit (Le Beausset, Var).

Observations morphologiques dans l'abîme de Maramoye (Le Beausset, Var), pp.27–38.

Jean-Yves Bigot

Maramoye pit is a two-levels cave around the Beausset Clay, and near to a 6 Ma old lava flow. On one hand, the description of the deposit's cuts, and of galleries features, on the other hand, show a run of events whose relative chronology can be recreated. The siliceous cover, developed by the crypto-corrosion, then the volcanic event and at last, the "red event" showing limestones out of their siliceous toping, stand for the great phase inferred from observations in the cave. The upper level galleries morphology shows a connection between lower and upper levels linked by a "puits-cheminée" (phreatic lift). The corroded speleothems and partly removed fillings point out a flooding of the upper level. It has not been possible to show obviously that one or other levels of Maramoye is formed before the other. In compensation, the observations suggest that the lower level after the basaltic event have been picked up, so that the paleogeographic precising back get complicated.

Morpho-climatic features of Japanese karst areas.

Diversité morpho-climatique et intérêt des karsts japonais, pp.39–48.

Jean-Noël Salomon

The Japanese karsts are practically unknown in Europe because few karstologists from this continent have visited Japan, and the studies completed there have been written in Japanese. Still, Japan has numerous karstifiable terrains of various locations and ages (from the Primary era to the Holocene) that are subject to significant climatic ranges. For this reason many caves exist and many have been sheltered through the ages (archaeological) up until recent times (World War II). Some are sufficiently large and well decorated

to have consequently generated tourist activities, added by mystic and religious aspects. The understanding of karsts has also allowed remarkable management of underground systems for surface irrigation. Finally, due to their recording abilities, karsts developed in uplifted marine terraces offer better prospects for understanding the local tectonic patterns that concern the Japanese. These reasons make the Japanese karsts interesting.

Dye tracing between the lake of Salanfe and thermal springs of Val d'Illeiez (Wallis, Switzerland): tectonics, lithology and geothermics.

Traçage entre le lac de barrage de Salanfe et les sources thermales de Val d'Illeiez (Valais, Suisse) : tectonique, lithologie et géothermie, pp.49–54.

Jean Sesiano

A detailed fieldwork has allowed us to locate a sinkhole where some water from the artificial lake of Salanfe disappears. Two dye tracing experiments have proved the link with hot springs in Val d'Illeiez, 9km to the NW. The temperature increase is due to the depth the water reaches before coming up, following an alpine inverse fault.



KARSTOLOGIA 2003/42

ABSTRACTS

About the genesis of Vaucluse Plateaux (France): the lessons from karstic landforms.

Eléments de réflexion sur la morphogenèse des plateaux de Vaucluse (France) : les apports du karst superficiel.

Christophe Depambour and Jean-Louis Guendon

The study of the principal forms of the surface karst gives a first diagram of evolution of the plates of Vaucluse. Paleo-surfaces now perched and/or deformed are witnesses of old major phases of flattening, in regional matter, undoubtedly of pre-Miocene age. The whole of intermediate surfaces (850m) seems to cut the Miocene deposits (Burdigalian) of the ditch of Aurel-Sault. It thus reveals a major phase of post-Miocene flattening. These surfaces of karstic flattening were to be in relation to the vast poljes of the sectors of Saint-Christol and the ditch of Sault. Their genesis, dependent on dysfunction of the endokarstic drainage, could be related to the Pliocene transgression. Canyon of Nesque, structuring elements major landscape, present, on both sides Rocher du Cire, two distinct parts, having own morphologies. The downstream part, wide open, would have grown hollow by headwater erosion from a karstic steephead perhaps since the end of the Miocene. The narrow upstream part would have incised itself, after capture of the polje of Sault, undoubtedly at the time of the cold phases of the Quaternary one.

Subterranean aquatic fauna of France: database and biogeography.

Faune aquatique souterraine de France: base de données et éléments de biogéographie.

David Ferreira, Marie-José Dole-Olivier, Florian Malard, Louis Deharveng and Janine Gibert.

Many data exist on the aquatic subterranean fauna of France but they are scattered. Thus, large-scale patterns of ground water biodiversity are still poorly documented due mainly to the lack of synthesis. Since 2002, we are currently gathering existing information on the distribution of stygobite species in France. A first inventory is presented in this paper. The present database contains 381 species and subspecies corresponding to more than 5700 records. This diversity indicates that the stygobite fauna of France is among one of the richest ground water faunas in Europe. Our current knowledge of groundwater biodiversity varies markedly among zoological groups and regions. We are currently implementing the present data set in order to provide a distribution pattern as complete as possible of stygobite richness in France. The database will be used for delineating hot spots of biodiversity (specific richness, endemism), for identifying priority areas for conservation and for formulating and testing hypotheses on the origin and drivers of groundwater biodiversity.

Englacial caves observed by speleologists.

Les cavités glaciaires sous le regard spéléologique.

Marian Pulina, Joseph Rehak senior and Jacques Schroeder

Speleological investigation of moulins, intraglacial conduits and subglacial tunnels allows collection of information, which provides better understanding of the behaviour of the glacier in motion. To find these field data it is first necessary to conceive how intra- and subglacial cavities appear and evolve. They consist of four types: 1) those opened by meltwater; 2) properly so-called crevasses; 3) cavities of volcanic origin; 4) cavities in the lee of bedrock bumps. Directly observable data by the cavers must always be supported by time information. They concern: 1) the location of cavities and their zone of drainage; 2) the morphology of accessible entrances; 3) the state and the stress of the ice hosting the cavities; 4) an informed morphometry of the investigated voids; 5) level variations and relative age of the trapped waters, and present solid load, the nature and its disposal if necessary. All these data should be represented on the plans, profiles and cross sections that cavers usually draw, because these documents are easily conveyed and available for consultation by a widened scientific community.

Glaciological and climatological studies in ice-caves of Moncodeno (north Grigna, province of Lecco, Lombardy).

Etude glaciologique et climatologique des cavités glacées du Moncodeno (Grigna septentrionale, province de Lecco, Lombardie.

S Turri, M Citterio, A Bini, V Maggi, R Udistj and B Stenni

The existence of perennial ice and snow deposits in the karst shafts of the Moncodeno area, at altitudes of about 1800 to 2100m a.s.l., has long been known. Even so, no detailed study has been formerly carried out. Three ice and snow cores have been drilled in the glaciated cave environment and chemical, isotopic, crystallographic and textural analyses were carried out on them. By linking these observations with the morphology, stratigraphy and internal structures of the deposits, and with the hypogean and epigean climate records, we were able to identify the accumulation processes and to give one upper and some lower limits to the age of these deposits. The most notable deposit shows a more than 15m-thick succession of clear-ice layers, found at a depth of about 80m and suspended between two shafts in the cave "Abisso sul margine dell'Alto Bregaia". Because of the relative position to the cave entrance, no snow can reach this deposit. The crystallographic and textural features, confirmed by the chemical and isotopic trends, show that this is lake-ice. At present no accumulation can be observed and the top surface is now at least 3m lower than it was three decades ago. The underlying shaft, deglaciated at some time in the past by the air circulation drains the water so that hypogean lakes can no longer develop. We have found sound stratigraphic and glaciotectionic evidences of at least three accumulation and three ablation phases. When compared to current local precipitation and to the values available from literature, the ice chemical composition and 6110 values show that this ice must be younger than the end of the last ice age, while preceding the beginning of industrial activity related contributions.

Are there karstic landforms under the Antarctic ice cap?

Un karst sous la glace de l'Antarctide?

A Bini, A Forieri, F Remy, I E Tabacco, A Zirizzotti and L Zuccoli

A new bedrock map of the Dome C area based on all radar data collected during Italian Antarctic Expeditions in 1995, 1997, 1999 and 2001 is presented. The map can clearly distinguish the Dome C plateau, along with some valleys and ridges develop. The plateau develops at three different altimetric levels and its morphology is characterised by hills and closed depressions. There are no visible features, which can be ascribed to glacial erosion or deposition. The major valley is 15km wide and 500m deep; its axis is parallel to that of other valleys and ridges in the plateau. The valley bottom is not flat, but contains a saddle in its centre. The morphology of the major valley could be considered as a relict one, which was not modified by the overlying ice cap. Two big ridges, characterised by hills, saddles and depressions, lie near the boundaries of the area. The hill

and depression landscape may be the result of two different processes the weathering of granitic rocks, with the development of a "Demi-oranges" and inselberg landscape, or the karstification of limestones, and development of a cone karst. The karstic hypothesis should be the more suitable, but it is impossible to exclude the granitic rock weathering. Both proposed genetic hypotheses calling for a warm- humid climate and a long period of stability in a continental environment. Consequently, the ice cap did not largely modify the landscape.



KARSTOLOGIA 2004/43

ABSTRACTS

Cave of Alisadr: a geomorphological site of outstanding interest in the Zagros Mountains of Iran.

La grotte d'Alisadr, un témoin exceptionnel de l'évolution morphologique du Zagros (Iran).

Dominique Dumas

The tourist cave of Alisadr, located on the eastern boundaries of the Zagros Mountains, is biggest subsurface cave visited in Iran. Most part of the karstic underground galleries is permanently filled with water: on the sides of the galleries former water table levels are indicated by numerous calcareous sinters. The sub-surface karst has preserved numerous relics and paleoenvironmental residual deposits, which show the geomorphologic karstic development. Dating of the three conspicuous calcareous levels in the cave and that of the surface basaltic mesa, to be established a few kilometres from the cave enable a chronology the stages of karstic evolution. The place of pre-quaternary vestiges in the landscapes of this country is also determined. For example, no typical landform of glacial erosion has been identified. The current karstic denudation rate is about 3mm/Ky. The geomorphological evolution of surface and sub-surface landforms during the Quaternary era is shown and deduced from the processes, which have led to breccia formations in calcareous rocks.

Keywords: karst, karstogenesis, speleogenesis, hydrogeology, endokarstic fillings, endokarstic morphology, Alisadr Cave, Zagros, Iran

Subterranean molluscs of the karstic network of Padirac (France, Lot) and micro-distribution of *Bythinella padiraci* Locard, 1903 (Mollusca, Caenogastropoda, Rissooidea).

Les mollusques souterrains du réseau karstique de Padirac (Lot, France) et micro-répartition de *Bythinella padiraci* Locard, 1903 (Mollusca, Caenogastropoda, Rissooidea).

Jean-Michel Bichain, Christian Boudsocq and Vincent Prié

During a Padirac expedition in November 2003, about ten biological samplings were carried out in the deep karstic network. The first aim of this biospeological mission was to update the data on stygobites molluscs in this subterranean ecosystem. The results show that *Bythinella padiraci* Locard, 1903, species listed as vulnerable in the 2004 IUCN world Red List of threatened animals, although absent in the upstream part of the Padirac subterranean river, is present in its downstream part after the Déversoir and in the De Joly affluent. An hydrobioid belonging to the genus *Islamia* was recorded as a component of the stygobiontic biocenose of Padirac as well as *Moitessieria rolandiana* Bourguignat, 1863. In addition, 3 epigeal freshwater molluscs were observed alive in the deep network, *Potamopyrgus antipodarum*, *Ancylus fluviatilis*, *Pisidium* sp. as well as a terrestrial mollusc, *Discus rotundatus*.

Keywords: Gouffre de Padirac, biospeology, subterranean snails, hydrobioids, *Bythinella padiraci*, *Islamia* sp., *Moitessieria rolandiana*

Relationship between karst and tectonics in the Han-sur-Lesse area (Luxembourg province, Belgium).

Tectonique et karstification. Le cas de la région de Han-sur-Lesse (Belgique).

Cécile Havron, Yves Quinif and Sara Vandycke

The structure of four limestone massifs around Han-sur-Lesse (Belgium) has been studied with the aim of understanding the

relationship between karst and tectonics. In the massifs of Han and Wellin, a swallow-hole – resurgence system is observed, on the contrary of Grignaux-Turmont and Resteigne massifs. The structural analysis involves a geometric study of tectonic objects as the faults or the joints, to establish the structural evolution of the massif. With such an analysis, it is possible to describe more accurately the relationships between the tectonic evolution of a massif and its speleogenesis defined by the presence of a structured endokarstic hydrosystem.

A study of the karstified joint's directions has showed that the karstogenesis developed during two successive stages. Indeed, we can observe that the Han tectonic network is mainly structured according to two directions: the first one – N50°E – N65°E – was caused by a Mesozoic extensional tectonic stage, without any hydrodynamic potential. It induced a ghost-rock karstification. The second one – N140°E – is due to another tectonic extensional stage during the Cenozoic; this second stage, in relation with the Ardennes uplift is combined with the appearance of a hydraulic gradient, which allows the structuring of karstic systems. The hydraulic gradient together with the extensional tectonics lead to the karstification of Han and Wellin massifs.

Keywords: karstification, tectonics, morpho-structural analysis, Han-sur-Lesse cave, Belgium.

Chronologies and means of prehistoric human and animal frequentations into Aldène cave, Cathala level (Hérault, France). Sedimentology and geochronology studies.

Âges et modalités des incursions humaines et animales préhistoriques dans l'étage Cathala de la grotte d'Aldène (Hérault, France). Apport des analyses sédimentologiques et géochronologiques.

Jean-Louis Guendon, Paul Ambert, Yves Quinif, Bernard Baumes, Albert Colomer, Denis Dainat, Philippe Galant, Alain Gruneisen and Nathalie Gruneisen

The Aldène cave forms a long network of galleries on four levels. Only the first two of these contain prehistoric vestiges. Superior level (Bousquet storey) presents a Lower Palaeolithic stratigraphy in the porch. It contained also, in the deep areas, a thick filling of clays and speleothems with bear bones, intensively quarried during the 19th and 20th centuries for phosphate ore. These workings allowed discovery of the second level (Cathala storey) and, in these new galleries, human footprints trail with sooty marks on the walls, numerous animal paw prints, hyena coprolites, scratches and nests made by bears. After study establishing Mesolithic age of human footprints (8 200 ± 130 BP, 7 790 ± 60 BP) and anteriority of animal passages, researches were directed on sedimentological and geochronological study (U/Th dating of speleothem). First, the age of the last animal presence in the second level of Aldène was precised, between 41 500 BP to 25 000 BP. Second, means and chronologies of closing of the prehistoric entrance of Cathala storey were revealed. The actual access in these galleries is only an artificial entrance opened up for phosphate mining. It begins by a "cat-flap" and shafts about twenty meters high. The access used by prehistoric humans and animals is completely obstructed by a very important boulder choke with speleothems interstratified, situated in the north part of Cathala gallery. The studies of this boulder choke showed three principal phases of closing of this primitive access:

- a first collapse of the roof during the mid Pleistocene;
- an important bedded rock-fragments produced by frost shattering of primitive entrance porch, which filled principal gallery during periglacial stages of the late Pleistocene;
- and a second roof collapse, during the Holocene. The burnt pieces of brand left on the ground allowed recognition of the last narrow passage taken by the Mesolithic humans before this last collapse finally obstructed this entrance.

Keywords: Palaeo-speleology, prehistory, human and animal traces, late Pleistocene, Holocene, speleothem, U/Th dating, AMS 14C, Aldène cave, Hérault, France.

Karstic landscape on the south face of Lure range (Alpes-de-Haute-Provence, France).

Le paysage karstique du versant sud de la montagne de Lure (Alpes-de-Haute-Provence, France).

Grégory Dandurand

The karstic landscape of the “Montagne de Lure” seems neither attractive nor spectacular. Karstic forms are badly developed; sinks are small and filled in with red clays. Caves are narrow and their size doesn't enable man to visit them. Only the “aven des Cèdres” reaches 172m deep. Still, it's a major contradiction that surface runoff observed in the area are thin and as poor as karstic shapes. Infiltration and subterranean water flow are fast.

Neither exhaustive inventory, nor precise study about the Lure range's karsts have been published yet. Perhaps due to the mediocrity of their superficial and subterranean shapes, or perhaps in the benefit of the more spectacular karstic landscapes of the “Plateau d' Albion”, to the west part of studied area! Still, the main problem about Lure range is the question of the relation with the “Fontaine de Vaucluse” and maybe with any others springs in Durance valley. Finally, the progression of woods at the end of 19th century and at the beginning of 20th century, then the increase of population since the 1970s, created a lot of environmental dysfunctions, which require a specific management. But karstic shapes are unexploited; protection or valorisation plans don't exist, when interrogation about the future of biological and landscape diversity is at the top. These reasons give a particular interest to the karst landscape of the south face of the “Montagne de Lure”.

Keywords: Mediterranean and mountain karst, karstic landscape, Fontaine de Vaucluse, Lure range, Durance river.

Hydrogeological studies of the Alpe du Lauzet range (Hautes-Alpes, France): Dye-tracing in the Clôt des Vaches cave.

Recherches sur le karst de l'Alpe du Lauzet. Massif des Cerces, Hautes-Alpes. Le traçage du gouffre du Clôt des Vaches.

Jean-Louis Flandin, Marie-Pierre Martin and Jean-Pierre Mettetal

The discovery, in 2002, of the Clôt des Vaches Cave and its sinkhole gave us the idea to look for possible resurgences and to use tracers in order to identify part of the underground circulation of the Alpe du Lauzet Range. This successful endeavour confirmed the hypothesis of a hydrological communication with the springs of Alpe du Lauzet. Hence we warned the owners of chalets and cabins about the possibility of contaminated spring water. A link with the springs of Plan Chevalier remains possible, but would be a lot less direct and slower.

Keywords: karst, springs, resurgences, water tracing, Briançon area, Cerces, Bruyère Ridge, Clôt des Vaches.



KARSTOLOGIA 2004/44

ABSTRACTS

Hydrological methods for the study of river flows in limestone areas: the Marne basin in the Jurassic low plateaux (NE France).

Apports des méthodes hydrologiques dans la compréhension des écoulements en pays calcaire : exemple des bas plateaux jurassiques du haut bassin de la Marne (France).

Olivier Lejeune and Alain Devos

We investigated the geographical heterogeneity of river flows in limestone areas in the upper Marne valley (interfluvies of the Marne-Aube and Marne-Meuse) by using low water profiles, the modelling of discharges and the study of physicochemical parameters. We studied five basin-slopes belonging to the Marne-basin (4500km²) and the measurements were taken between 2001 and 2003 at times of low water. We used an instrument (“perche à intégration type Pirée”) in order to measure the stream flows of river water. We also measured temperature and electrical conductivity in order to identify the origin of the water. The measurements allowed us to identify low water profiles of the river and we can also map the discharge in low water periods. The methods show the water flow inside a basin-slope and also hydrogeological connections to the adjacent basin-slopes.

Thus, they revealed that the divergence or the concentration of discharges depends on the limits of the aquifers sections related to their morphological structure and on the differential incision of the valleys. We obtained a hydrogeological pattern of interfluvies and we can distinguish between areas of water lost and areas with an increase in water volume. We confirmed this process of water transfers, called “active stream piracy”, which is often approved by hydrogeological tracers. This active stream piracy revealed by these methods in warm or interglacial period, prepare future stream piracy of surface, collectively recognised at the beginning of a cold phase.

Keywords: Marne basin, active stream piracy, flow mapping, geoprospective, interfluvies, low water profiles.

Interest of the morphogenesis approach to improve the knowledge of a high-value heritage: Chauvet Cave (Ardèche, France).

Intérêt de l'approche morphogénique pour la compréhension globale d'une grotte à haute valeur patrimoniale, la grotte Chauvet (Ardèche - France).

Jean-Jacques Delannoy, Yves Perrette, Evelyne Debard, Catherine Ferrier, Bertrand Kervazo, Anne-Sophie Perroux, Stéphane Jaillet and Yves Quinif

This paper describes the shapes and cave deposits of the Chauvet Cave. Especially, the geomorphological approach improves the global understanding of the Chauvet Cave characteristics during prehistoric occupancies by Man and animals. Access to the cave, painting location in the cave, and finally cave closing, are discussed on a geomorphological basis to answer the questions posed by pre-historians and archaeologists. The ultimate goal of this paper is to enhance the contribution of high-resolution geomorphological mapping to prehistoric investigations. To answer the three questions above, we used shapes and deposits to relate the past cave environments. Detailed soil mapping allows description of deposits and shapes by a stratigraphical approach. Some U/Th dating completes the chronology, especially during the period of human and animal occupancy; thus, the closing of the prehistoric entrance has been dated older than 15,000 years. Also, this paper shows the interest of crossing the disciplinary approaches in the understanding of such a complex scientific object: the Chauvet Cave, a high value human heritage site.

Keywords: Speleogenesis, karstogenesis, geomorphology, cartography, prehistory, palaeontology, Chauvet Cave, Ardèche, France.

“Outside stalactites” in humid tropical karst – Stalactitic deposits of calcareous tufa.

“Stalactites extérieures” dans les karsts tropicaux humides. Dépôts stalagmitiques de tufs calcaires.

Danko Taboroši and Kazuomi Hirakawa

Friable and porous stalactitic deposits composed of calcareous tufa – rather than sparry calcite characteristic of normal cave stalactites – are often encountered in the entrances of caves and plastered to cliffs in the humid tropics. Tufaceous stalactitic outside deposits are frequently mentioned in literature but are typically dismissed in a few sentences, even in review articles dedicated to calcareous tufa. Mostly based on fieldwork in the Mariana Island, we have identified a variety of depositional settings where stalactitic tufa occurs. These settings can be grouped into spelean, transitional, epigean, and littoral realms. Centimetre to tens of meters in scale, their overall shapes can be quite irregular, with crooked, bulbous, pendant-like, light-oriented and other deflected forms exceedingly common. The outside surfaces of these “stalactites” invariably lack the crystalline luster of cave speleothems and feel wet and pasty, or powdery and earthy when dry. They are commonly covered with organic coatings. Stalactitic tufas are generally lightweight, porous, and friable, and many small specimens are weak enough to be plucked by hand. Composed of layered microcrystalline material, sometimes reminiscent of chalk, these “stalactites” exhibit a bewildering variety of fabrics, which can be classified as encrusted, amorphous, and laminated. In addition, they contain much organic material,

microbial structures, and detrital grains. A wide array of biota is associated with these features, and they are thought to form by biogenic mechanisms superimposed on abiotic physico-chemical precipitation from karst water. Biologic processes involved in the formation of stalactitic tufa are numerous and appear to involve hundreds of species. While it is now clear that stalactitic tufas are a result of abiotic and biogenic deposition, an additional possibility remains to be considered. It is not improbable that tufa-like stalactites could form by decay and diagenesis of true cave speleothems, if the latter are exposed at the land surface conditions. Stalactitic tufas represent a unique, subaerial variety of calcareous tufa rarely deliberated in karst literature.

Keywords: Phytokarst, biokarst, twilight zone, biofilm, speleothems, stromatolites

Geothermal flux with deep karstic waters: the surprise relating to transitory phenomena.

Le flux géothermique avec circulation d'eau profonde dans les karsts : la surprise des transitoires.

Baudouin Lismonde

After a recall of some generalities about geothermal flux and its origin, the effect of deep karstic water on the temperatures in karstic areas is analysed. Under conditions of a constant flow, two properties are well known:

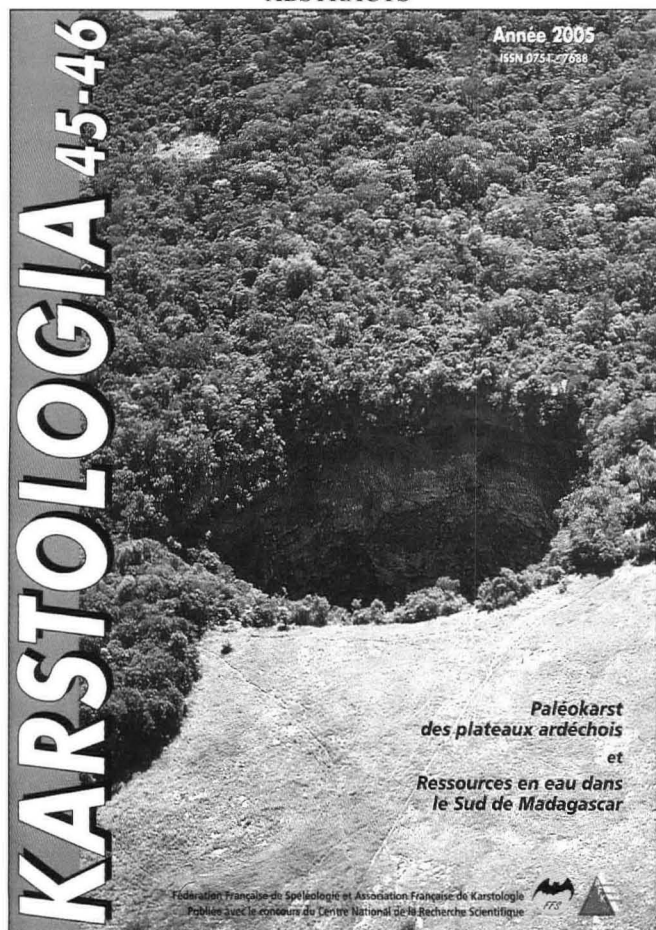
- decrease of geothermal flux in the karstic area;
- convergence of flux lines in the neighbourhood of collector.

The surprise occurs in relation to the transitory phenomena: the greater the depth of the subterranean river, the greater and faster the amplitude of thermal perturbation. Indeed, when some galleries dry up completely, the heat flow from the rock can warm up the galleries by tenths of a degree in a few weeks. This is in contradiction with the idea of permanent deep temperatures.

Keywords: Geothermal flux, computed model, transient temperature, subterranean climatology.



KARSTOLOGIA 2005/45-46 ABSTRACTS



France discovery of an underground river fossilized during the Messinian salinity crisis.

Etude des paléokarsts des environs de Saint-Remèze (Ardèche, France): mise en évidence d'une rivière souterraine fossilisée durant la crise de salinité messinienne.

Jacques Martini

The palaeokarst features studied in this paper are hosted in Lower Cretaceous limestone and generally appear as filled caves, subsequently unroofed by denudation. The most important of them forms a sequence of segments developed at a relatively constant elevation of 360–380m above sea level and can be traced over a length of 5.2km. The ancient cave passages generally appear as soil covered bands, 5 to 20m in width and limited on both sides by limestone outcrops. At surface the nature of the cave filling is revealed mainly by scattered blocks: calcite from speleothems and calcified clay, silt, sand and breccia. In the best preserved places, the earth band lies in a trench, where the walls may display a cave morphology and where the filling is commonly exposed in an undisturbed state. Three types of detrital cave filling have been identified, which in stratigraphical order are as follows:

1) Beige-grey silt, sand and microconglomerate of immature alluvial material, with elements of Palaeozoic granites and metamorphic rocks, and Upper Miocene volcanic rocks, both originating from the Cévennes Mountains 30km to the NW. The lithological composition is comparable to the recent alluvial deposits of the Ardèche River, which flows a few kilometres to the SW and is deeply entrenched into a canyon at elevations of 40 to 80m. The karst context, combined with the biostratigraphical data obtained from rodent molars in the alluvial material, suggests an Uppermost Miocene age, comprised between ~5.8 and ~5.45 Ma.

2) Red mature alluvial and colluvial deposits originating from local reworking of surficial karst residual material. At one spot they gave a paleontological age of 3.6 to 3.0 Ma, but from the local karst context one may expect ages from latest Miocene to Pleistocene in other spots.

3) Monogenetic breccia generated from wall gelification, which is Pleistocene in age, as confirmed by rodent molars found in two places.

The paleocave is visualised as formed by an underground stream fed from swallow-holes on the bank of the Ardèche River, when it was flowing more than 300m higher than its present bed. With regard to its relatively constant elevation and a discordant relationship with the country rock bedding, it is interpreted as a vadose cave controlled by a palaeo-water-table. The other fillings (2 and 3) were deposited during subsequent vadose speleogenesis and after considerable water-table lowering.

The elevation of this fossilised underground river coincides fairly well with the pre-salinity crisis abandonment surface (5.52 Ma), which is evidenced in the area by high-level perched gravel relics. The end of the speleogenesis could have taken place just before this event (~5.6 Ma) or at an age not younger than ~5.45 Ma. In the latter possibility, speleogenesis had to be working before the regressive erosion generated by the drastic lowering of the Mediterranean Sea [5.52 to 5.33 Ma, Clauzon *et al.*, 2005] reached the area and de-watered the deep karst aquifer. This fossil underground river provides also information about the morphological evolution of the area. For instance the nature of the immature alluvials suggests that the torrential regime of the Ardèche was about the same than today. It also indicates that the important and famous cave systems in the area (Grotte de Saint-Marcel, Aven d'Ornag, Système de Foussoubie, Grotte Chauvet), which are developed at lower elevations, cannot be older than ~5.6 Ma and most likely formed mainly during the Plio-Pleistocene, although most of them were initiated during the salinity crisis.

Keywords: paleokarst, Ardèche, fossil underground river, Messinian salinity crisis, rodents.

The lateritic karsts of New Caledonia.

Les karsts latéritiques de Nouvelle-Calédonie.

Antonin Genna, Laurent Bailly, Yves Lafoy and Thierry Augé

The metallogenetic role of karst phenomena has been known for a

long time. The main ore bodies formed in this way contain aluminium, lead-zinc, nickel, or copper. In New Caledonia, the humid tropical climate was the reason for the development of various karst types within carbonate formations and ultramafic rocks of the caledonian ophiolite. Nickel concentrated in altered pockets has been mined since the 19th century. The genesis of the ore was debated controversially, and different geological models had been proposed. Initially, the ores were interpreted as being hydrothermal deposits. Then, they were considered supergene, with meteoric fluids using pre-existing fractures. They also were considered as being contemporaneous to radially expanding neotectonic activity.

The lateritic alteration of the peridotites began on a Miocene palaeosurface. By means of a structural analysis, we show that the listric faults containing the mineralisation are due to karstic collapses. A detailed analysis of the complete karst buildup is made, where hydraulic fracturing plays a dominant role in the dynamics and structuration of the karst.

Keywords: karst, laterite, alteration, nickel, garnierite, New Caledonia.

Structural and tectonic control on karstic hydrogeology of the plateau Mahafaly (semi-arid coastal area, southwest Madagascar)

Contrôle structural et tectonique sur l'hydrogéologie karstique du plateau Mahafaly (domaine littoral semi-aride, sud-ouest de Madagascar)

Grégoire André, Gilles Bergeron and Luc Guyot

The southwestern coast of Madagascar is characterized by a semi-arid climate and low fresh water resources, which slow down economic development. The studied area, located south of Toliara, is separated into a western coast of aeolian dunes and sandstones, where most of the people live, and the eastern, almost unoccupied, calcareous Mahafaly plateau. The coastal aquifer is dominated by salty water. The conductivity, close to 6000 $\mu\text{S}/\text{cm}$ in the north, decreases to 3000 $\mu\text{S}/\text{cm}$ in the south. The coastal plain is bordered to the east by highly karstified Cenozoic limestone, separated by a north-south cliff corresponding to the Toliara fault scarp. Surveys in coastal wells and in karstic aquifers clearly point out tidal influence on piezometric level and conductivity. In the north, the limestone cliff is directly in contact with the sea, whose water contaminates the karstic aquifer according to tidal variations. In the south, fresh water flows out on the beach by resurgences in the Quaternary sandstones, probably connected to the Eocene limestones, 5 km to the east. Drillings and exploration of some shafts on the plateau permitted access to the ground water table. It displays various conductivities ranging between 1500 $\mu\text{S}/\text{cm}$ and 5000 $\mu\text{S}/\text{cm}$, unusually high for a karstic aquifer far away from the coast. The mapping of such conductivities suggests more complex phenomena than only marine intrusions into the different aquifer systems. Chemical and isotopic analyses show an obvious seawater intrusion and evaporation influence for the coastal aquifer. In the karstic aquifer, however, trace element analyses evoke contamination by upwelling of deep mineralized water. Salty water is frequent eastward on the basement and in the Mesozoic formations. Today, fracture zones in both the coastal sandstones and in the Cenozoic limestone units control ground water circulations. Such fractures result from extensional phases in the past. The surface joint directions N-S, NE-SW and NW-SE reflect the deep-seated horst and graben structures. Microtectonic analyses give evidence of a post-Eocene WNW-ESE extension, and recent seismic data define an E-W extensional regime. The underground flowpaths are mostly on fractures oriented along the present stress field. The tectonic history in the area and the chemical composition of the waters suggest a connection of the karst aquifer with circulations from deep formations through deep-seated faults belonging to the Toliara fault system. This could explain abnormal salinities in the karstic system, far away from the coast.

Keywords: hydrogeology, salt-water intrusions, coastal aquifer, karstic aquifer, fracturing, palaeo-stress, Mahafaly plateau, Madagascar.

The state of underground tourist sites in France: the end of a cycle?

Etat des lieux du tourisme souterrain en France : la fin d'un cycle?

Vincent Biot and Christophe Gauchon

The aim of the branch of geography dealing with tourism and recreational activities is to analyse where, how and why these activities take place, and how the interrelations between their components and their natural and socio-economic environment are. From this point of view, underground tourism is a good example. After a century of – sometimes spectacular – growth, bringing France to the first place among the European countries, with 97 tourist caves and about 4 million visitors per year, the last 10 years saw a steep decline in underground tourism. Causes, effects, and measures to stop or invert this evolution are put forward here. Theories about creation of tourist sites and their life cycles are analysed to see the evolution: how far can those theoretical models be applied in this case? And to what extent can the caves contribute to understanding the spatial dynamics of tourism? Underground tourism is first described in its historical and spatial dimensions, to show its impact on many rural areas. Then, the present crisis is described, and possible ways to rejuvenate the activity are examined, even though the reorganisation of a tourist cave is never easy.

Keywords: underground tourism, life cycle of touristic sites, touristic development, touristic image, caves.

Don Quijote, espeleólogo anticipadamente, y Sancho Panza accidentalmente

Don Quichotte, spéléologue avant la lettre, et Sancho Panza par accident

Jean-Noël Salomon and Fernando Díaz del Olmo

In the novel "Don Quixote" by Cervantès, whose 400th birthday anniversary is in 2005, exploration of the underground world is mentioned several times. This is not total invention by the famous Spanish author, because he based his ideas on concrete reality. The cave of Montesinos as well as the karst lagoons of Ruidera exist. We visited them in 1961, out of curiosity, after having read the novel. As a matter of fact, these famous localities of the Mancha are karstic areas with notable characteristics, foremost the lagoons of Ruidera, that have been made accessible for tourists. The 400th anniversary is an opportunity for the authors of this article to compare fiction (the "exploration" of Don Quixote) and the real karst morphologies, and to draw some general conclusions.

Keywords: Cervantès, Don Quixote, Guadiana, karst, tufa, natural parks, Mancha.

Résumé : Dans le « Don Quichotte » de Cervantès, dont c'est en 2005 le 400^{ème} anniversaire, il est fait allusion, à plusieurs reprises, à l'exploration du monde souterrain. Il ne s'agit pas d'une totale invention de la part du célèbre auteur espagnol car ce dernier s'appuie sur une « réalité » bien concrète. La grotte de Montesinos, tout comme les lagunes karstiques de Ruidera existent bien : nous les avions visitées en 1961, par curiosité, après avoir lu le roman. De fait, ces lieux célèbres de la Manche sont des lieux karstiques avec des caractéristiques remarquables notamment les lagunes de Ruidera, qui ont été aménagées pour le tourisme. Le 400^{ème} anniversaire est pour les auteurs de cet article l'occasion de se pencher sur la fiction (l'« exploration » de Don Quichotte) et la réalité des morphologies karstiques, par le biais d'une comparaison, et d'en tirer des enseignements plus généraux.

Mots-clés : Cervantès, Don Quichotte, Guadiana, karst, travertins, parcs naturels, Manche

The dryness of 2003 and the temperature measurements in the Trou qui Souffle (Méaudre, France): the role of geothermal flux.

La sécheresse 2003 et les mesures de température au Trou qui Souffle de Méaudre : rôle du flux géothermique

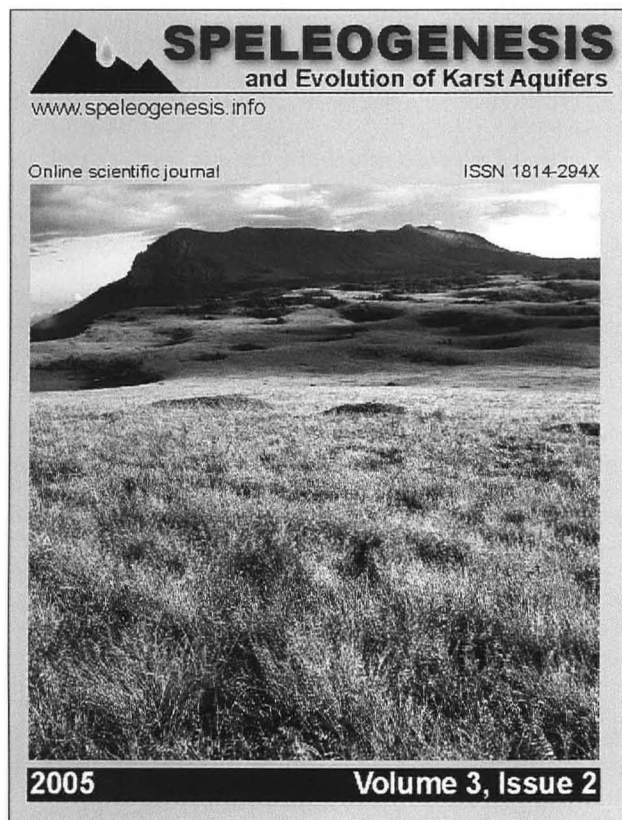
Baudouin Lismonde

A deep passage in the Trou qui Souffle (Vercors, France) was equipped with a Luidrographe that allows continuous recording of

variations in both water level and temperature. The results show that the dryness of 2003 induced an air temperature rise of 1°C. In autumn and winter 2003-2004, several floods were recorded which were coupled with a decrease in temperature. These measurements allowed to evidence thermal heterogeneities within the massif. We attribute these to the geothermal flux. A theoretical model (published in a previous article) provides an interpretation of the observed phenomena: the geothermal flux is focalised, thus the change of temperature in that deep level is very rapid.

Keywords: underground temperature, underground climatology, transitory phenomena, geothermal flux.

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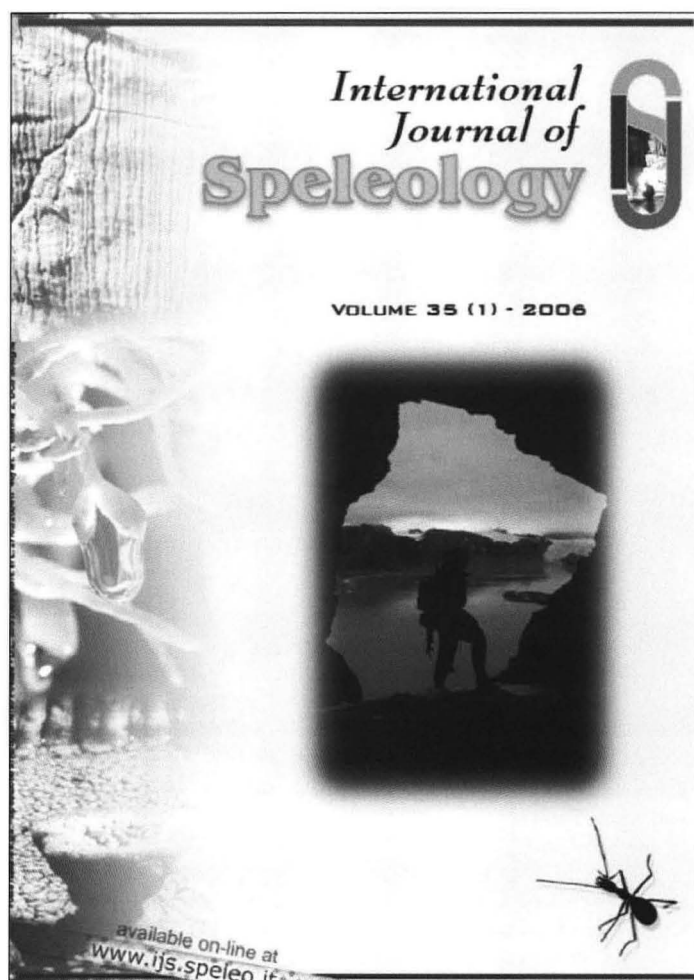
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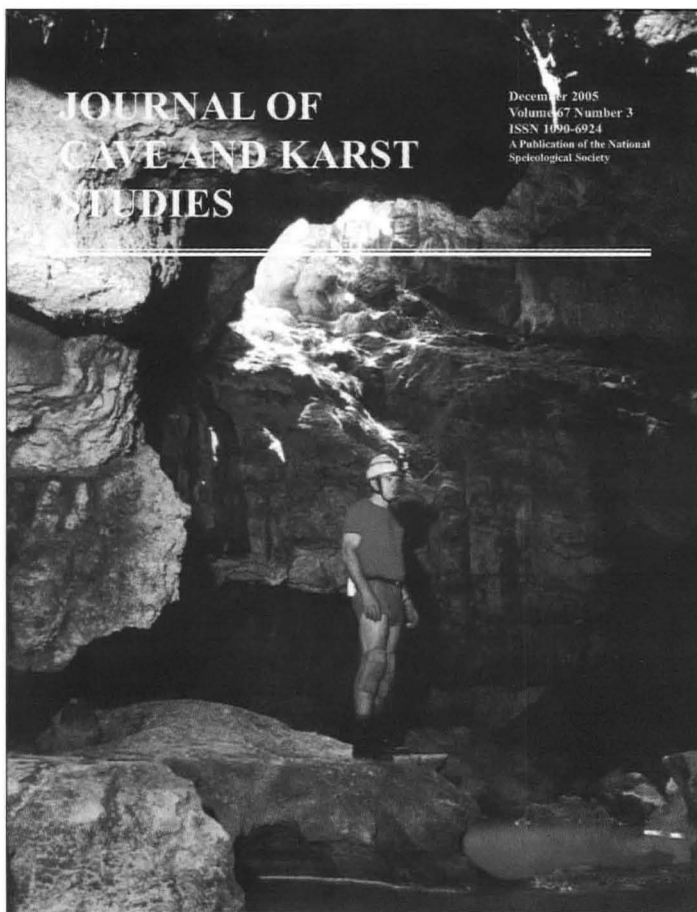
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BOOK REVIEW

Processes of speleogenesis: a modeling approach.

By Wolfgang Dreybrodt, Franci Gabrovšek and Douchko Romanov, with guest contributions by Sebastian Bauer, Steffen Birk, Rudolf Liedl, Martin Sauter and Georg Kaufmann. Published by Karst Research Institute at ZRC SAZU, Postojna B Ljubljana, 2005. ISBN 961-6500-91-0. 376pp.

Processes of speleogenesis provides a useful up-to-date summary of the rapidly-growing field of computer modelling of the development of karst aquifers, which in technical terms are known as distributed-parameter aquifer-evolution numerical models. This book would be a very useful addition to the libraries not only of karst specialists but also of all those hydrogeologists who work with carbonate aquifers.

Computer models have become an important part of hydrogeology in the last thirty years, as a way to understand the complex patterns of flow in the subsurface. The most popular is MODFLOW, which is a public domain distributed parameter model produced by the United States Geological Survey. A distributed parameter model allocates values of parameters such as hydraulic conductivity, porosity, or recharge to a large number of locations in an aquifer, so that water levels and flow can be calculated. These models have increased in complexity over the years, from about 1000 points in 1970 to at least 100,000 points today. Such complexity is impressive, and the beautifully neat and colourful computer outputs are superficially compelling. However, these models are usually based on assumptions that are overly simplistic for limestone aquifers – for instance that the aquifer behaves as if the water flowed through the pores in the rock rather than through fractures and conduits.

Until the 1970s it was known that there is rapid dissolution at the surface in limestone, which produces epikarst, but the details of conduit dissolution in the subsurface were largely unknown. But then lab experiments on dissolution kinetics showed that there is slow dissolution throughout the length of a limestone aquifer, and it is this process that forms conduits. Simple one-dimensional conduit models were produced in the 1990s, and in recent years the modelling has extended to two-dimensional models. These 2D models are similar to a MODFLOW model of a sand aquifer, except that fractures are added and dissolution along the fractures is included. This results in a karst aquifer being formed over time. There have now been some forty papers published in the mainstream scientific literature on this topic.

The book starts by summarising previous work. The first three chapters provide a brief introduction, a concise outline of the dissolution chemistry of limestone, and then a longer chapter on the evolution of a conduit along a single fracture. This is essentially a revised version of Gabrovšek's PhD thesis, which was published as a book in 2000. That book is out of print, so it is useful to have the information reproduced here.

Chapters 4, 5 and 6 provide the heart of the book, and include 155 figures. Many of the figures are in colour and have multiple panels. Commonly one set of panels displays fracture widths and dissolution rates over a series of time steps and the adjacent set of panels shows flow rates and flow directions at the same time steps. Some figures also include head data. The rectangular grids used typically have 20,000 conduit segments shown, and thus the use of colour is welcome. Furthermore, the accompanying CD has 51 animations in PowerPoint format. These animations are also very welcome. The figures in the text are necessarily small and have a maximum of six time steps, whereas those on the CD have up to forty time steps and can be displayed at the size of a computer screen. Many start with time steps of 1000 years, reducing in some cases to steps of less than a year at times close to breakthrough, when evolution proceeds very quickly. These animations will be very useful for anyone wishing to understand or to teach how karstification occurs.

Chapters 4 and 5 look at the horizontal and vertical dimensions, respectively, of karst aquifers, and chapter 6 shows how the high water levels behind dams inevitably results in rapid karstification. Some of the results in these chapters have been published before, but

they are more comprehensively dealt with here, and also there is much new material. The main section of the book ends with a very brief concluding chapter, and then there are guest chapters by two other leading modelling groups. The approach used by these other groups is very similar, and the results are broadly similar. The conclusion of all three groups is that wherever there are limestone aquifers exposed at the surface a karst aquifer inevitably forms over a period of, typically, 10,000 – 100,000 years.

The authors present the modelling results but make no attempt to suggest which of various models presented might apply to specific caves or karst aquifers. That task is beyond the scope of the book and is left for others to do. It can also be argued that some of the simulations are simplistic and omit important variables. This is particularly the case in chapter 5, where the modelling shows that caves form at the water table. If this were true then caving trips from sink point to spring would be common. In reality, they are rare, and cave diving in the last few decades has started to show the large extent of cave passages below the water table. Most of the simulations deal with aquifers just 1km in length, whereas many karst aquifers extend to lengths of 10km or more. Hopefully, future modelling will deal with longer aquifers and include the effects of density, temperature and viscosity differences on flow and dissolution rates. Similarly, most of the model runs terminate when the conduits are about 1cm in diameter and the discharge is about 1 L/s. Future modelling could be extended to include larger conduits with higher discharges, where it would be useful to include the complicating effects of turbulent flow, vadose conduits, and the presence of sediments. These ideas are pointers to the future rather than criticisms of the present book, which does an excellent job in presenting the results of the first fifteen years of numerical modelling of conduit evolution.

Steve Worthington
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SCIENTIFIC NOTE

Radiocarbon dates from Tynings Great Swallet – there is no substitute for data.

Tynings Great Swallet is located immediately above the terminal boulder choke of Charterhouse Cave, on Mendip. The University of Bristol Speleological Society has been digging in this doline since the early 1980s, in an attempt to reach the continuation of the Charterhouse stream and hopefully follow it to join the continuation of the G.B. Cavern stream beyond that cave's terminal choke.

Following a minor breakthrough in 2002, we found that the doline seemed to be situated over a large shaft, up to 10m in diameter, almost completely filled with loose rock. Such features are quite common on Mendip and a number of similar shafts have been dug at various times. However, we also started to find amongst the rocks a quantity of bone, both human and animal. We also found a single artifact identified as a late Neolithic thumb scraper. This material caused the site to be compared directly with other, similar, shafts that have yielded significant quantities of archaeological material, notably Charterhouse Warren Farm Swallet and Brimble Pit. Details of the work at Great Swallet were published by Boycott and Mullan in January 2005.

At this stage, we had a reasonable hypothesis that Tynings might be a late Neolithic - early Bronze Age formal deposition site, but the fact that it had been dug as a cave rather than as an archaeological site meant that only part of the potentially available material had been recovered. The mud and rock choke through which we have dug makes recovery of material extremely difficult as it is difficult to tell mud-covered bone apart from mud-covered rock. However this idea needed to be tested. Accordingly, on the advice of Dr Roger Jacobi of the British Museum, two bones were submitted to the Oxford University Research Laboratory for Archaeology and the History of Art for AMS radiocarbon dating. We are grateful to the Research Fund of the BCRA for funding this part of the work.

The two bones submitted were from *Bos primigenius*, found at a depth of approximately 40m and *Homo sapiens*, found at a depth of approximately 30m. When the dates were received, the *Bos* was

dated, at 95.4% probability to 2480 BC – 2290 BC, largely as anticipated. However the *Homo* date came out at 400 BC (34.8%) 340 BC, 320 BC (60.6%) 200 BC. (The reason for the split probabilities here is due to the uncalibrated date being just on a “wobble” in the calibration curve.) This was clearly much younger than anticipated, being firmly in the middle of the Iron Age. These data are described in more detail by Mullan (*in prep.*)

The data have completely altered our view of the site. It is patently not simply a further example of a late Neolithic – early Bronze Age formal deposition site, though it was of a similar outward appearance at that time. Unlike the intentionally infilled sites from that time, where deposition was rapid, accumulation of sediment here seems to have been quite slow, at approximately 0.5m per century. What the presence of Iron Age human material shows is harder to say, given the lack of artifacts from this period. It is known that Iron Age peoples did use caves as burial sites, but whether this was a formal burial or something else is impossible to say at present. Work continues at the site.

References

- Mullan, G J and Boycott, A, 2005. Archaeological Note: Skeletal Material recovered from Tynings Great Swallet, Charterhouse-on-Mendip, Somerset. *Proceedings of the University of Bristol Speleological Society*. Vol.23. 2, 135–140.
- Mullan, G J (*in prep.*) Radiocarbon dates from Tynings Great Swallet, Charterhouse-on-Mendip, Somerset. *Proceedings of the University of Bristol Speleological Society*. 24. 1.

Graham Mullan
Bristol, UK.



ESTABLISHMENT OF THE UKRAINIAN INSTITUTE OF SPELEOLOGY AND KARSTOLOGY

On March 28, 2006 the Ministry of Education and Science of Ukraine and the National Academy of Sciences of Ukraine have jointly established, as a state scientific organization, the Ukrainian Institute of Speleology and Karstology. The Institute is based on the Tavrichesky national University at Simferopol, Crimea. The main office/facilities are located in Simferopol, in a historic building in the University's botanic garden. Other facilities include a speleological science field station in the Chatyrdag Plateau in the Crimean Mountains and an office in Kiev based in the Institute of Geological Sciences of NASU (to be opened in 2007).

The Institute's mission is to serve as a robust cave and karst research center to foster and coordinate respective research and documentation activity on the national level and to further international cooperation in the science of speleology and karstology through the UISK involvement into multilateral and bilateral research programs. The Institute is involved in fundamental and applied research, protection of karst and subterranean environment and specialized training of planners, engineers, managers, geologists and ecologists.

The Institute's staff and affiliate members currently include 32 scientists with background and expertise in hydrogeology (Dr.V. Dubljansky, Dr.G.Dubljanskaya, Dr.Gudzenko, Dr.A.Klimchouk, Dr.A.Lushchik), hydrochemistry (Dr.S.Aksem, Dr.Yu.Shutov), geomorphology and physical geography (Dr.V.Andrejchuk, Dr.B. Vakhrushev, Dr.G.Amelichev), geophysics (Dr.V.Bakmutov, Dr.S. Levashev), geology-paleontology (Dr.Lysenko), mineralogy (Dr.Yu. Polkanov), biology (R.Vargovich, G.Prokopov), microbiology (Dr.A. Tashirev), archeology (Dr.B.Ridush, M.Sokhatsky), cave management (A.Kozlov, E.Lukjanenko) and other disciplines. The UISK is closely linked with the Ukrainian Speleological Association that provides support in cave documentation and in pursuing researches in complex cave systems.

The speleological science field station of UISK is established in the Chatyrdag Massif, a classical middle-altitude karst plateau with numerous caves, two of which, Mramornaya and Emine-Bair-Khosar are large ancient caves with exceptionally rich and varied speleothems and sediments. Parts of these caves are developed for

tourism, being the core of a single large show cave complex. The Emine-Bair-Khosar cave contains an enormous site of Plio-Pleistocene fauna of great paleontological significance. The field station will conduct systematic detailed and regime investigations in the mountain karst environment, aimed to reconstruction of past environmental conditions from cave records and to study the modern cave environment and physical processes operating in it through an instrumented monitoring system. The infrastructure of the show cave complex and the UISK field station in Chatyrdag karst plateau provides excellent conditions for conducting regular international thematic field seminars and schools, planned to launch from 2007 onward.

The UISK would welcome proposals for collaborative projects, especially those which would serve to develop instrumentation, monitoring system and detailed cave studies in the Chatyrdag field station.

Inauguration of the UISK and its speleological science field station will be held in April 11-12 in Simferopol and on the Chatyrdag, together with first scientific session of the Institute.

Dr Alexander Klimchouk
Director, Ukrainian Institute of Speleology and Karstology



ADDENDUM

In an attempt to bring the stratigraphical nomenclature in Dr Trevor Ford's paper in *Cave and Karst Science* Vol.32, No.1 right up to date, an extra (unpublished but imminent) reference citation was inserted in the text. Unfortunately, due to oversight, the related details were not added to the reference list. We apologize to readers and to the paper's author for this editorial omission, and reproduce the full reference below:

Waters, C N, Browne, M A E, Dean, M T and Powell, J H. In Press. BGS Lithostratigraphical framework for Carboniferous successions of Great Britain (Onshore). *British Geological Survey Research Report*, RR/05/06.



EDITORIAL ENDNOTE

The editors thank Dr Tony Waltham for his invaluable contribution as Guest Editor of the scientific part of this largely thematic issue of *Cave and Karst Science*, and for his role in the organization of the Tiankeng Investigation Project, which led to the development of the published papers. As the material submitted for the "thematic" issue took the publication well beyond its customary length we decided to extend the content, by including some of our existing stockpile of "Forum" material, and produce a double issue.

This double issue completes Volume 32, so we extend our customary thanks to all contributors and to all those who have given their time and expertise to help review the Journal's potential content. In this respect we acknowledge the valued input of Armstrong Osborne, Jamie Pringle, Chris Smart, Andrej Tyc and Tony Waltham, some of whom have cast their eyes over more than one submission.

Once again our thanks are also extended to Becky Talbot who, despite having to deal with serious health problems, has continued to labour on the Desk Top Publication aspects of our production against a background of constantly moving goalposts. Last but not least we add our continuing gratitude to Steve Summers, Sales Director of the Sherwood Press, and to his colleagues, for their continued patience and the efficient and high quality service that they provide.

We are pleased that in the Forum space available in this issue we have been able to include substantial sections covering publications elsewhere in the world of cave and karst science. Hopefully, such international liaison will form a continuing aspect of Forum whenever material is available and when space allows. The existing functions of Forum – publication of scientific notes, correspondence, book reviews and research abstracts, etc, will of course continue, as evidenced by the three items reproduced immediately above, as well as the occasional inclusion of addenda, corrigenda and errata.

Dave Lowe and John Gunn

RESEARCH FUNDS AND GRANTS

The BCRA Research Fund

The British Cave Research Association has established the BCRA Research Fund to promote research into all aspects of speleology in Britain and abroad. A total of £2000 per year is currently available. The aims of the scheme are primarily:

- a) To assist in the purchase of consumable items such as water-tracing dyes, sample holders or chemical reagents without which it would be impossible to carry out or complete a research project;
- b) To provide funds for travel in association with fieldwork or to visit laboratories that could provide essential facilities;
- c) To provide financial support for the preparation of scientific reports. This could cover, for example, the costs of photographic processing, cartographic materials or computing time;
- d) To stimulate new research that the BCRA Research Committee considers could contribute significantly to emerging areas of speleology.

The award scheme will not support the salaries of the research worker(s) or assistants, attendance at conferences in Britain or abroad, nor the purchase of personal caving clothing, equipment or vehicles. The applicant must be the principal investigator, and must be a member of the BCRA in order to qualify. Grants may be made to individuals or groups (including BCRA Special Interest Groups), who need not be employed in universities or research establishments. Information about the Fund and application forms for Research Awards are available from the Research Fund Administrator (address at foot of page or e-mail research-fund@bcra.org.uk).

Ghar Parau Foundation Expedition Awards

An award, or awards, with a minimum of around £1000 available annually, to overseas caving expeditions originating from within the United Kingdom. Grants are normally given to those expeditions with an emphasis on a scientific approach and/or pure exploration in remote or little known areas. Application forms are available from the GPF Secretary, David Judson, Hurst Barn, Castlemorton, Malvern, Worcestershire, WR13 6LS, e-mail: d.judson@bcra.org.uk. Closing dates for applications are: 31 August and 31 January.

The E K Tratman Award

An annual award is made for the most stimulating contribution towards speleological literature published within the United Kingdom during the past 12 months. Suggestions are always welcome to members of the GPF Awards Committee, or its Secretary, David Judson (see above for contact details), not later than 31 January each year.

BRITISH CAVE RESEARCH ASSOCIATION PUBLICATIONS

Cave and Karst Science – published three times annually, a scientific journal comprising original research papers, reports, reviews and discussion forum, on all aspects of speleological investigation, geology and geomorphology related to karst and caves, archaeology, biospeleology, exploration and expedition reports.

Editors: Dr D J Lowe, c/o British Geological Survey, Keyworth, Nottingham, NG12 5GG, UK, (e-mail d.lowe@bcra.org.uk) and Professor J Gunn, Limestone Research Group, University of Huddersfield, Queensgate, Huddersfield, HD1 3DH, UK (e-mail j.gunn@bcra.org.uk).

Speleology - published three times annually and replacing BCRA's bulletin '*Caves & Caving*'. A magazine promoting the scientific study of caves, caving technology, and the activity of cave exploration. The magazine also acts as a forum for BCRA's special interest groups and includes book reviews and reports of caving events.

Editor: David Gibson, 12 Well house Drive, Leeds, LS8 4BX, (e-mail: speleology@bcra.org.uk).

Cave Studies Series - occasional series of booklets on various speleological or karst subjects.

No. 1 *Caves and Karst of the Yorkshire Dales*; by Tony Waltham and Martin Davies, 1987. Reprinted 1991.

No. 3 *Caves and Karst of the Peak District*; by Trevor Ford and John Gunn, 1990. Reprinted with corrections 1992.

No. 4 *An Introduction to Cave Photography*; by Sheena Stoddard, 1994.

No. 5 *An Introduction to British Limestone Karst Environments*; edited by John Gunn, 1994.

No. 7 *Caves and Karst of the Brecon Beacons National Park*; by Mike Simms, 1998.

No. 8 *Walks around the Caves and Karst of the Mendip Hills*; by Andy Farrant, 1999.

No. 9 *Sediments in Caves*; by Trevor Ford, 2001.

No. 10 *Dictionary of Karst and Caves*; by D J Lowe and A C Waltham, 2002.

No. 11 *Cave Surveying*; by A J Day, 2002.

No. 12 *Underground Britain-Legal + Insurance Issues*; (2nd extended/revised edition) by David Judson, 2005.

No. 13 *Exploring the Limestone Landscapes of Upper Wharfedale*; by Phillip Murphy, 2003.

No. 14 *Swildon's Two and Three*; by Dave Irwin, 2004.

No. 15 *Exploring the Limestone Landscapes of The Three Peaks + Malham*; by P Murphy, 2005.

Numbers 2 and 6 are out of print, but have been updated by numbers 11 and 10 respectively.

Speleohistory Series – an occasional series.

No. 1 The Ease Gill System – Forty Years of Exploration; by Jim Eyre, 1989.

BCRA SPECIAL INTEREST GROUPS

Special Interest Groups are organised groups within the BCRA that issue their own publications and hold symposia, field meetings, etc.

Cave Radio and Electronics Group promotes the theoretical and practical study of cave radio and the uses of electronics in cave-related projects. The Group publishes a quarterly technical journal (c.32pp A4) and organises twice-yearly field meetings. Occasional publications include the Bibliography of Underground Communications (2nd edition, 36pp A4).

Explosives Users' Group provides information to cavers using explosives for cave exploration and rescue, and liaises with relevant authorities. The Group produces a regular newsletter and organizes field meetings. Occasional publications include a Bibliography and Guide to Regulations, etc.

Hydrology Group organizes meetings around the country for the demonstration and discussion of water-tracing techniques, and organizes programmes of tracer insertion, sampling, monitoring and so on. The Group publishes an occasional newsletter.

Speleohistory Group publishes an occasional newsletter on matters related to historical records of caves; documentary, photographic, biographical and so on.

Cave Surveying Group is a forum for discussion of matters relating to cave surveying, including methods of data recording, data processing, survey standards, instruments, archiving policy, etc. The Group publishes a quarterly newsletter, Compass Points (c.16pp A4), and organizes seminars and field meetings.

Copies of BCRA Publications are obtainable from: Ernie Shield, Publication Sales, Village Farm, Great Thirkleby, Thirsk, North Yorkshire, YO7 2AT, UK.

BCRA Research Fund application forms and information about BCRA Special Interest Groups can be obtained from the BCRA Honorary Secretary: John Wilcock, 22 Kingsley Close, Stafford, ST17 9BT, UK.

