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STRUCTURAL GEOLOGICAL CHARACTERISTICS OF KARST CAVES AND MAJOR STONE FOREST, YUNNAN, CHINA

STRUKTURNO GEOLOŠKE ZNAČILNOSTI KRAŠKIH JAM IN GLAVNEGA KAMNITEGA GOZDA, YUNNAN, KITAJSKA

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Abstract UDC 551.435.84:551.243(510)
Stanka Šebela & Liu Hong: Structural geological characteristics of karst caves and Major stone forest, Yunnan, China
Karst areas of Shilin County southeast of Kumning were studied to understand the role of geological structures in the formation of karst features as stone forest and selected caves. Detailed structural geological mapping of fissure orientations within selected caves and of the Major stone forest was accomplished and presented as rose diagrams. Regional geological structures were compared with statistical evaluation of structural geological elements obtained from field mapping. There is a good correlation between surface and underground fissure orientations and cave passage orientations with regionally important fault zones, including the Xiaojiang Fault (N-S direction) and Red River Fault (NW-SE direction). The most frequent cave passages orientation, in a nearly N-S direction, is associated with nearly E-W compression and nearly N-S extension from late Pliocene to mid-Pleistocene. A second tectonic stage from late-Pleistocene to the present, with the tectonic stress field mainly of NNW-SSE compression and NEE-SWW extension, is in accordance with the most frequent fissure orientations in Major stone forest with a direction of N20–30°W (11.4%).
Keywords: structural geology, rose diagrams, karst caves, Major stone forest, Yunnan, China.

Izvleček UDK 551.435.84:551.243(510)
Stanka Šebela & Hong Liu: Strukturno geološke značilnosti kraških jam in glavnega kamnitega gozda, Kitajska
Proučevali smo kraške terene v okrožju Shilin JV od Kumninga, da bi razumeli vlogo geoloških struktur pri oblikovanju kraških pojavov kot kamnitih gozdov in izbranih jam. Izvedli smo podrobno strukturno geološko kartiranje smeri razpok v izbranih kraških jamah ter v glavnem kamnitem gozdu, kar je predstavljeno z rozetami. Rezultate strukturnih geoloških elementov pridobljenih s terenskim kartiranjem smo primerjali z regionalnimi geološkimi strukturami. Obstaja dobra korelacija med površinskimi in podzemeljskimi smermi razpok ter med smerjo jamskih rovov in regionalno pomembnimi prelomnimi conami, to je s prelomom Xiaojiang (smer S-J) in s prelomom Red River (smer SZ-JV). Najpogostejša smer jamskih rovov v generalni smeri S-J je povezana s kompresijo v smeri skoraj V-Z ter z ekstenzijo v generalni smeri S-J iz obdobja zgornjega Pliocena do srednjega Pleistocena. Druga tektonska faza iz zgornjega Pleistocena do danes, z napetostjo tektonskega polja predvsem s kompresijo v smeri SSZ-JJV in ekstenzijo v smeri SVV-JZZ je v skladu z najpogostejšo smerjo razpok v glavnem kamnitem gozdu v smeri S20–30°Z (11,4%).
Ključne besede: strukturna geologija, rozete, kraške jame, glavni kamniti gozd, Yunnan, Kitajska.

INTRODUCTION

Exposed karst areas in China comprise about 9.3% of the territory. In Yunnan karst landscapes comprise 44% of the area. Stone forests (shilins in Chinese) are the most notable karst areas in Yunnan. The Major and Naigu stone forests are part of the South China Karst region inscribed in UNESCO World Heritage List since 2007. The South China Karst region encompasses over half a million square km, and represents one of the most spec-

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tacular examples of humid tropical to sub-tropical karst, a type of terrain formed mainly by dissolving rock that usually features fissures, sinkholes, underground streams and caves.

The Major stone forest was visited by an average of 1 million people per year by 1988 and by 2.05 million visitors in 2005. Karst areas are important for tourism as well as the economic development of the area (Knez *et al.* 2012a, b).

Recent investigations of Chinese karst geomorphology are numerous (Luo *et al.* 2003; Gu *et al.* 2002; He *et al.* 2001; Song & Liang 2001; Frančišković-Bilinski *et al.* 2003; Šebela *et al.* 2001; Šebela *et al.* 2004; Kogovšek 2010; Knez & Slabe 2010; Knez *et al.* 2010; Knez *et al.* 2011; Knez *et al.* 2012a, etc.).

Karst caves are also good places to study different climate conditions (Wang *et al.* 2001), as well as paleomagnetic and tectonic conditions in the last 100,000 to 500,000 years.

The principal aim of this study was to identify the significant structural geological elements that influence the formation and shaping of selected karst caves and shilins in Shilin County (Yunnan) and to identify possible connections between karst forms and active tectonic structures.

STRUCTURAL GEOLOGY OF THE STUDY AREA

The study area shows tectonic deformation due to the movement of the Asian continent caused by the thrust of the Indian collision. The great geological discontinuity that separates Cambodia, Laos and Vietnam from China results from Cenozoic strike-slip strain. This suggests that this narrow zone acted as a continental transform plate boundary in the Oligo-Miocene. Extrusion of Cambodia, Laos and Vietnam alone accounted for 10–25% of the total shortening of the Asian continent. The territory of Cambodia, Laos and Vietnam was extruded towards the SE as a result of the India-Asia collision (Leloupe *et al.* 1995).

The Tibetan Plateau is a region where modern tectonic movement is the most intensive. The collision between the Indian Plate and Eurasian Plate, the uplifting of the Tibetan Plateau, and its influence on the tectonic movement of eastern part of the Asia Continent represent an important influence on the region. The collision between the two plates leads to the sharp upheaval of the Tibetan Plateau and the obvious thickening of its underlying crust (Wang *et al.* 2003).

Crustal motion in the eastern Tibetan Plateau is caused by Indo-Asian collision (Gang & Mian 2010). Tectonic stress from the relative movement between the Indo-Australian and Eurasian plates causes a strong compressive stress in the NNE-SSW direction and the N-S crust shortening in the Tibetan plateau and its surroundings (Xu & Zhao 2010).

Present-day tectonic styles and rates cannot be extrapolated far into the past because the deformation of Asia started only with the onset of collision, prior to 50 Ma. Large-scale left-lateral shear followed by a reversal to right lateral occurred along the Ailao Shan-Red River zone in the mid-late Cenozoic (Leloupe *et al.* 1995).

The Red River Fault zone (Fig. 1) is the major geological discontinuity that separates South China from territory of Cambodia, Laos and Vietnam. Motion along the Red River Fault zone switched from left lateral in the Oligo-Miocene to right lateral in the Plio-Quaternary. Estimates have ranged from 200–250 km right lateral to more than 1500 km left lateral movement (Leloupe *et al.* 1995). The current dextral slip-rate is 2–10 mm/yr (Allen *et al.* 1984; Wang & Burchfield 2000). The present-day stress field is NNW-SSE shortening. The Ailao Shan-Red River shear zone is mostly strike-slip with transpression in the NW and transtension in the SE (Briais *et al.* 1993).

Tomography shows that there is an obvious lower velocity plume upwelling at 450-km depth at the western side of the Red River Fault. Studies provide seismic evidence for the subducting slab, which is located at around western side of the Red River Fault, and for subduction towards the northeast. Seismic evidence is presented for an upwelling mantle plume, the main cause of which is leading to subduction in West Yunnan (He 2011).

The Xianshui He Fault is an active left-lateral strike-slip fault in the southeastern Tibetan Plateau. It is a major strike-slip fault accommodating the east-southeast extrusion of the Tibetan lithosphere. Both geological and GPS measurements indicate 10–20 mm/year slip on the northwestern segments and 5–9 mm/year on the southeastern segments of the Xianshui He Fault. There were six $M \geq 6.9$ earthquake events between 1893 and 1981. However, no $M \geq 5$ events have occurred on the fault since 1981. Because of its high slip rates and frequent earthquakes, the Xianshui He Fault has been the focus of attention within the seismological community (Gang & Mian 2010).

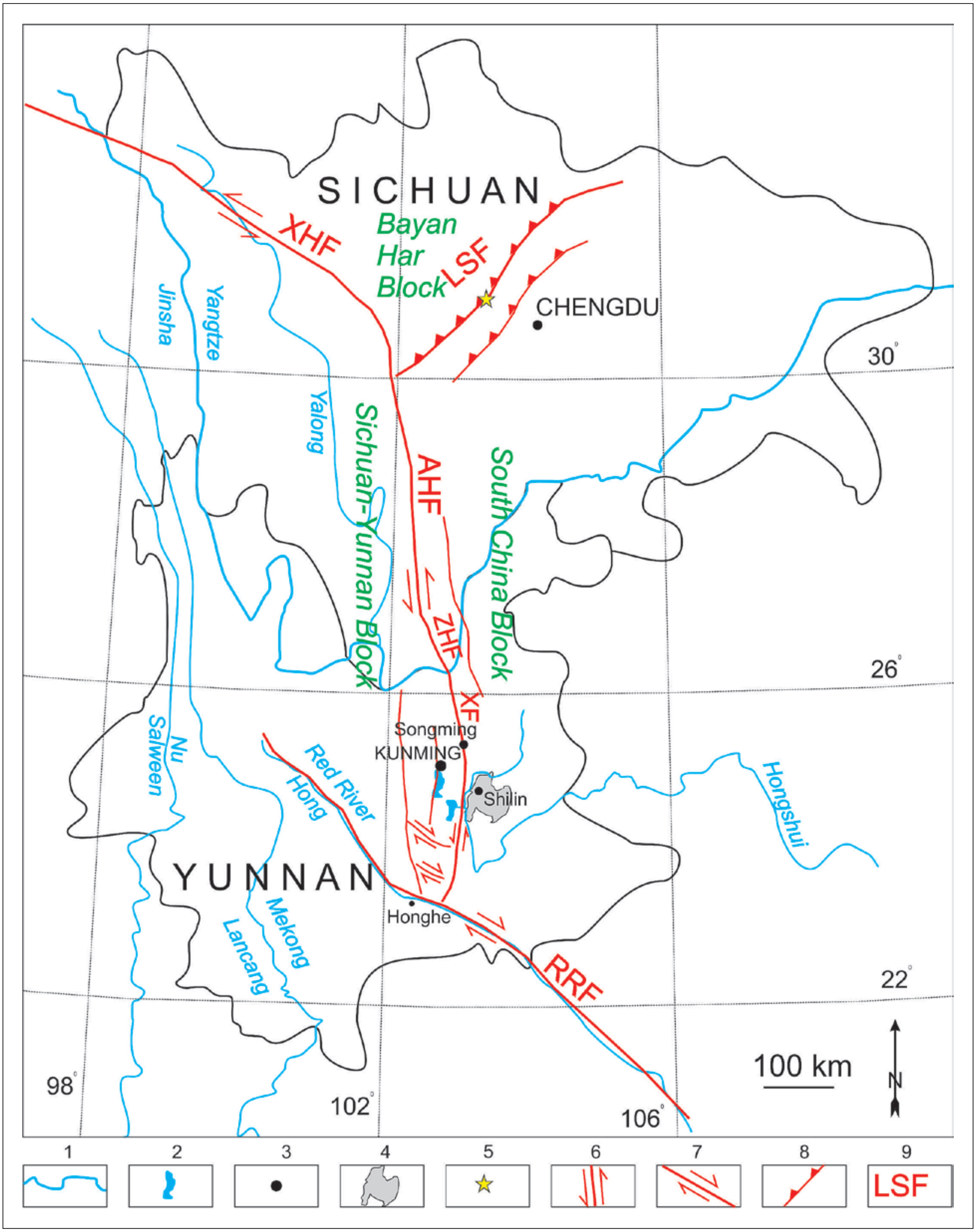

Fig. 1: Structural-geological position of Shilin County in Yunnan Province, south China. 1– river, 2– lake, 3– town, 4– Shilin county, 5– 2008 Wenchuan earthquake, 6– sinistral horizontal strike-slip fault, 7– dextral horizontal strike-slip fault, 8– thrust fault, 9– faults (LSF– Longmen Shan Fault, XHF– Xianshui He Fault, AHF– Anning He Fault, ZHF– Zemu He Fault, XF– Xiaojiang Fault, RRF– Red River Fault).

Major earthquakes along the Xianshui He Fault zone all occurred within the region with positive Coulomb failure stress change, except for Zhuwo earthquake in 1967. In other words, the occurrence of major earthquakes along the Xianshui He Fault zone influences the occurrence of subsequent earthquakes (Wang *et al.* 2008).

The Xianshui He-Xiaojiang Fault zone and the Longmenshan Fault zone divide this region into 3 tectonic blocks: the Sichuan-Yunnan Block, the Bayan Har Block and the South China Block. The Xianshui He-Xiaojiang fault is also one of the most active fault zones in Chinese mainland. Although present-day activity in the Longmenshan fault zone is weak, the seismogenic fault produced the $Ms = 8.0$ Wenchuan earthquake (Fig. 1) on 12 May 2008 (Wang *et al.* 2010). The arc-like Xianshui He-Xiaojiang Fault system extends for 1500 km within Qinghai, Sichuan and Yunnan province and ends at point north of the Red River Fault zone (He & Yasutaka 2007).

The Anning He-Zemu He-Xiaojiang Fault system, also called the Xiaojiang Fault system is the southward continuation of the Xianshui He Fault. Geological and GPS slip rates are 5–10 mm/year along the northern segments and 4 mm/year along the southern segments. More than ten $M > 6$ earthquakes have occurred along the Xiaojiang Fault system in the past 500 years; the largest one was the 1833 M 8.0 Songming earthquake on the central segment of the Xiaojiang Fault. After the 1850 M 7.5 Xichang earthquake, three M 6.5–6.8 earthquakes occurred on this fault system in 1909, 1952, and 1966 (Gang & Mian 2010). The average sinistral strike-slip rate on the Anning He Fault since the Late Pleistocene is about 3–7 mm/a (He & Yasutakyr 2007).

The Kunming basin is a new generation faulted basin, which is controled by active north-south trending faults. Stress fields in the region of Kunming had two major stages. In the first stage (from late-Pliocene to mid-Pleistocene) the tectonic stress field was characteristic of nearly E-W compression and nearly N-S extension. In the second stage (from late-Pleistocene to the present) the tectonic stress field has been mainly consistent with NNW-SSE compression and NEE-SWW extension (Yi *et al.* 2010).

The Kunming basin is the largest Quaternary-inherited downfaulted basin in the Yunnan-Guizhou plateau, where the strata deposited in Quaternary are characterized by large variations of thickness and complicated facies. The Quaternary tectonic activity of the Xiaojiang Fault zone is characterized by strong sinistral strike slip (Wang *et al.* 2009).

During the late Cenozoic, inhomogeneously distributed extension has been expressed by numerous Quaternary basins along the southern part of the Xianshui He-Xiaojiang Fault system (Fig. 1). Quaternary basins and lakes north of Dali and within the southern part of the Xiaojiang Fault zone are areas of local active extension (Wang & Burchfield 2000).

The Pliocene-Quaternary sedimentary fill in pull-apart basins associated with the left lateral Xianshui He-Xiaojiang Fault system indicates that this structure was initiated by at least 2–4 Ma ago (Wang *et al.* 1998).

Xianshui He-Xiaojiang Fault is left lateral structure. There is southwestward extrusion from eastern Tibetan Plateau and clockwise rotation around the Eastern Himalayan Syntaxis of the rhomboid-shaped Sichuan-Yunnan block, which is moving faster than the plateau. The Xiaojiang Fault zone has N-S strike and a total length of 400 km in Yunnan Province. The Xiaojiang Fault zone is exhibiting significant neotectonic activity. Since the end of Late Pleistocene the strike slip rate has been found to be about 6 mm/yr along the southern segment of the eastern branch of Xiaojiang Fault zone (Paradisopoulou *et al.* 2007).

The crustal structure shows remarkable contrasts between the two sides of the Xiaojiang Fault zone. The crust to the east of the Xiaojiang Fault zone presents characteristics of crustal structure in a stable platform, while the crust to the west is complicated with a lower velocity zone in middle of the upper crust. It is inferred that the Xiaojiang Fault zone has cut through the entire thickness of the crust (Wang *et al.* 2009).

Assuming that the slip rate of 15±2 mm/yr is constant throughout the entire history of the Xianshui He-Xiaojiang Fault system, 11±1.5 Ma is needed for the Xianshui He-Xiaojiang Fault system to attain the 160 km of total offset. This implies that left-slip faulting on the Xianshui He-Xiaojiang Fault system might have started at 11±1.5 Ma (He *et al.* 2006).

The Longmen Shan Fault zone is the boundary between the Tibetan Plateau and the rigid South China Block. The loading rate on the Longmen Shan Fault is lowered when the Xianshui He Fault experiences clusters of big earthquakes (Gang Luo & Mian Liu 2010).

Crustal motion in the western Sichuan area presents a clockwise rotation around the Eastern Himalayan Syntax. The crust moves southward in the interior of Sichuan-Yunnan Block, and moves southwestward in the southwest Yunnan region (Wang *et al.* 2010).

The focal mechanisms of the 1966 earthquakes on the N-S striking Xiaojiang Fault (Fig. 1) imply left-lateral slip along it. A normal component of slip on the roughly N-S faults south of Kunming has created several Quaternary half-grabens, some of them filled by lakes (Tapponier & Molnar 1977).

The 12 May 2008 Wenchuan earthquake ruptured about 300 km of the Longmen Shan Fault (Fig. 1) in the eastern Tibetan Plateau. In spite of stress increase from the Wenchuan earthquake, the southeastern segments of the Xianshui He Fault stay in a stress shadow because of the stress release by six $M \geq 6.9$ events in this part of the Xianshui He Fault since 1893 (Gang & Mian 2010). The Great Wenchuan earthquake came as a surprise, because that part of the fault has low fault slip rates, which are less than 3 mm/year, one order of magnitude lower than slip rates on the Xianshui He Fault and other major faults in eastern Tibet (Gang & Mian 2010).

METHODOLOGY

Detailed structural geological mapping was accomplished in the studied area, including the area of Major Shilin (0.7 km²) and selected caves (Jibailongdong, Dieyundong, Zhiyundong, Baiyun cave, Guanyindong, Xinshidong, Niubizidong, Xifenlandong and Shimalogdong). Fissure orientations were analysed by RockWare softwear and presented by rose diagrams at 10 degree class intervals. Cave passage orientations were weighted according to speleological maps, analysed by RockWare softwear and presented by rose diagrams as well. Finally, the obtained results were compared with regional structural geological conditions and active tectonic situation regarding studied references.

RESULTS

MAJOR STONE FOREST

The Major stone forest (Figs. 2, 3 and 4) is one of the best known tourist sites in Yunnan. It is situated about 80 km southeast of Kunming (Fig. 1). Shilin is a type of pinnacle karst formed on a plateau of gently dipping limestone (Knez & Slabe 2002). Subsoil karren and stone forests are one of the most characteristic features of the karst surface in Yunnan. Carbonate rocks are in many places covered by thick sediments under which subsoil karren developed into stone forests (Knez & Slabe 2010).

Stone forest refers to a particular karst landscape, composed of a group of densely distributed limestone columns standing on an undulating karst plateau. The columns are usually 10 m high, with their upper part decorated with sharp karren. The formation of rocky columns is closely related to the subsoil dissolution by the CO_2-rich vadose water (Xie & Li 1995–1999).

The main strata in the Major stone forest area include carbonate rocks of the Qixia Formation and Maokou Formations of Lower Permian age. These units average 505 m thick and consist of shallow sea platform facies, massive dolomites, bioclastic limestones, calcarenites and calcilutites. Most of the carbonate rocks in the area are coarsely crystalline, which makes dissolution relatively easy (Chen *et al.* 1998). Basalts of the Late Permian age (Song & Liang 2009) and red mudstones, siltstones, sandstones and conglomerates of the Tertiary age, constitute the cover of karst terrain (Xie & Li 1995–1999).

The strata are part of a westward dipping (2–6°) monocline. Conjugate shear joints (NE-SW and NW-SE) are well developed and these fractures provided the main passageways for surface water and underground water in the pre-karst development stage. The distribution, density and orientation of the fractures controlled the depth, size and orientation of the karst topography.

The Shilin karst area covers 350 km². Around 70 caves (Fig. 2) have been explored from 1995–2000. They can be classified into three types. The first are fracture-like caves, formed by enlargement by water along fractures. The second types, horizontal caves, are mainly developed in the Fengcong (peak cluster) shallow depression landscape areas, adjacent to the Shilin landscapes. The third types, slope caves, are mainly distributed at Fengcong-depression karst areas or hillsides of lower mountains, where ground water table is around 100–150 m deep. Generally cave development in Shilin area has five characteristics. (1) Cave development is mainly concentrated in three elevation zones. (2) The development of caves is strongly controlled by the lithology of carbonate rocks. Most caves developed in Permian and Carboniferous carbonates. (3) Small (some 10 m long) and medium (some 100 m long) scale caves dominate. (4) Most caves have active water flow. (5) The orientation of cave passages is obviously controlled by structural orientation of fissures. There is a great difference between caves of the east and west part of the region. In west the orientation of caves is dominantly

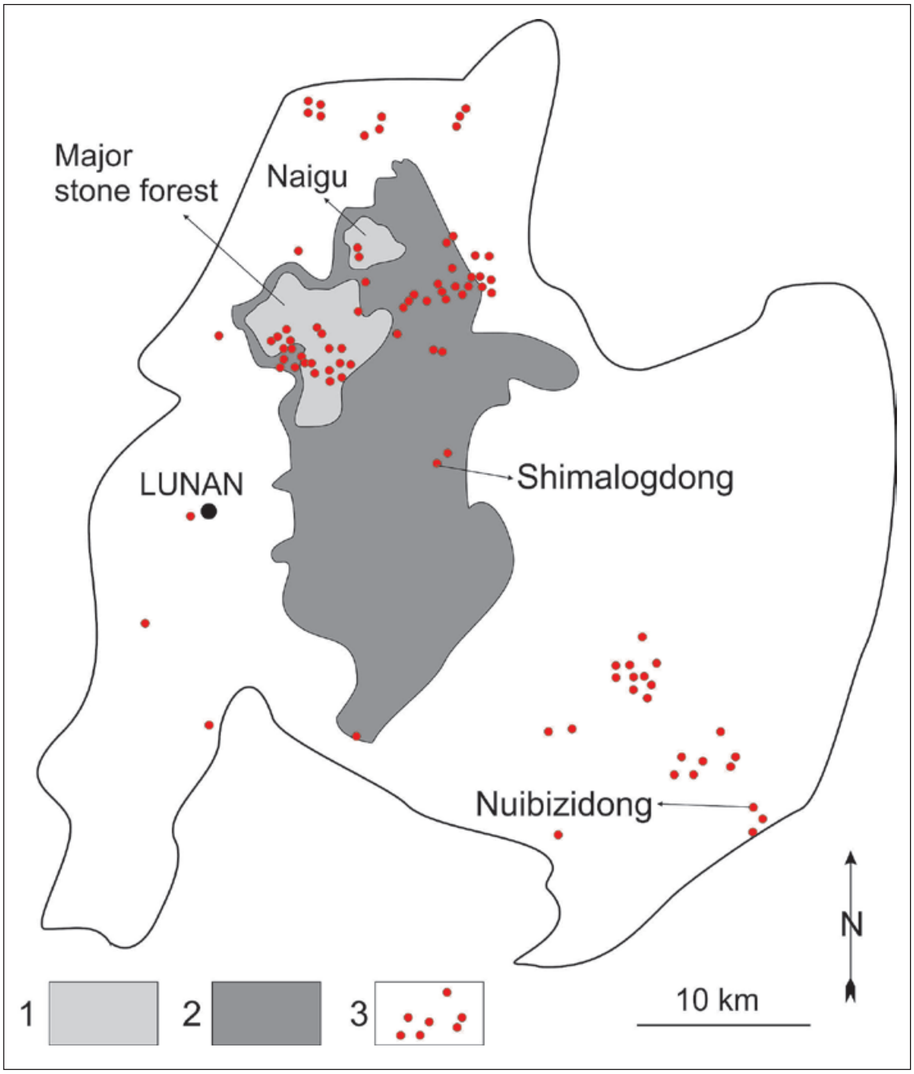

Fig. 2: Protected karst areas of Shilin County. 1 – 1st and 2nd class protected area (Major and Naigu stone forests), 2 – 3rd class protected area, 3 – karst caves (after Knez et al. 2011).

N-S or near N-S direction. But in the east the W-E or near W-E orientation predominates (Liu & Yan 2003). Song & Liang (2009) presented two evolution models of Shilin landscapes. In first model the shilin landscape on karst hilltops is guided by spacing of fractures, where soil and residuum are very thin. The second model represents shilin development in the basalt area that covers palaeokarst features. Karst development in limestone

Fig. 3. Major stone forest (Photo: S. Šebela).

Fig. 4. Major stone forest (Photo: S. Šebela).

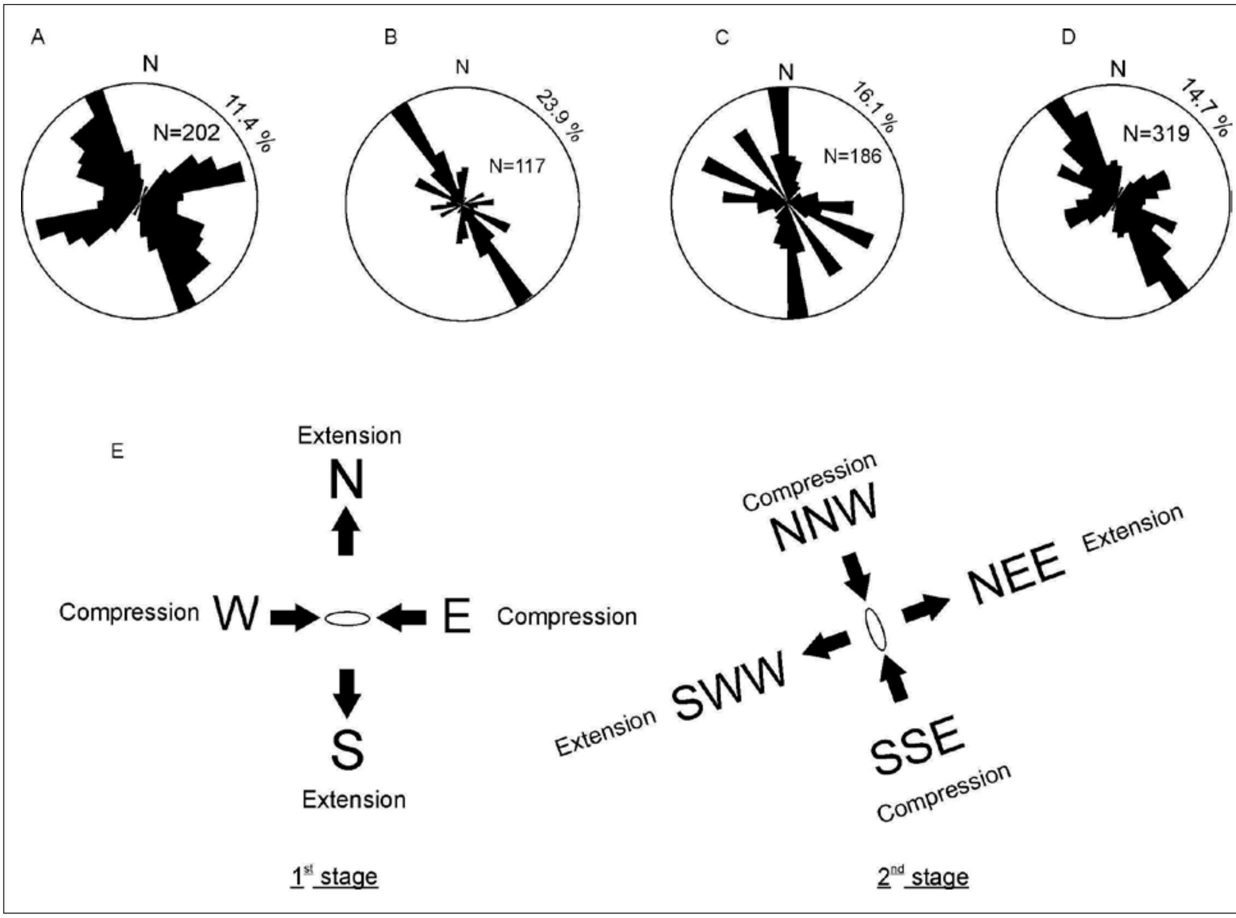

Fig. 5: Rose diagrams with 10° class intervals. A – Fissure orientations at the Major stone forest, B – Fissure orientation of cave passages (Jibailongdong, Dieyundong, Zhiyundong, Baiyun Cave), C – Passage orientations of caves (Jibailongdong, Dieyundong, Zhiyundong, Baiyun Cave, Guanyindong, Xinshidong, Niubizidong, Xifenlandong and Shimalogdong), D – Fissure orientations of the Major stone forest and caves (Jibailongdong, Dieyundong, Zhiyundong, Baiyun Cave), E – Quaternary tectonic stress field (1st stage – late Pliocene-mid Pleistocene; 2nd stage – late Pleistocene-present, after Yi et al. 2010).

under the basalt is stronger than in soil-covered limestone (Song & Liang 2009; Ginés *et al.* 2009).

The Major stone forest is situated at about 1750 m above sea level and Naigu stone forest at 1820 m above sea level (Fig. 2). Main geomorphological types are plateau hills, low mounts, depressions, basins, stone hillocks, stone forests, fields of "stone teeth", lakes and river valleys (Xie & Li 1995–1999).

The results of detailed structural geological field mapping of Major stone forest are presented as rose diagrams (Fig. 5, A). The prevailing fissure orientation at Shilin is N20–30°W and represents 11.4%. The second most frequent is the direction N70–80°E (11%). Generally there are two prevailing fissure orientations, the most represented NW–SE and the second-one NE–SW (almost close to E–W).

Limestone bedding-planes in Major stone forest are mostly subhorizontal or dip at a 5° angle. There are some gentle anticlines.

SELECTED KARST CAVES OF THE SHILIN COUNTY

In the vicinity of the Major stone forest, we studied nine karst caves (Jibailongdong, Dieyundong, Zhiyundong, Baiyun cave, Guanyindong, Xinshidong, Niubizidong, Xifenlandong and Shimalogdong, Fig. 6) and performed structural geological mapping of four caves (Jibailongdong, Dieyundong, Zhiyundong, Baiyun cave (Šebela *et al.* 2001; Šebela *et al.* 2004)). Karst caves are found below densely packed pinnacles. Rose diagrams of cave passage orientations are presented for 6.2 km of cave passages.

DIEYUNDONG

The northern cave entrance is situated at 1715 m above the sea. The cave is 280 m long (Fig. 6). At the SE part of the cave the bedding-planes dip at 5° towards south and the rock is mostly Permian thick-bedded limestone.

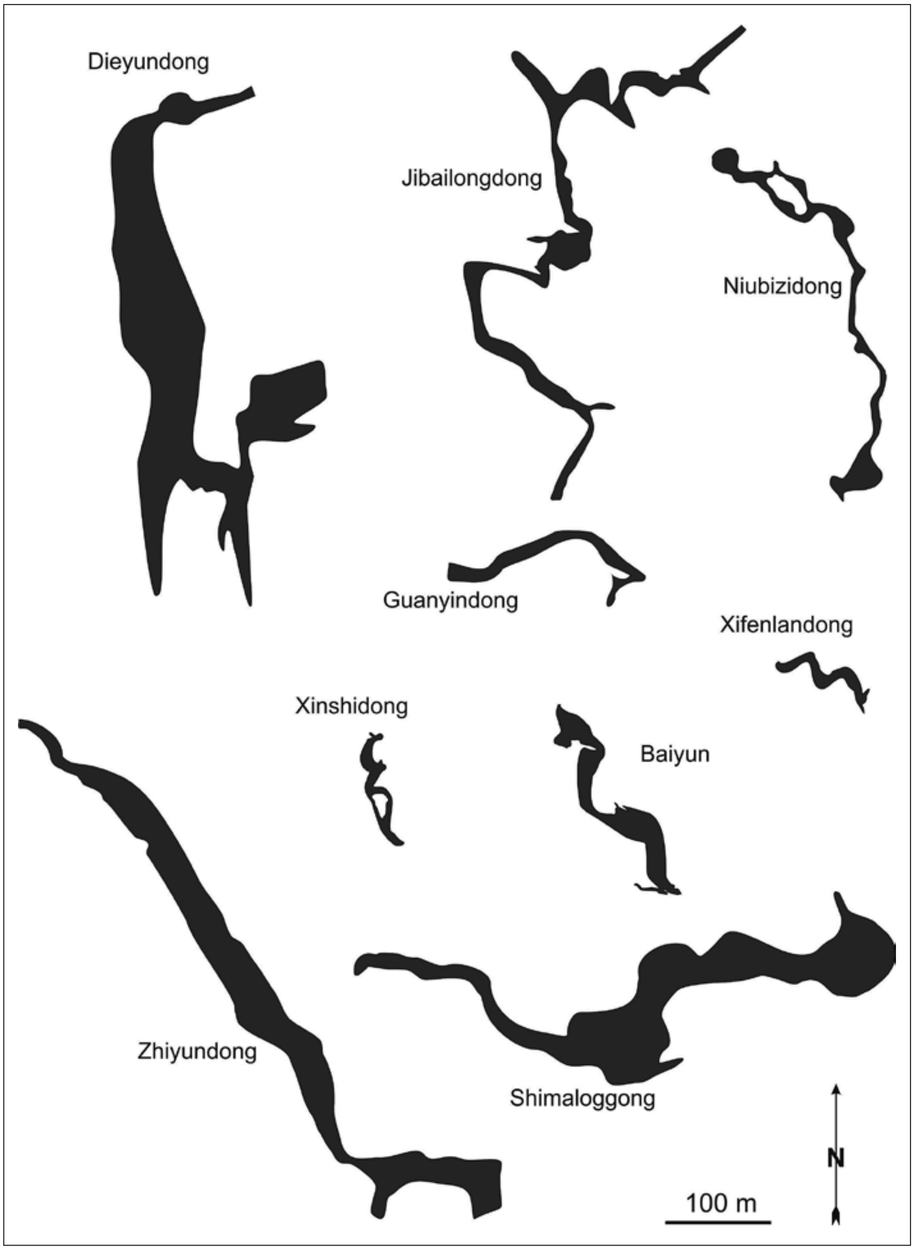

Fig. 6: Studied caves ground-plans (maps are not in the actual relative location with respect to one another).

The most frequent passage orientation is N0–10°W (48.7%), the second direction is N0–10°E (23%) and the third direction is N50–60°E (15%). Prevailing fissures are oriented N0–10°E (40.9%) and N0–10°W (35%). Passages and fissures are prevailingly oriented in the direction N–S (Šebela *et al.* 2004).

JIBAILONGDONG

The cave (1730 m above the sea) is 460 m long (Fig. 6). The passage is developed mostly in Permian thick bedded limestone. The dip angle of the bedding-planes is 0–5° mostly towards NW, and in southern part also towards SE. In the cave three main passage directions are observed: N0–10°W (21.9%), N50–60°W (17%) and N80–90°E (9%). The passage runs in the general directions of N–S and NW–SE. The most frequent fissure orientation measured in the cave is N60–70°W (35%), the second direction is N10–20°W (20%) and the third one is N30–40°W (15%). The prevailing fissure orientation is NW-SE (Šebela *et al.* 2004).

ZHIYUNDONG

The general passage orientation is NW–SE (Figs. 6 and 7). The cave is 360 m long and situated 1755 m above the sea. The predominant thick-bedded Permian limestone dips towards W and NW at 5°. Along the 172°/90°

joint at northern part of the cave a small (0.5 cm) dextral horizontal strike-slip movement was determined. Most fissures run in NW–SE direction. The most frequent orientation of the passage is N30–40°W (47.1%), in the second place are two directions N90–100°E (16%) and N60–70°W (16%). Most fissures in the cave are oriented N40–50°W (35.7%) and N50–60°W (28%) (Šebela *et al.* 2004).

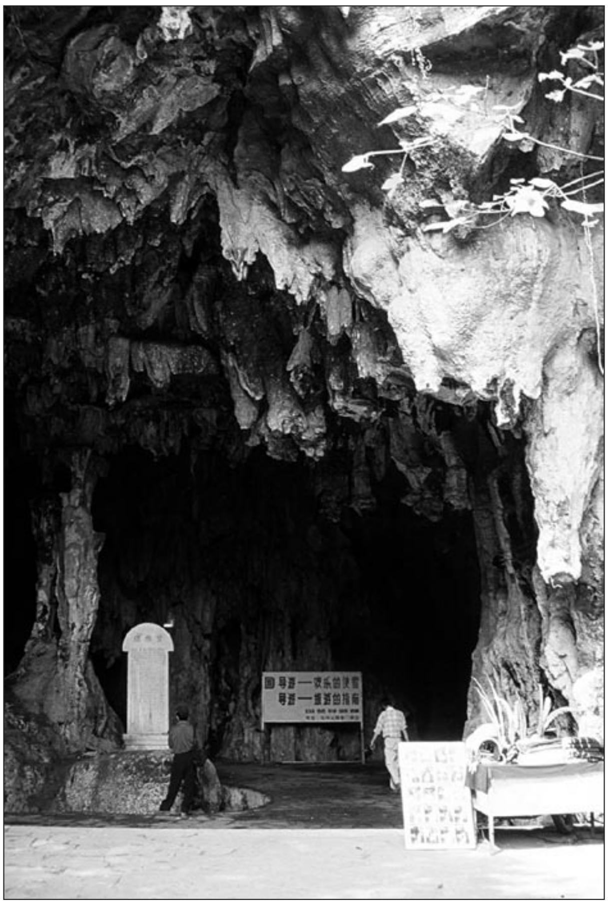

Fig. 7: Zhiyundong entrance (Photo: S. Šebela).

GUANYINDONG

The cave is situated about 10 km NE from the Major stone forest. It is 240 m long and represents an active ponor cave (Fig. 6). The prevailing passage direction is N60–70°E (29.4%), the second direction is N40–50°W (24%) and the third N80–90°E (17%). There are two principal fissure orientations N–S and almost E–W. Permian limestones dip for 5–10° mostly towards SE.

BAIYUN CAVE

Baiyun Cave is situated inside the Naigu stone forest (Figs. 2, 6 and 8), which covers an area of 8 km^2 and is developed in the dolomite and limestone of the Permian Qixia formation. There are unique shapes like mushrooms, resulting from the differential dissolution of the different lithologies.

The cave is situated at an altitude of 1700 m. The general direction of the cave is NW–SE. The passage is up to 25 m wide and 380 m long. The prevailing fissure direction in the cave is N30–40°W (36.1%). The second prevailing direction is N20–30°W (23%). Regarding the tectonic situation, the Baiyun Cave is situated about 20 km east of the Xiaojiang fault system (Fig. 1), which runs in the general direction N–S. The cave has 36.6% of its passages in the direction N0–10°W, and in second place 27% in the direction N110–120°E.

The prevailing fissure direction and prevailing direction of cave passages of Baiyun Cave do not compare well (Šebela *et al.* 2004).

Fig. 8: Naigu stone forest (Photo: S. Šebela).

XINSHIDONG

The cave (Fig. 6) is situated at the SE corner of Naigu stone forest at 1785 m above the sea and has 175 m of passages developed in Permian limestones. At the northern entrance the beds dip for 5° towards NW. The prevailing passage orientation is N20–30°W (25%), the second is N20–30°E (21%) and the third is N10–20°E (18%). The cave walls have been covered by cave sediments and fissures are not well detected.

The rose diagram for combined fissure orientations for four caves (Jibailongdong, Dieyundong, Zhiyundong, Baiyun Cave) includes a population of 117 measurements (Fig. 5, B). The maximum percentage of 23.9% belongs to the N30–40°W direction, 13% has a N20–30°W direction and 11% belong to N60–70°W. The N-S direction (N0–10°W) represents 6% and direction N0–10°E is 7%. The standard deviation is 5.84% and confidence interval 13.67°.

DISCUSSION

These basic statistics, giving the most frequent directions of studied cave passages (Fig. 5, C) at the distribution intervals of 10°, indicates that most passages (16.1%) have developed in the direction of N0–10°W. The second most prevalent direction is N60–70°W (13%) and the third N30–40°W (12%). The interval of confidence is 27.12°, with a standard deviation of 4.29%. The results represent the most frequent directions for nine studied caves (Jibailongdong, Dieyundong, Zhiyundong, Baiyun Cave, Guanyindong, Xinshidong, Niubizidong, Xifenlandong and Shimalogdong; Fig. 6).

Field structural geological mapping showed that in some cases cave passages run along fractures. In this manner, we were able to follow a well-defined fracture in the ceiling of Zhiyundong running in a NW-SE direction. The fractures in the cave ceiling are mainly subvertical. The main passage in Dieyundong, running in the direction N0–10°W, corresponds to the direction of the ceiling fracture. Clear slickensides in studied karst caves are rare. The clearest one studied in this project is visible in Zhiyundong, where along the subvertical almost E–W oriented fissure (dip direction 172°) a small (0.5 cm) dextral horizontal strike-slip movement was determined.

To get the better general view of the fissure orientations in the studied area we united the data obtained from Major stone forest (Fig. 5, A) and from four structural-geologically mapped caves (Jibailongdong, Dieyundong, Zhiyundong, Baiyun Cave; Fig. 5, B). Combined data for 319 fissures are presented on Fig. 5, D. Combining fissure populations gives representative view of the fissure orientation on the karst areas in Shilin County (on the surface and in underground). The prevailing fissure orientation is NW–SE (N30–40°W = 14.7%, N20–30°W = 11.8%, N40–50°W = 9.5%), and the second orientation is NE-SW (N60–70°E = 7.5%, N70–80°E = 7.5%).

It is interesting that in the Major stone forest (Fig. 5, A) less than 4% of surface fractures lie in a N0–10°W direction whereas this is the most frequent (16.1%) direction of all studied cave passages (Fig. 5, C). Otherwise, the direction N30–40°W, which is the most frequent for united fissures data (14.7%; Fig. 5, D) represents 12% of cave passages orientation (Fig. 5, C).

The stress field in the region has had two major stages. From late Pliocene to mid-Pleistocene the tectonic stress field was characteristic of nearly E-W compression and nearly N–S extension (Yi *et al.* 2010). The most frequent cave passage orientation (Fig. 5, C) in the direction almost N–S has to be connected with this tectonic episode. In the second stage from late-Pleistocene to the present the tectonic stress field has mainly been characteristic of NNW–SSE compression and NEE–SWW extension. This second stage is in accordance with the most frequent fissure orientations in Major stone forest in the direction N20–30°W (11.4%), representing the orientations of the surface karren karst features. The formation of karst underground and surface features depends on regional tectonic deformations on Cenozoic extension of the studied area.

CONCLUSIONS

Detailed structural-geological mapping was carried out in Major stone forest and in 9 karst caves (Jibailongdong, Dieyundong, Zhiyundong, Baiyun Cave, Guanyindong, Xinshidong, Niubizidong, Xifenlandong and Shimalogdong, Fig. 6) in the Shilin County. Field measurements of fissures, bedding-planes, and cave passage orientations were accomplished (Fig. 5). In the studied caves the bedding-planes are mostly subhorizontal, and in most cases the caves are formed within massive or thickbedded Permian limestone or dolomitic limestone. The bedding-plane dip angle generally does not exceed 5°. Gentle folds, such as an anticline in the Jibailongdong, are present. It has been pointed by Sweeting (1995) that the structures in the limestones of the Major stone forest are open synclines and anticlines.

Statistical evaluation of the most frequent directions of passage orientation (Fig. 5, C) and fissure orientation in caves (Fig. 5, B) is illustrated by rose diagrams. The best comparison between passage and fissure orientation is the example of Dieyundong (Fig. 6), where the passage is significantly developed along N–S trending fissures and joints.

The data, including all nine studied caves (Fig. 5, C), show that most (16.1%) passages are oriented in the direction N0–10°W, being followed by the directions N60–70°W (13%) and N30–40°W (12%). The most frequently (23.9%) oriented fissures from four mapped caves are evaluated in a N30–40°W direction (Fig. 5, B), which is the third common orientation of nine studied cave passages.

The most prevailing cave passage orientation in N-S direction is parallel to closest Xiaojiang Fault, and the general direction NW–SE of the fissures orientation (underground and surface, Fig. 5, D) to southern more distant Red River Fault (Fig. 1). Both faults are active faults and development of karst features (stone forest and caves) is connected with active tectonics of central Yunnan.

Considering that the region around Kunming is still tectonically active (Wang & Burchfield 2000) and considering the age of cave sediments in the Baiyun Cave (112,300–117,900 years; Šebela *et al.* 2004) and several older periods of the cave development we can rank this cave and probably many others at least in the Upper Pleistocene (less than 780,000 years).

In the vicinity of the Major stone forest (Fig. 1), in a diameter of 30 km, all 9 karst studied caves are formed below shilin karst topography. Yu and Yang (1997) determined from absolute age analysis of related secondary carbonate accumulation that the earliest modern shilin had begun to evolve in the Naigu region, where the Baiyun Cave is situated, in the late Pliocene (about 2 Ma).

The most frequent cave passages orientation (Fig. 5, C) in the direction almost N–S is connected with nearly E-W compression and nearly N–S extension from late Pliocene to mid-Pleistocene (Yi *et al.* 2010). The second tectonic stage from late-Pleistocene to the present with tectonic stress field mainly of NNW–SSE compression and NEE–SWW extension is in accordance with the most frequent fissure orientations in Major stone forest in the direction N20–30°W (11.4%), representing the orientations of the surface karren karst features (Fig. 5, A).

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