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Study On The Development Patterns And Influencing Factors Of Karst In The Dalongtan Spring Catchment Area, Huaning County, Yunnan Province

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Abstract:
The Dalongtan Spring Catchment Area is located in the sloping zone between the Nanpan River and Dianxi River, characterized by complex geological structures and intense karst development. In this study, various methods such as data collection, field surveys, hydrochemical experiments, and connectivity tests were employed to systematically analyze the karst development characteristics of the study area, including lithology, geological structures, topography, and hydrodynamic conditions. The research revealed that karst features such as dissolution channels and stone teeth are well-developed. The study area is situated in the sloping zone between the Nanpan River and Dianxi River, with significant terrain undulations in the northeast. The groundwater circulation is rapid and dynamic, leading to strong karst processes. Due to crustal uplift, the Nanpan River valley has undergone deep incision, resulting in steep slopes. Surface water on both sides of the valley infiltrates rapidly through fractures or swallow holes. Therefore, karst hills and depressions, peak clusters, sinkholes, and karst shafts are mainly developed in the northeastern part of the study area. Karst development is primarily controlled by stratigraphic sequences, followed by lithology. The Permian Qixia Formation (P1q), Maokou Formation (P1m), Carboniferous Datang Formation (C1d), Weinong Formation (C2w), and Maping Formation (C3m) exhibit continuous distribution of limestone and pure dolomite. These carbonate formations have thick aquifers, leading to intense karst development. The Devonian Qujing Formation (D2q) and Zaishan Formation (D3zj) exhibit continuous distribution of dolomite, with a presence of minor shale and marl, resulting in strong karst development, rounded mountain tops, and prevalent stone teeth slopes on the surface. The Devonian Xuanwutian Formation (D2x) and Yidadu Formation (D3y) have interbedded distribution of dolomite, marl, and sandstone-mudstone, with relatively poor continuity of aquifers, resulting in comparatively weaker karst development. Sparse outcrops of carbonate rock formations are observed on the surface, and the valleys exhibit typical V-shaped characteristics with rounded mountain peaks. Shallow and wide valleys and saucer-shaped depressions are common features.

Keyword: *Karst development patterns, Influencing factors, Panxi Dalongtan*

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I. INTRODUCTION

The karst distribution area in Yunnan Province is $11.09\times10^4 km^2$, accounting for 28.14% of the province's total area. Among the 128 counties (cities, districts) in the province, karst is found in 115 counties, with karst areas ranging from 30.0% to 96.6% in 60 counties (cities), totaling 94,100 square kilometers. Among the 31 impoverished counties, the karst area covers 54,300 square kilometers. In 1994, the 60 karst counties (cities) had a population of 22.44 million, accounting for 56.9% of the province's total population, including nearly 5 million ethnic minorities（WANG Y 2001）. Karst regions exhibit a typical dual-layer structure of surface and underground, and the combination of karst landforms reflects the comprehensive manifestation of geological processes such as geological background conditions, crustal uplift, tectonic movements such as faulting and folding, and erosional processes including dissolution and erosion. Specific combinations of karst landforms can reflect the development process and characteristics of underground karst, as well as the movement and occurrence of groundwater, making them useful indicators for identifying and delineating groundwater-enriched zones(WANG Y,WANG ZW 2015). Landforms are the comprehensive products of internal and external geological processes occurring within a specific geological and geographical background, and specific landforms leave traces of their formation conditions and the effects of internal and external geological processes. Therefore, through investigation and analysis of landforms and their combinations, it is possible to trace the formation process of landforms and analyze the transformation and results of surface and subsurface runoff processes. Karst landform combination refers to the combination of closely related karst landforms in terms of their genesis(YUAN DX 1991). In the karst region of the southwestern subtropics, landform combinations are a group of landforms primarily formed by surface and subsurface water erosion, serving as records and representations of the historical and current activities of groundwater. They provide more accurate reflections of the types of aquifers and the formation, movement, and occurrence characteristics of karst water, offering effective bases for karst water exploration（WANG Y 2010）. Research on karst development patterns and erosion mechanisms shows that karst development is stronger near fold axes, inflection ends, and fractured zones, and the degree of erosion is closely related to the soluble rock composition, purity, and thickness of rock layers（YUAN DX 1992,MIU S X et a2017, WANG T et al 2007）. Erosion rate is positively correlated with the acidity, temperature, and hydrodynamic conditions of water solutions（ZHOU B etal 2017,JI S S et al 2017, WANG Z M et al 2016). From different scales, karst exhibits selective erosion at the water-rock interface（CHEN W C et al 2017, WANG T J et al 2000, ZHANG Kuan et al 2019). Erosion starts at intercrystalline surfaces and develops along joints and fractures, forming localized dissolution cavities（BERNER R A 1978, ZHANG A et al 2014, PENG J 2018).

Panxi Dalongtan (also known as Qixi Tan) is located in Panxi Town, Huaning County, Yuxi City, Yunnan Province. It is the largest karst plateau groundwater system in Yunnan and a prominent representative of the karst stone mountain region in Southwest China. It serves as an important drinking water source for the eastern area of Yuxi City and its surroundings. Due to the dual-layer structure and complex hydrogeological characteristics of karst water, the pollution prevention capacity of groundwater is relatively weak. There is a significant lack of research on the fundamental conditions and karst development patterns that contribute to the formation of the karst water system. Karst landforms, as one of the fundamental conditions for the formation, movement, and occurrence of groundwater, are indispensable in hydrogeological surveys and research. The research results can reveal the movement patterns of groundwater, distribution of water resources, and recharge mechanisms, which are of great significance for hydrogeological investigations and water resource management.

II. OVERVIEW OF THE STUDY AREA

The majority of the recharge runoff area in the study area is located within Mile City, while the spring outlet discharge area is situated at the foot of Guabang Mountain in Panxi Town, Huaning County, Yuxi City. This area is also known as Qixi Tan and spans the boundary region of Huaning County, Mile City, and Jianshui County.The study area falls within the subtropical monsoon climate zone and is influenced by the warm air currents from the Indian Ocean. It enjoys a moderate climate with adequate rainfall. The average annual temperature is 16.9°C, with the highest temperature recorded at 36.1°C and the lowest at -4.3°C. Typically, May experiences the hottest weather, while January is the coldest. The average annual precipitation is 977.8 millimeters, with a maximum of 1251.5 millimeters in 1971 and a minimum of 724.9 millimeters in 1963. Over 80% of the precipitation is concentrated between the months of May and October.

The Nanpan River is the local lowest erosion base level. The western part of the study area belongs to the main stream valley of Nanpan River, while the eastern part belongs to the basin area of Dianxi River, a tributary of Nanpan River. Huaning Panxi Dalongtan runoff supply area is actually a river-intermediate land block between the main stream of Nanpan River and the tributary of Dianxi River on the western slope. Carbonate rock formations are continuously distributed in the area, with the main exposed formations being the Yangxin Formation (P_1y), which consists of limestone and dolomite. The Carboniferous Datang Formation (C_1d), Weining Formation (C_2w), and Maping Formation (C_3m) consist of limestone interbedded with dolomite, while the Upper Devonian (D3) consists of limestone, dolomite, and locally interbedded shale. The Yadetaz Formation (D_3y) is composed of limestone, argillaceous limestone, and shale, and the Middle Devonian Qujing Formation (D2q) consists of limestone, dolomite, argillaceous limestone, and shale. The Xuanwutian Formation (D_2x) is composed of sandstone interbedded with dolomite. The plateau surface is flat and has a width of 3-5 km, with an elevation of around 2000 m. The topography has small undulations, with a relative elevation difference of 30-100 m. In the vicinity of a few deep funnels, the elevation difference can exceed 150 m, and dense funnels and wide shallow depressions are common. The region is located near the intersection of the Xiaojiang Fault and the Mile-Shizong Fault, with well-developed fault systems. The main faults trend in a nearly north-south, northeast, and northwest direction, with basalt distribution along the near north-south fault zone. Overall, it exhibits an anticline extending in a nearly north-south direction.

III. KARST DEVELOPMENT CONDITIONS

Distribution and burial conditions of soluble lava

Soluble lava forms the material basis for karst development. Differences in rock sedimentary environments lead to variations in the composition, structure, tectonics, and thickness of the rocks, resulting in varying degrees of karst development in different geological strata. The study area is situated east of the

Xiaojiang Fault and north of the Mile-Shizong Fault. The exposed carbonate rocks primarily consist of Middle to Upper Devonian, Carboniferous, and Permian formations (Figure 1). The following is a description of these formations in chronological order, from the oldest to the youngest.

(1) Devonian Period

Cuifengshan Formation (D_1c): Consists of gray-green to dark gray fine sandstone, siltstone, and mudstone interbedded with shale and mudstone. It has a thickness of 789m.

Xuanwutian Formation (D_2x): The lower part comprises fine sandstone with occasional conglomerate or variable-sized sandstone at the base. The middle part exhibits interbedded dolomite and mudstone, while the upper part consists of sandstone and mudstone with significant lithological variations. Its thickness ranges from 99 to 366m.

Qujing Formation (D_2q): It can be divided into two segments: the lower Poxi segment (D_2qp) and the upper Sandaoqing segment (D_2qs).

① Poxi Segment (D_2qp): The lower part consists of dolomite, mudstone interbedded with argillaceous limestone and shale, while the upper part comprises bioclastic limestone, mudstone, and shale. It has a thickness of 832m.

② Sandaoqing Segment (D_2qs): The lower part is characterized by dolomite interbedded with mudstone, and the upper part consists of bioclastic limestone interbedded with mudstone. It has a thickness of 410m.

Yiddade Formation (D_3y): The lower part consists of mudstone, argillaceous limestone, and the upper part is composed of limestone interbedded with shale. It has a thickness of 336-540m.

Zaijieshan Formation (D_3zj): The lower part is mainly composed of limestone, with some limestone and mudstone interbedded. The upper part consists of bioclastic limestone interbedded with limestone and mudstone. It has a thickness of 160-300m.

(2) Carboniferous Period

Datang Formation (C_1d): The lower part consists of fine silty sandstone, shale, and coal seams with a thickness of 0-60 meters. The upper part is composed of limestone and oolitic limestone interbedded with dolomite, with a thickness of 174-573m.

Weining Formation (C_2w): It is characterized by oolitic limestone interbedded with dolomite and micritic limestone, with a thickness of 166m.

Maping Formation (C_3m): The upper part consists of oolitic limestone, while the lower part is composed of micritic limestone and dolomite, with a thickness of 43-655m.

(3) Permian Period

Liangshan Formation (P_1l): It comprises quartz sandstone, siltstone interbedded with shale, with a thickness of 2.6-15m.

Qixia Formation (P_1q): This formation consists of limestone and chalky limestone, with a thickness of 30-59m. Maokou Formation (P_1m): It is characterized by massive limestone and limestone, with a thickness of 146-345m.

Geological structures

The study area is located in a segment between the Xiaojiang Fault and the Mile-Shizong Fault, both of which have exhibited multiple periods of activity, indicating a high level of tectonic activity. Overall, the area exhibits a predominantly north-south trending syncline, with well-developed faults along its flanks. The main fold structure in the area is the Daheshan syncline, which extends in a north-south direction. The western flank of the syncline has steeply dipping rock formations with angles ranging from 15 to 50 degrees, while the eastern flank has more gently dipping formations with dip angles generally below 30 degrees.

The study area is influenced by the activity of both the Xiaojiang Fault and the Mile-Shizong Fault, resulting in the presence of numerous faults of varying sizes (Figure 1). These intersecting faults have fragmented the rock formations along their paths and at their junctions. Several faults have a significant impact on the drainage and runoff supply in the Huaning Panxi Dalongtan area, including the northeast-trending Dalongtan Fault (F_1) and the northwest-trending Lime Kiln Fault (F_2), Dahetao Fault (F_3), Damaitan Fault (F_4), and Longli Fault (F_5), which intersect with each other. Additionally, the north-south trending Yanzizhai Fault (F_6) and Shegu Fault (F_7) are disrupted at their intersections.

Groundwater types and hydrodynamic conditions

Based on the characteristics of groundwater occurrence and aquifer properties, the main types of karst groundwater in the study area are pure carbonate rock and mudstone cave fissure water, as well as fissure water in carbonate rock interbedded with clastic rock and clastic rock interbedded with carbonate rock. These groundwater types primarily receive recharge from atmospheric precipitation. In the northeastern part of the study area, sinkholes are developed in areas such as Lanniqing, Yezhutang, Xiyi Town, Qifeicun, Wanhonglaozhai, and Shulongcun. In addition to recharge from atmospheric precipitation, there is also input from sinkholes, which act as the main conduits for vertical flow. The groundwater hydraulic gradient is relatively high in these areas, and flow occurs mainly through pipe and fissure networks.Influenced by factors such as topographic slope and hydraulic gradient, the infiltrated fissure recharge type is mainly distributed in the southwestern part of the study area. It primarily discharges towards the edge of the Panxi Basin in the form of underground rivers. Within the study area, groundwater primarily flows through pipe and fissure networks or karst fissures, and ultimately discharges in the form of large karst springs concentrated on the eastern edge of the Panxi Basin.

According to long-term monitoring data, the annual average flow rate of Dalongtan Spring in Panxi is 8.463 m3/s, with a maximum flow rate of 16,078.5 L/s and a minimum flow rate of 3,327.8 L/s. The maximum flow rate is 4.83 times higher than the minimum flow rate. The dynamic behavior of the groundwater is categorized as meteorological-type with abrupt changes (Figure 2). From the dynamic curve graph, it can be observed that during the rainy season, the spring flow rapidly increases, forming broad peaks during the main flood season from July to September. After the main flood season, the spring flow quickly decreases in October and November. From December to May of the following year, the spring flow gradually declines.

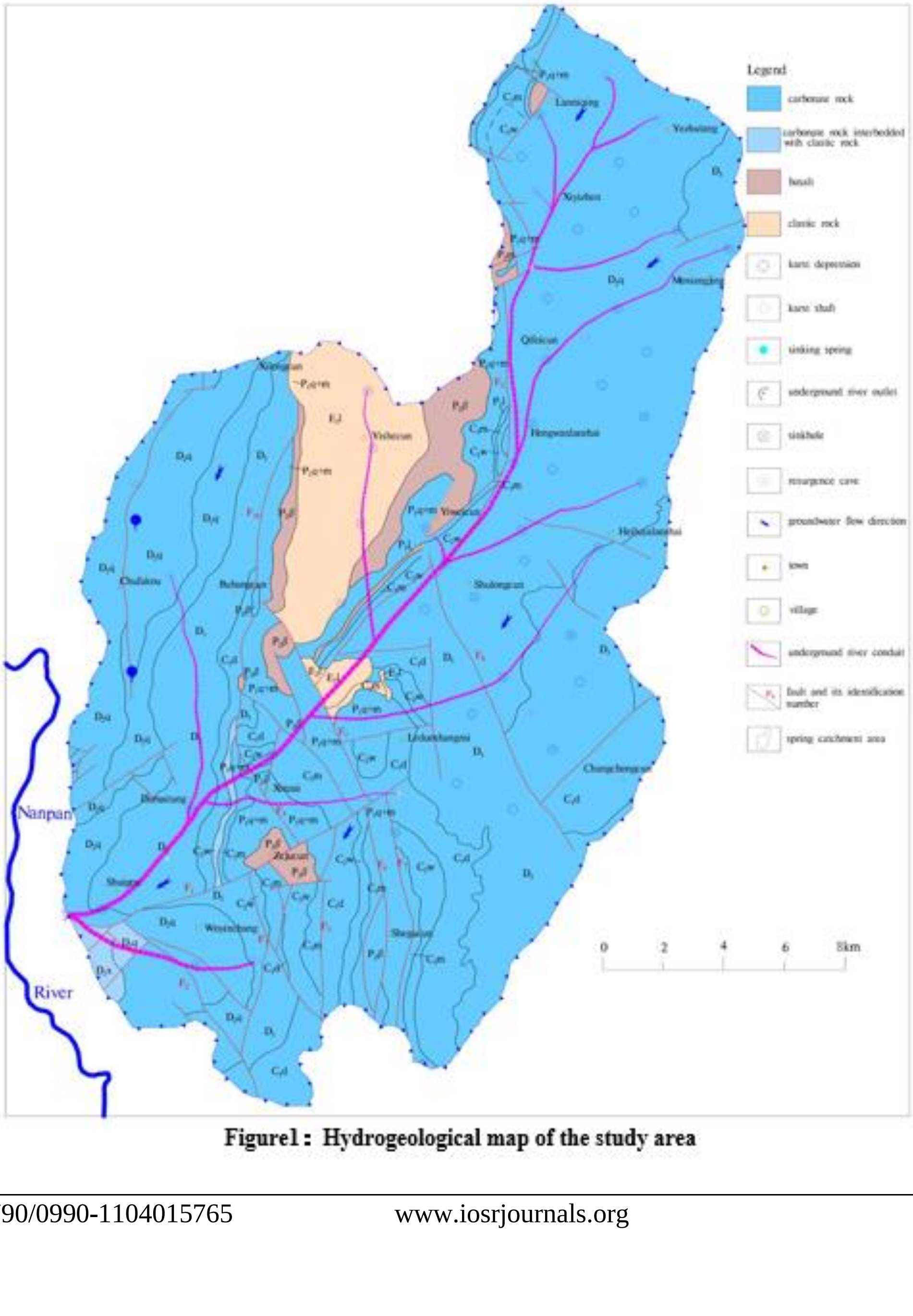

Figure1 : Hydrogeological map of the study area

IV. KARST DEVELOPMENT CHARACTERISTICS INFLUENCING FACTORS

Karst development patterns

The study area is located in the slope zone between the Nanpan River and the Dianxi River, particularly with significant terrain variations in the northeastern part. The groundwater circulation is fast and dynamic, leading to intense karst development. Due to crustal uplift, the Nanpan River valley is deeply incised with steep slopes, causing surface water on both sides of the valley to rapidly infiltrate through fractures or sinkholes. The karst hills and depressions are primarily distributed in the northeastern and eastern regions of the study area, featuring various forms such as karst hills, peaks, depressions, and funnels, forming a karst hills and depressions plateau. Some depressions at the bottom of the karst hills form water pools or recharge funnels when sinkholes are blocked, and many bead-shaped depressions serve as conduits for underground rivers. On the plateau, this type of karst landform has gentle undulations, with a relative elevation difference ranging from 10 to 150 meters. The exposed formations mainly include the Qujing Formation (D2q) and the Upper Devonian (D3), consisting of bioclastic limestone, dolomite, and marl. They are controlled by northwest-southeast-trending faults, and the depressions are often elliptical, with their long axes following the direction of the faults, predominantly trending northwest-southeast.

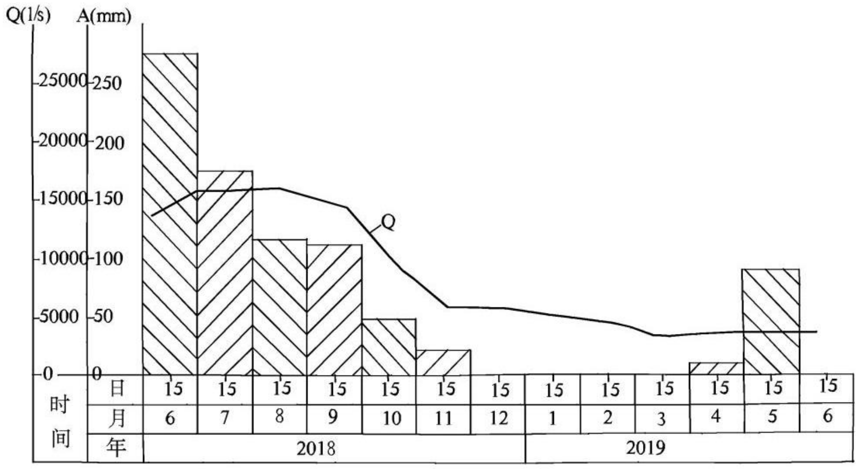

Figure2：Dynamic hydrograph of Panxi Dalongtan

Peak-cluster depression landforms are mainly distributed in the southwestern part of the study area, on the plateau stripping surface. These landforms are characterized by serrated arrangements of mountain peaks, with depressions located between them. The height difference between the peaks and depressions generally ranges from 50 to 100 meters. The depressions often form bead-like patterns, and vertical well-like sinkholes are observed within them, indicating the presence of surface expressions of underground rivers. Compared to karst hills and depressions, this landform has steeper undulations, with a relative elevation difference of 50 to 200 meters. The exposed formations mainly include the Carboniferous and Permian series, consisting of thick-bedded limestone and dolomitic limestone. They are controlled by northeast-southwest and nearly east-west-trending faults, with the long axes of the depressions often following the direction of the faults, predominantly trending northeast-southwest.

Karst trough valley landforms are mainly distributed in the northwestern part of the study area and represent the eastern side of the Nanpan River. These trough valleys occur in low-lying areas generated by folding and faulting. They are formed by the combined erosive and dissolution processes of flowing water due to crustal uplift. The depth of valley incision ranges from 300 to 600 meters. Most of the valley sections exhibit gorge-like morphology, with slopes ranging from 30° to 60° and steep V-shaped valleys. Some sections have fault cliffs on both sides, and the valleys are narrow, exhibiting gorge characteristics. The formations along the valley primarily consist of the Qujing Formation, Yadetaz Formation, and Zaijieshan Formation, mainly composed of limestone, dolomitic limestone, and dolomite. Groundwater is discharged through these formations. Along the valley, intermittent terraces can be observed. The first terrace is elevated 2-5 meters above the riverbed, with a width of 10-50m. The front edge of the terrace is often steep, composed of unconsolidated alluvial sand and gravel layers. The second terrace is elevated 10-30ms above the riverbed and represents a depositional or pediment terrace. The upper part of the sediment is sandy clay or clayey silt, and the lower part is gravel layers. The width of the second terrace is generally around 50-80m, and its front edge is also steep.

Controls on karst development

Karst development is controlled by the type of karst layer formation

The Permian Qixia Formation (P_1q), Maokou Formation (P_1m), Carboniferous Datang Formation (C_1d), Weining Formation (C_2w), and Maping Formation (C_3m) exhibit continuous distribution of limestone and dolomitic limestone. These carbonate rock formations have high purity and thickness of aquifers, resulting in intense karst development. The peaks are cone-shaped, with well-developed karst grooves and troughs. The dominant landform combination consists of densely clustered pointed deep funnels and large (valley) depressions, with underdeveloped surface water systems.

The Devonian Qujing Formation (D_2q) and Zaijieshan Formation (D_3zj) exhibit continuous distribution of limestone. Due to the presence of small amounts of mudstone and marl in the formations, karst development is relatively strong. The mountain tops are rounded, and stone tooth slopes are commonly observed on the surface, along with shallow funnels and small depressions.

The Devonian Xuanwutian Formation (D_2x) and Yadetaz Formation (D_3y) exhibit alternating distribution of limestone, dolomitic limestone, and siltstone. The continuity of aquifers is relatively poor, resulting in relatively weak karst development. Sparse outcrops of carbonate rock formations are observed on the surface. The valleys exhibit normal erosion features, and the mountain tops are rounded. Wide shallow valleys and dish-shaped depressions are commonly seen, forming a belt-like low-lying zone macroscopically, with numerous ponds within the belt.

The Paleogene Lumeiyi Formation (E_2l) exhibits alternating distribution of calcareous conglomerate and siltstone. The siltstone acts as a confining layer, restricting karst development to the areas with calcareous conglomerate. Karst development is weak, and the mountain tops are rounded. The valleys exhibit typical erosion characteristics. Surface features include stone buds, karst grooves, and occasional small caves.

Karst development is controlled by lithology

The lithology of rock formations forms the basis for karst development. Formations with high calcite content and low silica-aluminum-iron oxide content, predominantly composed of limestone, exhibit the most developed karst features. Various karst forms can be observed, including large depressions (valleys), deep funnels, and large caves. Areas with continuous limestone outcrops often have abundant springs and significant underground river flows.

Formations with high dolomite content and low silica-aluminum-iron oxide content, predominantly composed of dolomite, also exhibit significant karst development. Similar to limestone, these formations display diverse karst features, including large depressions (valleys), deep funnels, and large caves. Areas with continuous dolomite outcrops are associated with the emergence of springs and significant underground river flows.

Formations with low calcite or dolomite content and high silica-aluminum-iron oxide content, possibly composed of marly limestone, marly dolomite, or marl, generally exhibit relatively weaker karst development. The karst forms are relatively simple, with common small depressions (valleys), shallow funnels, and small caves. Areas with these formations often have limited springs and overall lower underground river flows.

The development of karst forms is closely related to the lithology of rock formations. In the study area, the Triassic Lower-Middle formations, Permian formations, and Carboniferous formations predominantly consist of pure limestone and dolomitic limestone. These formations are characterized by medium to thick layers, which favor the development of surface karst belts. Within these surface karst belts, karst grooves, fractures, karst pores, and stone buds are well developed. The formations have good connectivity, allowing strong infiltration and dissolution capabilities of groundwater. The dissolution action of groundwater in the surface karst belts provides favorable conditions for the development of deep karst features. In contrast, the Carboniferous formations, which are dominated by limestone, exhibit relatively weaker development of surface karst belts.

Karst development is controlled by landform

Landforms control the hydraulic conditions of karst development. In the watershed zone, the distribution of the Paleogene Lumeiyi Formation (E2l) is characterized by wide and shallow valleys, with sinkholes present at the valley bottoms and exposed carbonate rocks resembling stone buds at the valley edges. In the sloping areas along the watershed edges, fluvial erosion is more dominant than dissolution, resulting in fewer karst phenomena on the valley slopes.

In areas with extensive distribution of carbonate rock formations, particularly in the higher elevation watershed zones, vertical karst processes prevail. Karst landform assemblages are characterized by stone buds, funnels, and sinkholes, with fewer large interconnected depressions and valleys. In the sloping areas along the watershed edges, both horizontal and vertical karst processes occur alternately, with horizontal karst dominating. Multiple cave layers can be observed on the slopes of valleys and basins, while large springs and underground rivers are distributed along the edges of the valleys and basins.

In the region of karst peak-cluster depressions, surface karst belts are well-developed, but they are significantly influenced by topography. When the slope gradient ranges from 15-35°, the surface karst belt exhibits the most development with a thickness of 5-20m. In the karst trough-valley area where the slope gradient is often greater than 35°, the development of the surface karst belt is weaker with a thickness of 1-5m.

Karst development is controlled by Geological structure

The development of karst landforms is controlled by geological structures. In areas where folding, faulting, and other geological structures are well-developed, the near-surface karst exhibits significant development. The stress on the rock mass in these areas leads to fragmentation and disruption, resulting in the relative development of structural fissures, weathering fissures, and bedding plane fissures (Figure 3). This increases the contact area between the rock mass and flowing water, enhancing the hydrodynamic impact on the rock and promoting the development of karst landforms in the near-surface karst zone. Consequently, in the near-surface karst zone, typical karst landforms such as karren, dolines, and grikes tend to develop along the direction of the geological structures, displaying a clear directional pattern.

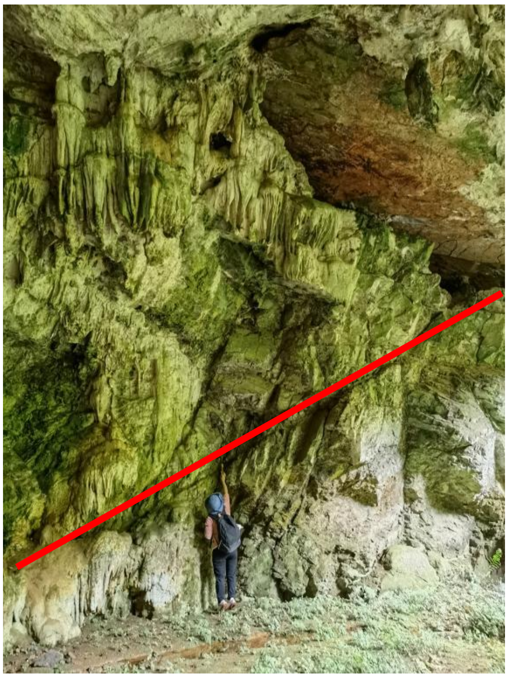

Figure3：Karst developed along faults

Repeated tectonic activities have caused rock fracturing and fragmentation, creating favorable conditions for groundwater flow and karst development. The study area is located in a region where the Xiaojiang Fault, running north-south, intersects with the Mile-Shizong Fault, oriented northeast-southwest. This area is characterized by the development of three sets of faults: north-south, northwest-southeast, and northeast-southwest. These fault zones exhibit the formation of funnel-shaped depressions, sinkholes, and cascading sinkholes. In the vicinity of Ju Village, the area intersects with the Dalongtan Fault and the Lime Kiln Fault (F_3), Longli Fault (F_5), and Damaitan Fault (F_4), resulting in the formation of large-scale karst valleys and small-scale dolines (Figure 4).

In the Yanzizhai area, which is situated between the Yanzizhai Fault (F_6) and the Shegu Fault (F_7), the rock formations are heavily fragmented. This area is characterized by the development of large karst sinkholes, Damaitan Fault, Dalongtan Fault, Longli Fault, dolines, and cascading sinkholes, with scattered locations of swallow holes (Figure 5). These features indicate that the faults have connections with the deeper rock strata. During the rainy season, these depressions (valleys) are prone to water accumulation and local flooding, locally referred to as "Daxiantang." This further demonstrates the favorable groundwater recharge potential of this landform type.

Figure4：Karst landscape in the vicinity of Zeju Village

Figure5：Karst landscape in the vicinity of Yanzizhai Village

V. CONCLUSION

Through data collection, field surveys, hydrochemical experiments, and connectivity tests, the development characteristics of karst landforms and factors influencing karst development in the Panxi Dalongtan Spring area have been studied. The research findings indicate the following:

(1)Karst landforms such as dolines and karren are well-developed throughout the area. The study area is located in the slope zone between the Nanpan River and Dianxi River, where the hydraulic gradient is high and groundwater circulation is rapid and dynamic, leading to intense karst processes. Additionally, due to crustal uplift, the Nanpan River valley is deeply incised with steep slopes, and surface water infiltrates rapidly along fractures or sinking streams. Therefore, karst landforms such as dolines, peak clusters, sinking streams, and karst shafts are predominantly developed in the northeastern part of the study area.

(2)Karst development is primarily controlled by lithology and stratigraphy. The Permian Qixia Formation (P1q), Maokou Formation (P1m), Carboniferous Datang Formation (C1d), Weinin Formation (C2w), and Maping Formation (C3m) consist of limestone and pure dolomite, with thick aquifers, promoting intense karst development. The Devonian Qujing Formation (D2q) and Zaijie Mountain Formation (D3zj) are characterized by continuous distribution of limestone, and their relatively high clay and marl content contributes to strong karst development, forming rounded hilltops, rock teeth slopes, and shallow dolines. The Devonian Xuanwutian Formation (D2x) and Yadade Formation (D3y) exhibit intermittent distribution of limestone, marl, and silty mudstone, with relatively poor continuity between aquifers, resulting in relatively weak karst development. Sparse outcrops of carbonate formations are observed on the surface, while the valleys exhibit typical linear forms, and the mountain peaks are rounded, with broad and shallow valleys and disc-shaped dolines being common.

(3)Karst development is also influenced by landforms, which control the hydrodynamic conditions of karst development. In areas where carbonate formations are extensively distributed and located at relatively higher elevations, vertical karst processes dominate, resulting in karst landforms such as rock teeth, funnels, and dolines. In the sloping areas of river valleys at the edge of watershed zones, horizontal and vertical karst processes alternate, with horizontal karst processes being dominant. Multiple layers of caves are commonly found on the slopes of river valleys and basins, while large springs and underground rivers are distributed along the edges of valley slopes.

(3)Karst development is further influenced by geological structures. In areas with well-developed folds, faults, and other geological structures, the rock masses are subjected to stress, causing fragmentation and disrupting the integrity of the rock mass. This leads to the relative development of structural fissures, weathering fissures, and bedding plane fissures. The study reveals that karst development in the research area is mostly oriented along the axes of folds and fractured zones. Some underground river channels are even developed along fault zones.

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