

Distribution patterns and controlling factors of cave saltpeter around the Sichuan Basin, China

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Abstract

As one of the major karst geomorphic regions in China, the cave systems of Sichuan Province are renowned not only for their spectacular chemical depositional landscapes but also for their well-preserved clusters of ancient saltpeter mining sites. These sites represent invaluable records for studying the history of traditional mineral exploitation. This study aims to investigate the genesis of cave saltpeter. Through systematic calibration and quantitative analysis, we examined the distribution patterns of caves and saltpeter deposits around the periphery of the Sichuan Basin, along with their controlling factors. The results reveal that caves are primarily distributed along the margins of the basin, with saltpeter-bearing caves displaying a distinct clustered pattern, 63% of them are located in the northwestern and southeastern sectors of the basin. Stratigraphic and petrographic analyses indicate a significant correlation between saltpeter occurrence and carbonate formations, particularly the Triassic Jialingjiang Formation, which accounts for 30% of all saltpeter caves identified in the entire basin. Tectonic analysis further indicates that the distribution of these caves is strongly influenced by a deep and extensive fracture system trending northeast-southwest, with the Guixian-Jiangyou and Qianjiang faults playing crucial roles in their development. Elevation data reveal that saltpeter caves are predominantly located above 1,000 meters above sea level, whereas most non-saltpeter caves lie below 800 meters. Furthermore, historical records and vegetation analysis indicate significant differences in plant communities during the Ming and Qing dynasties. The northwestern region was dominated by high-potassium tree species such as *pinus*, *vernica fordii*, *quercus*, *toona sinensis*, and *alnus spp.*, which contributed substantial potassium to support saltpeter mineralization. These findings not only provide a crucial foundation for understanding the material sources and genesis mechanisms of saltpeter but also offer new insights and a scientific basis for future resource exploration and conservation strategies.

1. Introduction

Saltpeter (also known as flame saltpeter and fire saltpeter) is a naturally occurring nitrate mineral. Cave saltpeter ore forms through microbial nitrification of nitrogenous organic matter, which produces nitrate. This nitrate, combined with potassium ions, is leached by surface water and transported into caves. Under the alternating dry and wet conditions typical of these environments, processes of evaporation and crystallization lead to the enrichment and formation of potassium saltpeter ore bodies (Hess, 1900; Hill et al., 1978, 1981, 1985). Historically, saltpeter played a pivotal role in ancient warfare as the essential ingredient in gunpowder, one of the most transformative inventions in human history. The origin of gunpowder has long been debated in academic circles (Wang et al., 2022). While some Western scholars have questioned China's claim as the birthplace of gunpowder (Guttmann et al., 1895, 1906; Wang et al., 2016), records in the *Wujing Zongyao* (an authoritative ancient Chinese military treatise) strongly counter this view (Wang et al., 2014). The explicit reference to “gunpowder” and its formulation in that text, dated to 1044 CE, indicates that the preparation of gunpowder had already matured in China by the mid-11th century (Liu et al., 2003). Additional historical sources confirm that during the Song Dynasty (1044 CE), China was already producing gunpowder weapons and employing them in combat

(Jiang et al., 2012), more than seven centuries before the extraction of saltpeter during the American Revolutionary War (1775) and its use as a gunpowder component (Hovey et al., 1897; Hill et al., 1978).

Numerous saltpeter mines have been developed in karst caves surrounding the Sichuan Basin, a distribution pattern closely linked to region's complex geological, tectonic, and climatic conditions. These factors play a crucial role in the formation and spatial distribution of saltpeter deposits. This interpretation is supported by the discovery of ancient saltpeter mining and refining at multiple locations around the Sichuan Basin, including Laojun Mountain in Jiangyou (Yang et al., 2012), Fengdongzi in Beichuan, and Shijia Town and Migong Gorge in Chongqing (Xu et al., 2016). These findings indicate that the unique karst landscape surrounding the Sichuan Basin provides a key setting for investigating the Chinese-origin theory of gunpowder. For example, the *Shennong Ben Cao Jing* references the "elimination of stone out of Longdao", where saltpeter, understood in the modern sense as potassium nitrate, is mentioned. The term Longdao, referring to present-day southeastern Gansu and the northwestern margin of the Sichuan Basin, suggests that this area has been an important center of saltpeter production since antiquity.

The significance of the Sichuan Basin as the birthplace of gunpowder culture is widely recognized within the academic community. Jiangyou Chonghua Town, located in the northwestern Sichuan Basin, has been officially designated as the "Township of gunpowder in China" (Jianhua et al., 2006), based on multidisciplinary lines of evidence. Historically, this designation stems from the relationship between Taoist alchemy during the Han Dynasty (202 BCE – 220 CE) and the early development of gunpowder. This connection is supported by archaeological remains of the Song Dynasty Taoist complex at Laojunshan (960–1279). More direct evidence is found in the *Zitong County Records* from the 37th year of the Qianlong era (1772), which detail saltpeter production at Laojunshan's Chaoyang Cave. These historical records are consistent with archaeological evidence recently uncovered at the Laogunshan saltpeter cave site (Lei et al., 2021), confirming the long-standing tradition of local saltpeter mining. The strategic value of saltpeter is particularly evident in military history. For instance, during the Battle of Jinchuan in 1773, Chonghua Town rapidly emerged as a vital hub for military logistics due to its rich saltpeter resources. Similar relationships between saltpeter and warfare have been documented globally, for example, Mammoth Cave in Kentucky (Hess et al., 1900) supplied over 70% of the U.S. Army's saltpeter during the Second American War of Independence in 1812. These examples demonstrate the irreplaceable role of saltpeter in the military-economic systems of the pre-industrial era. Furthermore, the saltpeter development history in the northwestern Sichuan Basin, particularly in Jiangyou, offers a critical geographical context for understanding the military-technical revolution in ancient China.

Despite its significance, cave saltpeter remains understudied, and disparities persist between Chinese and international studies. Research abroad has primarily concentrated on the sources, chemical composition, and spatial distribution of saltpeter (Hill et al., 1985), whereas Chinese research gained traction only in the early 21st century. Yan Zhiwei's team made important progress by identifying the distribution characteristics of cave saltpeter and exploring the source pathways of nitrogen and potassium (Yan et al., 2005, 2006; Ouyang et al., 2013). However, comprehensive studies addressing the

spatial distribution of saltpeter caves and the large-scale controls on their genesis within the Sichuan Basin remain limited, and a unified genetic model has yet to be established.

Given its strategic relevance in the pre-industrial era, the geological genesis and spatial distribution of saltpeter deposits remain a critical yet underexplored scientific topic. Traditional mineralogical theories, which focus primarily on metallic ore formation, do not adequately explain saltpeter mineralization in cave settings. This gap hinders our understanding of the history of gunpowder technology, the military geography of ancient China, and the geochemical dynamics of karst mineral systems. The Sichuan Basin stands out as the only karst region in the world with a complete archaeological chain connecting saltpeter mining, gunpowder manufacturing, and military application, making it an ideal study case for addressing these questions. Consequently, this study concentrates on the periphery of the Sichuan Basin to address two key scientific questions: (1) how karst development processes interact with the material sources of saltpeter; and (2) what geological and environmental factors control the distribution of saltpeter caves. By analyzing the geological characteristics of representative saltpeter caves in the region, this study proposes a conceptual model linking “cave development - material sourcing - saltpeter genesis,” offering new theoretical insights and a methodological framework for advancing the study of cave-hosted saltpeter mineralization.

2. Research Background

2.1 Physical and Geographic Conditions

The Sichuan Basin, located in southwestern China, encompasses parts of central and western Sichuan Province as well as the Chongqing Municipality. It is one of the four major basins in China. The basin's distinctive diamond-shaped morphology is bounded by several mountain ranges (Fig. 1). The Micang and Daba Mountains delineate the northern and northeastern margin, while the Dalou, Qiyao, and Wushan Mountains define the southern and southeastern edges. The northwestern and southwestern margins are framed by the Longmen, Qionglai, and Daxiangling Mountains. These orogenic belts are not only geologically and tectonically significant but also exert a strong influence on the basin's interior in terms of climate, vegetation, and cultural development. The Sichuan Basin lies within a subtropical monsoon humid climatic zone. The temperature gradient generally decreases from east to west and from south to north, with cooler temperatures at higher elevations around the periphery and warmer conditions in the central plains. The region experiences high humidity, with hot, humid summers and mild, wet winters. This distinctive climatic regime strongly influences vegetation distribution: zonal vegetation consists mainly of subtropical evergreen broad-leaved forests, while coniferous and bamboo forests dominate higher elevations. Vegetation patterns are further shaped by variations in altitude, slope orientation, and soil characteristics (Gong et al., 2016; Liu et al., 2016).

2.2 Geological and Tectonic Conditions

The Sichuan Basin is situated in the western part of the Yangzi quasi-platform (Fig. 2a). It developed on the foundation of the Yangzi Paleoplate and Craton Plateau, and displays both marine and terrestrial depositional characteristics (He et al., 2011). From the Early Paleozoic through the Middle Triassic, the basin was affected by multiple tectonic phases, including the Caledonian, Indo-Chinese, Yanshanian, and Himalayan orogenies. These episodes of tectonic activity caused differential uplift and denudation of the strata, resulting in the formation of widespread ancient uplifts and weathered crusts (Zhang et al., 2004). Each tectonic phase imposed a distinct stress field, giving rise to the diverse structural features observed today.

The Sichuan Basin is characterized by a well-preserved, thick, and multilayered stratigraphic sequence with multiple sedimentary cycles (He et al., 2011). Jurassic strata are widely exposed at the surface, while Triassic layers are locally interbedded within the Jurassic in eastern Sichuan. Cretaceous deposits form a narrow belt along the Longmen Mountain front and in the Yi-Chishui area in the basin's southern sector. Paleocene and Quaternary deposits are concentrated mainly in the southwestern part of the basin. In addition, magmatic rocks crop out along the Longmen and Micang Mountain ranges (Fig. 2d) (Li et al., 2019).

From a tectonic framework perspective, the basin lies within the Sichuan Plateau Depression in the western section of the Yangzi quasi-plateau. It is bordered by major orogenic belts and deep fault zones, and its interior can be subdivided into five structural units (Fig. 2c): the East Sichuan High Steep Tectonic Belt, the South Sichuan Low Steep Tectonic Belt, the Central Sichuan Low-gentle Tectonic Belt, the West Sichuan Depression Belt, and the Micangshan-Dabashan Foreland Fold Belt (Gong et al., 2016). The western boundary of the basin is defined by the Longmenshan Fault Zone, which forms the margin with the Songpan-Ganzi Fold Belt. To the north, the Micangshan-Dabashan tectonic belt transitions into the Qinling orogenic belt, while to the southeast and southwest, it connects with the Yunnan-Guizhou-Chuan-Edai fold belt (Fig. 2b).

The present-day tectonic structure divide the basin into three major tectonic zones, delineated by the Huayingshan and Longquanshan dorsal belts (Fig. 2c). East of Huayingshan, the dominant structures are NE-trending Jurassic folds, characterized by asymmetrical anticlines with steep and gentle limbs, and frequently associated with reverse faults. The West Sichuan Low Steep Tectonic Zone, located west of the Longquan Mountains, exhibits gentle synclines in its northern sector, whereas the remaining areas exhibit NE-trending structures dominated by extensive fracture networks. The Central Sichuan Low-Gentle Tectonic Belt, situated between the Huayingshan and Longquan Mountains, features low-relief folds with variable orientations and relatively few fault systems (Qin et al., 2005; Chao et al., 2016)

3. Materials and Methods

This study aims to investigate the spatial distribution patterns of caves and saltpeter caves in the Sichuan Basin and its surrounding areas, as well as their correlations with key geo-environmental

factors. To achieve this objective, we employed a multidisciplinary methodology that integrates statistical analysis with geographic information system (GIS) technology.

Initially, a literature review and a preliminary field survey were conducted to compile data on the distribution of both solution caves and saltpeter caves around the periphery of the Sichuan Basin. The study by Luo Pei et al. (2019) provided a significant reference for this stage of the research (Luo et al., 2019).

Subsequently, ArcGIS software was employed to digitize relevant maps and generate thematic layers. Essential spatial datasets, including the geographic coordinates of caves, elevation data of cave entrances, stratigraphic lithology, and tectonic features such as faults and folds, were extracted. Using a geological map of the Sichuan Basin's periphery and integrating stratigraphic data from *the 1:200,000-scale geological map spatial database available on Cloud 3.0*, we accurately identified and matched the strata and lithologies in which the saltpeter caves are developed. This analysis allowed for a detailed assessment of the spatial distribution of saltpeter caves in relation to local geology.

To further explore the relationship between saltpeter cave distribution and structural features, we utilized tectonic and geological maps of the Sichuan Basin, including active fault data released by *the China Earthquake Disaster Defense Center*. With the aid of ArcGIS, we assessed the geological and tectonic context of all recorded saltpeter cave sites.

In addition, environmental factors such as elevation, altitude, climate, and vegetation were analyzed for their potential influence on saltpeter cave development. Elevation data were obtained from the *Resource and Environmental Science and Data Platform*, using *NASA's official ALOS 12.5m Digital Elevation Model (DEM) data*. Elevation values at cave locations were extracted using ArcGIS tools, enabling correlation analysis between saltpeter cave occurrence and elevation. Vegetation and climate data were compiled from local records and relevant literature, providing essential environmental context for the caves' development and preservation. This integrated approach enables a comprehensive understanding of the geological, geomorphological, and environmental controls on saltpeter cave formation and distribution across the Sichuan Basin and its margins.

4. Results

4.1 Spatial Distribution Characteristics of Caves and Saltpeter Caves

A total of 32 caves were accurately identified and mapped along the marginal zone of the Sichuan Basin through systematic calibration of karst features using Omap software (see Fig. 3). Further quantitative analysis, summarized in Table 1, reveals that the distribution of these caves is relatively dispersed. Notably, 63% of the caves containing relics of historical saltpeter refining (20 caves) are concentrated along the northwestern and southeastern margins of the basin. The ratio of saltpeter caves to total

caves in the northwestern region is 0.78, substantially higher than the corresponding ratio in the southeastern region (0.43). These data suggests a distinct regional pattern in the spatial distribution of saltpeter cave development.

Table 1

Statistical table of karst caves and saltpeter caves in the northwest and southeast concentrated areas

Distribution area of karst caves and saltpeter caves	Karst caves and saltpeter caves	
Northwest Sichuan Basin	saltpeter caves	Hanwang Cave□Chuanan Cave□Laojunshan Saltpeter Cave□Xiaodongzi Cave□Yuanwang Cave□Dongziping Cave□Pengdong Cave□Baihe cave□Foye Cave□Jinguang Cave□Yinguang Cave□Guanyin Cave□Pengzhou Saltpeter Cave□Shenxiandong Cave
	karst caves	Shangshixiang Cave□Tianyin Cave□Wolong Cave□Shuijing Cave
Southeast Sichuan Basin	saltpeter caves	Migongxia Saltpeter Cave□Hejia Cave□Hongyan Cave□Fenshui Cave□Jinfoshan Cave□Hushilin Cave
	karst caves	Zhangguanshui Cave□Laolong Cave□Xueyu Cave□Jiangjia Cave□Huangyingxiang Cave□Furong Cave□Jinyinshan Caves□Taigu Cave

4.2 Stratigraphic lithology and the distribution of caves and saltpeter caves

Comparison of the cave survey results with regional geological maps (Fig. 4) reveals clear spatial associations between stratigraphic lithology and the distribution of caves and saltpeter caves in the Sichuan Basin:

- (1) Northwestern margin of the basin: Caves in this region are primarily developed in Devonian strata, which account for 33% of surveyed caves. The dominant lithologies include carbonate rocks such as dolomite and limestone. Jurassic, Triassic, and Permian formations follow, comprising 22%, 17%, and 17% of surveyed caves, respectively, with lithologies including limestone, conglomerates, sandstones, and mudstones. In contrast, saltpeter caves are largely concentrated in the Devonian formations, accounting for 43% of the saltpeter caves in this area, and are also dominated by carbonate lithologies (dolomite and limestone). Permian strata contribute another 21% of the saltpeter caves, with lithologies including limestone, muddy limestone, and shales.
- (2) Southeastern margin of the Basin: Here, the caves are primarily situated within Triassic strata, which represent 43% of the surveyed caves. The lithology is dominated by limestone and dolomite. Saltpeter caves are enriched in the Triassic strata, comprising 33% of the total saltpeter caves in the region, with a similar dominance of limestone and dolomite lithologies.

Thus, these findings suggest a strong lithological control on saltpeter cave development. Statistical analysis indicated that 80% of all identified saltpeter caves are developed within the dolomite/limestone units. The Triassic Jialingjiang Formation alone accounts for 30% of the total saltpeter caves across the basin. More broadly, the Devonian-Permian-Triassic carbonate sequences, particularly those composed of high-purity carbonate rocks such as those in the Jialingjiang Formation, represent the most favorable lithological conditions for saltpeter deposits in the Sichuan basin.

4.3 Tectonic controls on the development of caves and saltpeter caves

Analysis of the tectonic distribution map of solution and saltpeter caves along the periphery of the Sichuan Basin (Fig. 5), reveals a clear structural control over their spatial patterns. While solution caves are broadly distributed around the basin's margins, saltpeter caves exhibit a marked clustering, with 90% located within two major tectonic zones: the depression belt in northwestern Sichuan (Longmenshan-Micangshan) and the high-steep fold belt in southeastern Sichuan (Daloushan-Qiyao Shan).

Detailed structural analysis indicate that the distribution of saltpeter caves is governed primarily by a northeast-southwest-oriented system of major deep-seated faults (Fig. 5). The Guixian-Jiangyou fault exhibits the highest control index, influencing 55% of all recorded saltpeter caves, followed by the Qianjiang fault, which accounts for 25%. Regionally, the northwestern tectonic zone, characterized by retrograde faulting, hosts 70% of the saltpeter caves, whereas the southeastern structural zone, dominated by strike-slip faults, contains the remaining 30%. These findings underscore the essential role of regional tectonic activity in facilitating saltpeter cave development, likely enhancing fracture permeability and enabling the migration of nitrate-bearing waters into favorable lithological units.

4.4 Elevation distribution patterns of saltpeter caves

Elevation data derived from ArcGIS analysis were used to generate scatter plots comparing the altitudinal distribution of saltpeter caves across the Sichuan Basin (Fig. 6). This comparison reveals pronounced differences in elevation patterns between the two cave types.

(1) Elevation Distribution Characteristics: as illustrated in Figs. 6a and 6b, saltpeter caves are generally located at higher elevations than non-saltpeter caves. Approximately 65% of saltpeter caves occur above 1,000 meters, with some reaching elevations exceeding 1,700 meters. In contrast, most other caves (83%) are found below 800 meters, with the lowest recorded entrance at just 382 meters.

(2) Regional differences: Figs. 6c and 6d illustrate clear contrasts in elevation patterns between the northwest and southeast sectors of the basin. In the northwest, 18 caves were recorded, 14 of which are saltpeter caves. Of these, 71% ($n = 10$) are situated above 1200 m. The four non-saltpeter caves in this region are generally at lower elevations, with 75% ($n = 3$) located below 600 meters. In the southeastern sector, 14 caves were identified in total. Saltpeter caves in this region are mainly concentrated between 600 to 850 m (50%, $n = 6$), with a maximum elevation of 1557 m. Notably, 88% ($n = 8$) of the other caves in this region are located below 800 meters.

(3) General Trends: Overall, saltpeter caves are preferentially distributed at elevations above 1,000 meters, markedly higher than most other caves, which cluster below 800 meters. Furthermore, both the number and elevation of saltpeter caves are greater in the northwestern part of the basin compared to the southeast. This pattern reflects the influence of the vertical elevation gradient and the complex topographic and geomorphic structure of the Sichuan Basin on karst and saltpeter cave development.

4.5 Vegetation Distribution Characteristics

Analysis of local records and relevant literature indicates a significant correlation between the formation and distribution of saltpeter caves and the surrounding vegetation types in the Sichuan Basin (Table 2). Historical records reveal that saltpeter production sites are closely aligned with the vegetation patterns prevalent during their periods of exploitation. For instance, the *Zitong County Records* note that the Laojunshan saltpeter cave in the northwestern Sichuan Basin was already being extensively mined prior to the twentieth year of the Qianlong reign in the Qing Dynasty (1755). It is inferred that the regional vegetation at that time was dominated by evergreen broad-leaved and coniferous forests. Similarly, the Labyrinth Gorge saltpeter cave in southeastern Chongqing has been tentatively dated to the late Qing Dynasty through the 1950s (Xu et al., 2016). Hejiadong nitro cave, also traced to the Qing Dynasty, is supported by spore-pollen evidence from Peiqikou along the Apongjiang River (Li et al., 2011), which suggest that subtropical evergreen broad-leaved forests were the dominant vegetation in the area during the Ming and Qing dynasties.

Table 2
Tree species in the research area

Terrain area	Region	Main tree species	Source
Hilly area of Sichuan basin	Chongqing	Cinnamomum camphora, Pinus, Vernicia fordii, etc.	Ba County Chronicles of the Republic of China, V. 19 Lower. Produce pp. 574.
	Mianyang	Cycas revoluta, Ginkgo biloba, Juniperus chinensis, Cunninghamia lanceolata, Pinus densiflora, Chamaecyparis obtusa, Juniperus procumbens, Podocarpus macrophyllus, Alnus cremastogyne, Quercus spp., Juglans regia, Pterocarya stenoptera, Populus tomentosa, etc.	Mianyang County Chronicles of the Republic of China, V. 3. Produce pp. 133.
Longmen Mountain area	Jiangyou	Pinus, Cupressus, Cunninghamia lanceolata, Vernicia fordii, Cudrania tricuspidata, Quercus, Toona sinensis, Alnus spp., etc.	Guangxu Jiangyou County Chronicles, V. 10. Produce pp. 35.
	Beichuan	Pinus, Cudrania, Oak, Cunninghamia lanceolata, Phoebe, Toona, Pterocarya, Cupressus, etc.	The Beichuan County Chronicles of the Republic of China, Food and Goods. Products pp.423.

Broader historical documents (Ma et al., 2015) confirm pronounced vegetation differentiation across the Sichuan Basin during the Ming and Qing Dynasties. In the hilly regions such as Chongqing, the dominant vegetation types included *cinnamomum camphora*, *pinus*, and *vernicia fordii*. In contrast, the mountainous areas of Longmen, including Jiangyou, were characterized by *pinus*, *cupressus*, *cunninghamia lanceolata*, *vernicia fordii*, *cudrania tricuspidata*, *quercus*, *toona sinensis*, and *alnus spp.* (Table 2). These species, including *pinus*, *vernicia fordii*, *quercus*, *toona sinensis*, and *alnus spp.*, are known to be potassium-rich and may have served as significant potassium sourced for saltpeter formation.

4.6 Climatic Characteristics of Saltpeter Cave Distribution

The Sichuan Basin has experienced long-term climatic influence from a tropical-subtropical monsoon system since the Triassic, with alternating humid, semi-humid, and semi-arid phases.

Paleoclimate reconstructions suggest that during the late Ming and early Qing dynasties, the region entered a cold phase associated with the Little Ice Age. The period was marked by lower temperatures, reduced precipitation, and a relatively drier climate (Ma et al., 2015). Local historical records from the Zhengde to Jiajing periods describe notable cold events, including episodes of “heavy snow in the fifth

month of summer” (Ma et al., 2015). A gradual warming trend followed during the Kangxi period, as reflected in climate records from the Jialing River basin. Historical references to “Chonghua” in the literature support the view of progressively more favorable climatic conditions during this time (Ma et al., 2015). Present-day Jiangyou City and surrounding areas in the northwestern Sichuan Basin are classified as having a humid subtropical monsoon climate. This climate regime features four distinct seasons, abundant precipitation, ample heat, and a prolonged frost-free period. Seasonal water availability is uneven, with droughts occurring mainly in winter and spring, while summer and fall are prone to flooding. Marked climatic gradients exist along both north-south and east-west transects of the basin (Guo et al., 2013; Ma et al., 2013, 2015).

In the southeastern part of the basin, particularly the region straddling Chongqing and Hubei where many saltpeter caves are located, modern climate data also support the presence of a humid subtropical monsoon climate. The region’s complex topography, with elevations ranging from 377 to 1557 meters, imposes a clear vertical climate zonation (Xu et al., 2007; Yang et al., 2011; Zhang et al., 2015). This vertical zonation is marked by cold winters, mild and pleasant summers, high annual rainfall, and summer-dominant rainfall patterns. These climatic conditions are conducive to the microbial and geochemical processes required for saltpeter formation and preservation, and play a key role in shaping the spatial patterns of saltpeter cave distribution around the Sichuan Basin.

5. Discussion

The United States, as an early pioneer in saltpeter cave research, has conducted extensive investigations into the diverse factors influencing cave nitrate formation across multiple regions. These studies highlight strong regional differences in the dominant controls: for instance, humidity appears to be the primary factor in the northeastern U.S., while lower temperatures shape the development of surface saltpeter caves in northern regions. In contrast, higher temperatures and low-organic soils are key controls in the southern U.S., whereas the arid conditions and sparse desert vegetation in the western U.S. hinder nitrate accumulation, as evidenced by low nitrate concentrations in the cave wall bedrock of New Mexico. Overall, the findings underscore that saltpeter cave development is not limited to a single region but is governed by an interplay of climatic, edaphic, and biological factors (Hill et al., 1985). In China, the work of Yan Zhiwei’s and colleagues has further shown that variables such as soil pH, temperature, water content, permeability, redox conditions (e.g., air oxygen content, cave ventilation), microbial species diversity, and the degree of karst development play key roles in regulating microbial nitrification within karst soils (Yan et al., 2006).

5.1 Factors Influencing the Development of Saltpeter Caves

In the Sichuan Basin, the formation and distribution of saltpeter caves are jointly governed by multiple factors, including stratigraphic lithology, tectonic structure, elevation, vegetation, and climate. These factors are interrelated, and their interaction controls both the enrichment and long-term preservation of nitrate minerals.

(1) Lithological control on cave formation

Among these, lithology, particularly the nature of the carbonate host rock, plays a critical role. Most saltpeter caves in the Sichuan Basin are developed within the pure carbonate sections of the Triassic Jialingjiang Formation (Fig. 4). These high-purity limestones and dolomites, due to their greater solubility, foster enhanced karst development (Hill et al., 1978; Whisonant et al., 2015), creating extensive cave systems that serve as natural storage spaces for saltpeter deposition. As previously demonstrated by Lv Yuxiang, pure carbonate strata exhibit more significant karstification compared to impure carbonate sequences, thereby exerting a first-order control on the spatial distribution of saltpeter-bearing caves (Lv et al., 2012).

The geochemical environment within these carbonate caves is also favorable to nitrate accumulation. Dissolution of carbonate rocks contributes calcium and bicarbonate ions to groundwater, while nitrate (NO_3^-) from microbial nitrification and organic matter degradation can combine with available cations such as potassium to form stable nitrate salts (Chalk et al., 1971; Hill, 1981; Swezey et al., 2004). The high porosity of the host rock enhances groundwater infiltration and enables downward transport of nitrogenous organic matter from overlying soils, supplying the necessary substrate for microbial nitrate production (Hess et al., 1900; Hill et al., 1981; Barton et al., 2007). In particular, the weakly alkaline pH (typically 7.5–8.5) buffered by carbonate dissolution creates optimal conditions for nitrifying bacterial to thrive (Drever et al., 1997).

The observed high nitrate content in saltpeter caves formed in the Jialingjiang Formation can be attributed to a combination of factors (Fig. 7): (1) Strong solubility and developed fracture networks promote karst formation and enhance water-rock interaction (Hill et al., 1978); (2) Clay-rich cave sediments, often residual products of limestone dissolution, act as effective media for nitrate retention and microbial activity (Hess et al., 1900; Xu et al., 2014; van Dijk et al., 2019); and (3) Stratigraphic interbedding with impermeable units restricts lateral groundwater flow, allowing localized accumulation and long-term preservation of nitrate-rich fluids and minerals (van Dijk et al., 2019; Zhao et al., 2020).

Comparative studies from other karst systems, such as Kentucky's Mammoth Cave and the nitrate-bearing nodules of the Atacama Desert (Hess et al., 1900; Ericksen et al., 1963, 1981), support the conclusion that carbonate-dominated environments offer three significant advantages: i) rapid formation of karst spaces, ii) stabilization of nitrate species in alkaline conditions, and iii) sustained nitrogen input via microbial processing. The Triassic carbonate succession of the Sichuan Basin exemplifies this interplay, illustrating how lithological and geochemical conditions converge to foster both karst development and nitrate mineralization.

(2) Influence of Geological Structures on Cave Formation

The formation and enrichment of saltpeter deposits in the Sichuan Basin are significantly influenced by the tectonic rift system (Figs. 2 and 5). Secondary tectonic fissures, trending northeast-southwest within the Longmenshan and Qiyao Mountain Fracture Zones, serve as favorable conduits for karst water

transport, playing a crucial role in the leaching and dissolution of carbonate rocks (Hill et al., 1978). In the northwestern Sichuan Basin, a series of fracture zones developed along the Guixian-Jiangyou Fault and the Beichuan-Yingxiu Deep Fault have notably enhanced rock permeability and accelerated cave within the pure carbonate units of the Jialingjiang Formation (Whisonant et al., 2015). This tectonic configuration facilitates the rapid infiltration of atmospheric precipitation and surface-derived organic matter (e.g., humus) into the groundwater (Fig. 7), continuously supplying nitrogen for in-cave nitrification processes and thereby promoting saltpeter precipitation (Barton et al., 2007).

The periodic activity of these fracture zones, which alternately open and close over time, facilitates nitrate precipitation through two principal mechanisms. (1) Formation of localized, confined environments: Northeast-southwest trending retrograde fractures (e.g., the Guixian-Jiangyou Fault and the Beichuan-Yingxiu Deep Faults) create relatively confined hydrogeological conditions that inhibit nitrate leaching. This phenomenon resembles the water-retention effect observed in the Feldbiss Fault, where impermeable layers helps concentrate and preserve nitrate deposits (van Dijk et al., 2019). (2) Rapid crystallization via ion-rich groundwater mixing: Subtensile fissures promote mixing between nitrate-bearing fluid and groundwater rich in K^+ , Ca^{2+} , and other ions, rapidly triggering nitrate crystallization (Hill et al., 1981). This mixing mechanism significantly increases the efficiency of nitrate precipitation and contributes to rapid enrichment.

In contrast to the weakly tectonically active nitrate-producing regions such as the Pampa of Chile (Jr. R. A. F. Penrose et al., 1910) and the relatively uniform karst terrain of Kentucky, USA (Maxson et al., 1932; Hill et al., 1979; O'Dell et al., 2014), the Sichuan Basin exhibits pronounced tectonic zoning (Fig. 5). In the northwestern uplift zone, high-angle extensional fractures dominate and control vertical cave development, whereas in the southeastern strike-slip zone, near-vertical fractures favor lateral seepage and horizontal karstification. This structural differentiation underlies a tectonic framework for saltpeter mineralization that is distinct from regions with minimal tectonic influence (Maxson et al., 1932; Hill et al., 1979).

(3) Effect of altitude on saltpeter formation

Saltpeter caves around the periphery of the Sichuan Basin exhibit a distinct enrichment zone at mid-elevations (800–1700 m) (Fig. 6a). In the Jiangyou area of northwestern China (Fig. 5), the development of saltpeter caves at these altitudes is closely linked to tectonic uplift associated with the Xishan phase of the Longmenshan rift zone. The steep topographic gradients caused by active extrusion of the Tibetan Plateau (Fig. 2a) enhance the infiltration of precipitation through fracture systems and reduce the flushing of nitrate by surface runoff (Brüggen et al., 1925; Ericksen et al., 1981; van Dijk et al., 2019). This mechanism aligns with similar processes observed in the nitrate-rich Andean caves (Ericksen et al., 1981).

Climatic conditions in the mid-altitude range (800–1700 m) are particularly favorable for saltpeter enrichment (Fig. 6a). Moderately low temperatures and suitable humidity levels inhibit rapid decomposition of organic matter and maintain optimal conditions for nitrifying microorganisms (Hill et

al., 1978; O'Dell et al., 2014). Moreover, moisture levels are stable enough to facilitate salt accumulation and nitrate crystallization. For instance, in the northwestern mountains (Table 2), mixed pine-oak forests provide a continuous nitrogen supply via litterfall, while moderate evapotranspiration helps maintain water balance within caves. In contrast, low-elevation regions (< 800 m) experience higher temperatures (> 25°C) that accelerate microbial decomposition but increase nitrate leaching, thereby limiting saltpeter accumulation. Very high-elevations (> 1700 m), on the other hand, are too cold (< 5°C) to sustain sufficient microbial activity, hindering nitrification and nitrate accumulation (Ericksen et al., 1981).

This elevation dependence is consistent with global saltpeter occurrences. Deposits described by Hess (1900) and Hess et al. (1900), as well as those from Andean caves (O'Dell et al., 2014), highlight the role of mid-elevation zones in facilitating hydrological connectivity, reducing groundwater disturbance, and maintaining microenvironments favorable for microbial nitrate generation and preservation (Ericksen et al., 1963, 1981; van Dijk et al., 2019). However, in the case of the Sichuan Basin, the interplay between active tectonic uplift and a monsoonal hydroclimate has created an optimal elevation window (800–1700 m) for saltpeter preservation. This window is defined by a consistent supply of meteoric water modulated by monsoonal precipitation, a tectonically enhanced hydraulic gradient promoting infiltration, and altitude-controlled biogeochemical cycling. Together, these factors make the formation and long-term preservation of saltpeter deposits at these elevations particularly favorable.

(4) Influence of vegetation on saltpeter formation

As a key factor in the formation of saltpeter caves, vegetation types profoundly influence the development and evolution of cave saltpeter systems in the Sichuan Basin through complex material-energy exchange processes. This study reveals that potassium-rich vegetation communities, such as *pinus*, *vernica fordii*, *quercus*, *toona sinensis*, and *alnus spp.*, which are endemic to the region (Table 2), promote potassium saltpeter mineralization through a dual mechanism (Fig. 7). On one hand, the continuous input of organic nitrogen sources from plant litter decomposition significantly enhances soil nitrifying microbial activity (Xu et al., 2014; Barton et al., 2007; Hill et al., 1978). On the other hand, biologically enriched potassium (K⁺) in plant tissues directly supplies the essential elements required for the precipitation of potassium saltpeter minerals (Hill et al., 1981). This mechanism is notably comparable to the vegetation regulatory processes observed in classic saltpeter-producing areas worldwide, such as oak-hickory forest ecosystems in North America (Hill et al., 1978, 1979, 1981, 1985). However, the high-potassium, nitrogen-fixing plant assemblage found in the Sichuan Basin, represented by species such as *vernica fordii*, and *alnus spp.* etc. (Table 2), exhibits even more efficient nutrient cycling characteristics.

Comparative cross-regional studies further demonstrate that vegetation functions as a dynamic regulator within the saltpeter geochemical cycle. In contrast with the long-term saltpeter preservation under sparse vegetation in the hyperarid Atacama Desert, and the intense leaching resulting from high productivity in Kentucky's temperate forest zone, the subtropical monsoon zone of the Sichuan Basin stands out due to its continuous nitrogen input and vertical stratification of vegetation, which promotes

directional nutrient transport. This unique biogeochemical environment distinguishes the region's saltpeter deposits from those formed in bat guano-enriched systems (Onac et al., 2011) or in purely evaporative contexts typical of desert environments (Ericksen et al., 1963).

In addition, the succession of vegetation communities during the Ming and Qing dynasties may have further optimized the metallogenic microenvironment by altering the chemical composition of plant litter (Table 2). For instance, potassium-rich trees increase the K^+/Na^+ ratio in karst water systems, favoring the crystallization of potassium nitrate over sodium nitrate. Nitrogen-fixing species enhance the turnover of ecosystem nitrogen pools, while the structure of mixed-forest canopies helps regulate cave microclimates, maintaining temperature and humidity levels conducive to nitrifying bacterial communities (Hill et al., 1979). This “vegetation-microbe-mineral” tripartite coupling mechanism (Fig. 7), in combination with leaching-evaporation dynamics modulated by the monsoon climate, has led to the formation of a globally rare subtropical karst-type saltpeter mineralization system. This provides a new theoretical framework for understanding the role of biotic factors in evaporite mineral genesis.

(5) Influence of climate on the formation of saltpeter caves

The formation and distribution of saltpeter caves in the Sichuan Basin are closely linked to regional climate fluctuations, particularly during the transitional phases of the Ming and Qing dynasties (Fig. 7). The cold and arid climatic phase associated with the Little Ice Age, coinciding with the late Ming and early Qing periods (Ma et al., 2013, 2015), created favorable conditions for saltpeter preservation through a dual synergistic mechanism: low temperatures suppressed soil nitrification rates (Ericksen et al., 1981), while drought conditions minimized hydrologic leaching (Mansfield et al., 1932; Barton et al., 2007). This preservation dynamic mirrors that of saltpeter deposits in the Atacama Desert, where aridity and limited precipitation (< 1 mm/year) result in long-term nitrate retention. (Ericksen et al., 1963, 1981) However, there are notable differences in how the Sichuan system responds to monsoonal variability.

During the Kangxi period, a climatic shift toward warmer conditions initiated a transformation in saltpeter mineralization dynamics. Rising temperatures accelerated karst dissolution, expanding pore networks for mineral transport, while increased summer precipitation (Xu et al., 2007) enhanced the delivery of soil NO_3^- and K^+ to the cave system (Fig. 7) (Hess et al., 1900; Jr. R. A. F. Penrose et al., 1910; Ericksen et al., 1981). At the cave-air interface, evaporative concentration, especially under hot and humid summer conditions (Brown et al., 1809; Hess et al., 1900; Onac et al., 2011), led to the supersaturation and crystallization of potassium nitrate. This process was temporally modulated by winter microbial dormancy, resulting in a distinctive seasonal deposition pattern. Concurrently, climate-driven altitudinal zoning produced spatial differentiation in saltpeter formation: high-altitude zones (> 1200 m) in the northwest (Fig. 6c) preserved deposits from the cold-dry period, whereas mid-altitude areas (800–1000 m) in the southeast (Fig. 6d) reflect new saltpeter formation during the warm-humid period.

This regional saltpeter system exemplifies a balance between three major elements: (1) monsoonal pulsation (in contrast to the constant aridity of the Atacama Desert) (Ericksen et al., 1963); (2) thermally

modulated karst dynamics (as opposed to the more stable temperate regime of Kentucky) (Hill et al., 1981); and (3) seasonal evaporative fractionation operating at microclimatic scales (Hess et al., 1900; Maxson et al., 1932; Hill et al., 1981; Swezey et al., 2004). This ternary control framework positions the Sichuan saltpeter cave system as a novel end-member among karst saltpeter mineralization environments, where the optimization of mineral formation depends not on climatic stability but rather on oscillatory patterns. Consequently, the enrichment of saltpeter around the margins of the Sichuan Basin results from the combined effects of terrain-induced precipitation, temperature-regulated evapotranspiration, and cave-specific microclimates, clearly setting it apart from systems in extremely arid or persistently humid settings.

5.2 Sources of Saltpeter Composition

Since the main component of cave saltpeter is potassium nitrate (KNO_3), determining the sources of nitrogen and potassium is critical to understanding its genesis. The formation of cave saltpeter deposits in the Sichuan Basin results from the complex interactions of geological, climatic, vegetative, and biological factors, constituting a unique mineralizing environment that differs significantly from other known saltpeter cave systems worldwide.

(1) Vegetation acts as a major potassium source. The mid-elevation zone of the basin (800–1700 m) (Fig. 6) is dominated by potassium-rich vegetation, including pine, tung tree, oak tree, toona sinensis, and alder (Table 2) (Ma et al., 2015). The decomposition of these plants continuously contributes large amounts of bioavailable potassium (Fig. 7). This mechanism is similar to that of the oak-hickory forest ecosystems in Kentucky caves (Maxson et al., 1932); but the subtropical mixed forests of Sichuan exhibit greater biodiversity and higher production of plant litter yield. The vertical stratification of vegetation thus creates a corresponding stratification of potassium sources, helping explain the altitudinal distribution of saltpeter deposits (Fig. 6).

(2) The nitrogen cycle is strongly modulated by climatic conditions. During the Little Ice Age of the Ming and Qing dynasties, cold and dry conditions suppressed denitrification and limited plant uptake of nitrate (Ericksen et al., 1981), promoting the preservation of paleo-nitrate at mid- to high-altitude caves in the northwest (> 1200 m) (Figs. 1 and 6). In contrast, the subsequent warm-humid phase during the Kangxi period, coupled with increased summer precipitation (Xu et al., 2007), favored the leaching and downward migration of NO_3^- from surface soils into karst systems. This climate driven transition between “preservation” and “migration” patterns distinguishes Sichuan saltpeter caves from both the persistent arid environment of Atacama (Ericksen et al., 1963, 1979, 1981) and the stable temperate humid systems of western Kentucky and Virginia (Ericksen et al., 1963; Swezey et al., 2004; Brick et al., 2013).

(3) Karst hydrogeochemical processes provide the alkaline setting required for nitrification. The dissolution of carbonate rocks generates an alkaline environment favorable for nitrifying bacteria (Onac et al., 2011), while fractured bedrock (Fig. 5) enhances water-rock interaction. This explains the particularly high concentration of nitrate in caves developed from dolomitic limestone, and the combined

effect of its high permeability and buffering capacity can maintain microbial activity even during drought periods.

Comparative analysis reveals a unique nitrate enrichment pattern around the Sichuan Basin (Fig. 7), which is not solely dependent on atmospheric deposition in the Atacama Desert region (Ericksen et al., 1963; Ericksen and Suarez et al., 1979; Ericksen et al., 1981), nor on bat feces from certain caves (Maxson et al., 1932; Onac et al., 2011; Carlson et al., 2020). Instead, it is a ternary system composed of vegetation providing potassium sources, climate regulating nitrogen migration and preservation, karst geology providing reaction interfaces, and alkaline environments. This model may be applicable to other subtropical karst areas with similar monsoon climate and mixed forest ecosystem.

5.3 Saltpeter Genesis Patterns

This study reveals a distinctive genesis mechanism for the formation and spatial distribution of saltpeter caves in the Sichuan Basin, its essence is the result of the synergistic effect of multiple systems including geology, climate, and biology. Compared with other global saltpeter deposits, the saltpeter caves in the Sichuan Basin exhibit three distinctive features:

(1) The carbonate rock formations such as dolomite and limestone, particularly the Triassic Jialingjiang Formation (Fig. 4), creates an ideal geochemical environment for saltpeter enrichment. The high solubility of carbonates fosters karstification (Hill et al., 1978; Whisonant et al., 2015), while the alkaline conditions produced by carbonate dissolution enhance the activity of nitrifying bacteria (Drever et al., 1997). These lithological properties have led to a concentration of saltpeter caves near the northeast-trending fracture systems (Fig. 5), where the saltpeter content in caves near the Longmenshan fault zone is higher than that in non fault areas (Fig. 5).

(2) The source-driving mechanism distinguishes the origin of mineralizing materials. External inputs, including potassium-rich vegetation and nitrogen cycling (Fig. 7), provide the main material basis for mineralization. Internal sources such as animal waste play a complementary role. This external-source dominance contrast with the atmospheric deposition-dominated system of Atacama (Ericksen et al., 1981) and the guano-driven accumulation model in Kentucky (Penrose et al., 1910).

(3) The climate-vegetation coupling governs the mineralization process (Fig. 7). Cold and dry conditions during the Little Ice Age favored the preservation of nitrate at mid to high elevations, while the subsequent warm and wet phase enabled the formation of new saltpeter layers at middle to low elevations (600–1000 m) (Fig. 6). This climatic stratification is unique in the global distribution of saltpeter deposits.

Overall, the genesis of saltpeter along the Sichuan Basin can be summarized as a mixed pattern characterized by external dominance and internal subordination (Fig. 7). The nitrogen cycle is the primary external nitrogen sourced (Nichols et al., 1901; Mansfield et al., 1932; Carlson et al., 2020). Atmospheric nitrogen is absorbed by vegetation and, upon decomposition, becomes soil organic nitrogen, which is then converted into ammonium and further into nitrate via nitrification (Hess et al.,

1900; Hill et al., 1985; Yan et al., 2005; Ouyang et al., 2013). Groundwater transports these compounds into surrounding cave walls and ceilings, eventually leaching or dripping into the cave (Yan et al., 2005; Ouyang et al., 2013). Simultaneously, capillary water in the vadose zone transports NO_3^- , and K^+ into the cave, where they react with potassium-rich clay and, through the action of nitrifying bacteria, form potassium nitrate (Yan et al., 2005; Ouyang et al., 2013). Evaporative crystallization occurs in response to fluctuations in temperature and humidity, leading to the deposition of saltpeter under favorable microclimatic conditions (Ericksen et al, 1979, 1981; Hill et al, 1979, 1981).

6. Conclusions

Based on the geological background and relevant data of the Sichuan Basin, this study systematically investigates the distribution patterns of peripheral caves and saltpeter caves in the region, with a particular focus on cave development and the origin of saltpeter-forming materials. By analyzing the correlations between stratigraphic lithology, tectonic structure, altitude, vegetation, and climatic conditions, this research clarifies both the spatial distribution of saltpeter caves and the genesis mechanisms of saltpeter mineralization around the basin. The key conclusions drawn from this study are as follows:

- (1) Stratigraphic lithology and tectonic strictures exert first-order controls on saltpeter cave development. Saltpeter caves in the Sichuan Basin predominantly occur within Devonian, Permian, and Triassic strata, where carbonate rocks constitute the predominant lithology. The highest concentration of saltpeter caves is associated with the northeast-southwest trending fault systems. Among these, the Triassic Jialingjiang Formation stands out for its purity and solubility, which enhance karstification and create large subterranean voids that favor saltpeter accumulation. Fractures along these fault systems significantly increase the permeability of the carbonate units, thereby enhancing groundwater transport.
- (2) The coupling of climate, vegetation, and altitude is critical for saltpeter genesis and preservation. The monsoonal climate regime, characterized by hot and humid summers and cool, dry winters, plays a dual role. In summer, high temperatures and elevated humidity intensify evaporation at the cave-air interface, promoting the supersaturation and crystallization of potassium nitrate. In winter, low temperatures suppress microbial activity, reducing nitrate turnover and enabling its preservation. Historical climatic phases, such as the Little Ice Age during the Ming and Qing dynasties, favored the preservation of nitrate in high-elevation caves by inhibiting denitrification. Warmer, wetter periods that followed induced greater nitrate leaching and migration, particularly in mid-elevation zones. In parallel, potassium-rich vegetation ensures a sustained supply of potassium under varying climatic regimes.
- (3) Saltpeter genesis in the Sichuan Basin reflects a mixed-source model with dominant external contributions and auxiliary internal processes. The principal source of nitrate derives from surface-derived nitrogen fixed by vegetation and transported via groundwater into cave systems. Infiltrating water carries nitrate and potassium ions into karstic voids, where, under favorable temperature and humidity conditions, microbial nitrification and evaporation lead to the precipitation of potassium nitrate.

In conclusion, the formation and spatial distribution of saltpeter in the Sichuan Basin result from the convergence of multiple environmental and geological controls, including lithology, tectonic setting, altitude, vegetation, and regional climate. These interdependent factors create a unique karst-type saltpeter system along the periphery of the basin, distinct from those found in arid (e.g., Atacama) or temperate (e.g. Kentucky) environments. Future research should prioritize quantifying the relative contributions of different nitrogen and potassium sources, investigating the structure and function of microbial communities involved in nitrification, modeling the impacts of climate change on saltpeter formation and preservation, and exploring the influence of historical and modern anthropogenic activities on the geochemical balance of these systems.

Declarations

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Author Contribution

S.C. wrote the main manuscript text, and conducted data analysis, and drew the main figures, F.D.W. conceived the research ideas and secured the research grants, Y.Y.Z. conduct field investigations and review and revise the initial draft, C.P.M. and D.M. revised the manuscript, W.H.Y. and Q.Y.Z.C. data collection and created the figures/maps, X.Q.Z. Provide research data.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to their containing information that could compromise the privacy of research participants.

References

1. Barton HA, Northup DE (2007) Geomicrobiology in cave environments: Past, current and future perspectives. *Journal of Caves and Karst Studies* 69(1): 163-178.
<https://doi.org/10.1016/j.jseaes.2006.11.004>
2. Brick GA (2013) The nitrate deposits of rock crevices in the Upper Mississippi Valley. The Department of Earth Sciences, University of Minnesota.
3. Brown S (1809) A Description of a Cave on Crooked Creek, with Remarks and Observations on Nitre and Gun-Powder. *Transactions of the American Philosophical Society* 6: 235-247.
<https://doi.org/10.2307/1004797>
4. Brüggén J (1928) La geología de los yacimientos de salitre de Chile y las teorías que tratan de explicar su origen. *Sociedad Nacional de Minería, Boletín Minero* 40: 394-406.
5. Carlson HK, Lui LM, Price MN, Kazakov AE, Carr , AV, Kuehl JV, Owens TK, Nielsen T, Arkin AP, Deutschbauer AM (2020) Selective carbon sources influence the end products of microbial nitrate respiration. *The ISME Journal* 14(8): 2034-2045. <https://doi.org/10.1038/s41396-020-0666-7>
6. Chalk PM, Keeney DR (1971) Nitrate and ammonium contents of Wisconsin limestones. *Nature* 229: 42.
7. Ericksen GE (1963) Geology of the salt deposits and the salt industry of northern Chile. United States Geological Survey open-file report pp 164. <https://doi.org/10.3133/ofr6331>
8. Ericksen GE (1981) Geology and origin of the Chilean nitrate deposits. U.S. Geological Survey professional papers. <https://doi.org/10.3133/pp1188>
9. Ericksen GE (1979) Origin of the nitrate deposits of northern Chile. *Congreso Geológico Chileno, Arica, Actas* 2: C181-C205. <https://repositorio.sernageomin.cl/handle/0104/19735>
10. Gao ZJ (2022) GeoCloud 3.0'—Introduction to the National Geoscience Big Data Sharing Service Platform. *Geological in China* 49(1): 02.
11. Gong DX (2016) The Triassic Salt-forming Environment, Potash-forming Conditions and Genetic Mechanism in Sichuan Basin. Chengdu University of Technology.
12. Guo XH (2013) The Research of Geological Disasters of JiaLing River in the Qing Dynasty. Southwest University.
13. Guttman O (1895) The Manufacture of Explosives: A Theoretical and Practical Treatise on the History, the Physical and Chemical Properties, and the Manufacture of Explosives. Whittaker and Company.
14. Guttman O (1906) *Monumenta pulveris pyrii: reproductions of ancient pictures concerning the history of gunpowder, with explanatory notes*. Balham S.W., London. <https://doi.org/10.3931/e-rara-13414>
15. He DF, Li DS, Zhang GW, Zhao LZ, Fan C, Lu RQ, Wen Z (2011) Formation and evolution of multi-cycle superposed Sichuan Basin. *Chinese Journal of Geology* 46(3): 589-606.
<https://doi.org/10.3969/j.issn.0563-5020.2011.03.001>

16. Hess WH (1900) The origin of nitrates in cavern earths. *The Journal of Geology* 8(2): 129-134.
<https://doi.org/10.1086/620781>
17. Hill CA (1978) *Geology and mineralogy of cave nitrates*. B.U.S., University of New Mexico.
18. Hill CA (1981) Origin of Cave Saltpeter. *The Journal of Geology* 89(2): 52-259.
<https://doi.org/10.1086/628584>
19. Hill CA, DePaepe D (1979) Saltpeter Mining in Kentucky Caves. *The Register - Kentucky Historical Society* 77(4): 247-262. <https://www.jstor.org/stable/23378600>
20. Hill CA, Huang LX (1985) Genesis of cave saltpeter. *Progress in Geography* (4): pp. [https://doi: 10.11820/dlkxjz.1985.04.006](https://doi.org/10.11820/dlkxjz.1985.04.006).
21. Hovey HC (1897) Our saltpeter caves in time of war. *Scientific American* 76(19): 291-291.
22. Jian H (2006) The invention of gunpowder is a mystery through the ages. *Science Grand View Park* (12): 56.
23. Jiang XY (2012) Controversies and reflections on the four great inventions. *Science and Technology Review* 30(02): 15-17.
24. Lei XS, Tian MX (2021) Explore the mysterious and rich cultural genes of the “Land of Gunpowder”. *Mianyang Daily*. doi: 10.28575/n.cnki.nmyrb.2021.003643
25. Li HK, Li ZQ, Long W, Wan SS, Ding X, Wang SZ, Wang QZ (2019) Vertical configuration of Sichuan Basin and its superimposed characteristics of the prototype basin. *Journal of Chengdu University of Technology (Science & Technology Edition)* 46(3): 257-267. [https://doi:10.3969/j.issn.1671-9727.2019.03.01](https://doi.org/10.3969/j.issn.1671-9727.2019.03.01).
26. Li J, Zheng Z, Zou HX, Yuan DS, Wang H, Luo CX, Yang SX (2011) Environmental research of a 3000 year record from fuqikou archaeological sites in APeng River, Chongqing. *J Quaternary Sciences* 31(3): 554-565. [https:// doi:10.3969/j.issn.1001-7410.2011.03.19](https://doi.org/10.3969/j.issn.1001-7410.2011.03.19)
27. Liu FZ (2003) The Value of “General Military Principles” in the History of Science and Technology. *Journal of Fuqing Branch of Fujian Normal University* 0(03): 9-14. [https:// doi:10.3969/j.issn.1008-3421.2003.03.002](https://doi.org/10.3969/j.issn.1008-3421.2003.03.002).
28. Liu W (2016) Basin Formation Mechanism and Evolution Process: A Case Study of Sichuan Basin. *China Petroleum and Petrochemical* 0(21): 17-18.
29. Luo P, Xu F, Han Y, Chen QY, Zhang FQ (2019) An analysis on distribution characteristics and influencing factors of karst caves in Nuoshuihe scenic spot in northern Sichuan . *Geological Review* 65(05): 1187-1197. [https://doi:10.16509/j.georeview.2019.05.009](https://doi.org/10.16509/j.georeview.2019.05.009)
30. Lv YX, Hu W, Zhou J (2012) Analysis on karst development law and its influencing factors in Jiaoshi area of Chongqing city. *The Chinese Journal of Geological Hazard and Control* 23(02): 59-63.
[https://doi: 10.3969/j.issn.1003-8035.2012.02.013](https://doi.org/10.3969/j.issn.1003-8035.2012.02.013)
31. Ma Q, Wei CL (2013) Categories, Features and Meanings of Local Documentation of Jialing River. *Yangtze River Civilization* 0(02): 65-71.

32. Ma Q, Yang X (2015) Local Literature and Environmental History Research of Ming and Qing Dynasties—Based on the Inspection of the Jialing River Basin. *Journal of China West Normal University(Philosophy and Social Sciences)* 0(03): 39-45. <https://doi:10.16246/j.cnki.51-1674/c.2015.03.007>
33. Penrose Jr. RAF (1910) The Nitrate Deposits of Chile. *The Journal of geology* 18(1): 1-32. <https://doi.org/10.1086/621691>
34. Pu DQ, Cui YT et al. (1992) Mianyang County Chronicles of the Republic of China. In: *Collection of Local Chronicles of China - Sichuan Prefecture and County Chronicles*, 17rd edn. Bashu Publishing House: Chengdu. pp. 1-396.
35. Mansfield GR, Boardman L (1932) Nitrate deposits of the United States. US Government Printing Office.
36. Maxson RN (1932) The niter caves of Kentucky. *Journal of Chemical Education* 9(11): 1846. <https://doi.org/10.1021/ed009p1846>
37. O'Dell GA, George AI (2014) Rock-Shelter Saltpeter Mines of Eastern Kentucky. *Historical Archaeology* 48(2): 91-121. <https://doi.org/10.1007/BF03376929>
38. Onac BP, Forti P (2011) Minerogenetic mechanisms occurring in the cave environment; an overview. *International journal of speleology* 40(2): 79-98. https://digitalcommons.usf.edu/geo_facpub/1031
39. OuYang HH, Yan ZW, Sui HS, Li SX (2013) Research Progress of Saltpeter in Karst Caves . *Water Conservancy Science and Technology and Economy* 19(2): 6-9. <https://doi: 10.3969/j.issn.1006-7175.2013.02.003>.
40. Qin QR, Su PD, Li L, Liu LP (2005) Origin of Low Structures in Central Sichuan Area. *Xinjiang Petroleum Geology* 26(1): 108-111. <https://doi: 10.3969/j.issn.1001-3873.2005.01.032>.
41. Swezey CS, Hadden RL, Piatak NM (2004) Nitrate concentrations of soils in “Saltpeter Caves” in West Virginia (USA). *NSS News* 62(12): 342-345.
42. van Dijk G, Wolters J, Fritz C, et al. (2019) Effects of Groundwater Nitrate and Sulphate Enrichment on Groundwater-Fed Mires: a Case Study. *Water, Air, and Soil Pollution* 230(6): 1-18. <https://doi.org/10.1007/s11270-019-4156-3>
43. Wang J, Cheng FY (2022) Is there any controversy about the right to invent gunpowder. *Encyclopedic Knowledge* 0(26): 22-28. <https://doi: 10.3969/j.issn.1002-9567.2022.26.006>.
44. Wang J, Gao C, Yang XM (2016) Formation and Distinction of the Modern and Contemporary Historiography of Gunpowder. *Studies in Dialectics of Nature* 32(09): 74-79. <https://doi: 10.19484/j.cnki.1000-8934.2016.09.013>
45. Wang J, Yang XM, Gao C (2014) Cao Huanwen and His Research on the Gunpowder of China. *Studies in the History of Natural Sciences* 33(4): 467-478. <https://doi: 10.3969/j.issn.1000-0224.2014.04.006>.
46. Whisonant RC (2015) *Arming the confederacy: How Virginia’s minerals forged the rebel war machine*. Springer Cham.

47. Wu CY (2012). Research on the General Essentials of the Martial Arts. East China Normal University.
48. (Qing) Wu PWX, (Qing) Ou PH et al. (1992) Guangxu Jiangyou County Chronicles. In: Collection of Local Chronicles of China - Sichuan Prefecture and County Chronicles, 18rd edn. Bashu Publishing House: Chengdu. pp. 242
49. Xu MY, Zhang Q, Xia CY, Zhong YM, Sun GP, Guo J, Yuan T, Zhou JZ, He ZL (2014) Elevated nitrate enriches microbial functional genes for potential bioremediation of complexly contaminated sediments. ISME J 8: 1932-44. <https://doi.org/10.1038/ismej.2014.42>
50. Xu Jin (2016) Chongqing fengjie labyrinth gorge nitrate cave site investigation. Popular Archaeology (10): 74-80.
51. Xu SL (2007) The study of Sequence-based Lithofacies-paleogeography between early to middle Triassic in the southeast of Sichuan Basin. Chengdu University of Technology.
52. Yan ZW (2006) A preliminary study on the distribution characteristics and causes of fire and nitrate in karst caves. Southern Land Resources (07): 30-32.
53. Yan ZW, Zhu XW (2005) A preliminary study on the distribution characteristics and causes of fire nitrate in karst caves. The 11th National Cave Congress pp. 96-100.
54. Yang DQ (2011) Reserccch of Chongqing's Natural disasters and Famine in Ming Dynasty. Chongqing Normal University.
55. Yang J, He SS (2012) Research on Tourism Development of Ancient Towns: A Case Study of Chonghua Ancient Town in Jiangyou, Sichuan. Sichuan Building Science 38(2): 268-271. <https://doi:10.3969/j.issn.1008-1933.2012.02.067>.
56. Yang JH, Huang SY et al. (1992) The Beichuan County Chronicles of the Republic of China. In: Collection of Local Chronicles of China - Sichuan Prefecture and County Chronicles, 23rd edn. Bashu Publishing House: Chengdu. pp. 353-572.
57. Yao DS, Yao WY, Li CY (2002) Geological Map of Chongqing City, Sichuan Province (1:2500000) // Ma LF. Chinese Geological Atlas. Bei Jing: Geological Publishing House.
58. Zhang C (2016) The Formation and Evolution of Kaijiang paleo-uplift In Eastern Sichuan Basin. China University Of Petroleum (Bei Jing).
59. Zhao HJ, Xiao Q, Miao Y, Wang ZJ, Wang QG (2020) Sources and transformations of nitrate constrained by nitrate isotopes and Bayesian model in karst surface water, Guilin, Southwest China. Environmental Science and Pollution Research 27: 21299-21310. <https://doi.org/10.1007/s11356-020-08612-8>
60. Zhang L, Wei GQ, Yang W, Jin H, Wu SX, Shen YH (2004) Analysis of the exploration prospect of stratigraphic lithologic reservoirs in the Sichuan Basin. The 8th Conference on Paleogeography and Sedimentology pp. 122-123.
61. Zhang M, Li JJ (2015) Historical Changes of Forest Vegetation in Southeast Chongqing. Journal of Yangtze Normal University 31(6): 30-40. <https://doi:10.3969/j.issn.1674-3652.2015.06.006>.

62. Bureau of Geology and Mineral Resources of Sichuan Province. (1991). Regional geology of Sichuan province. Beijing: Geological Publishing House.
63. Zhu ZH, Xiang C et al. (1992) Ba County Chronicles of the Republic of China. In: Collection of Local Chronicles of China - Sichuan Prefecture and County Chronicles, 3rd edn. Bashu Publishing House: Chengdu. pp. 783.

Figures

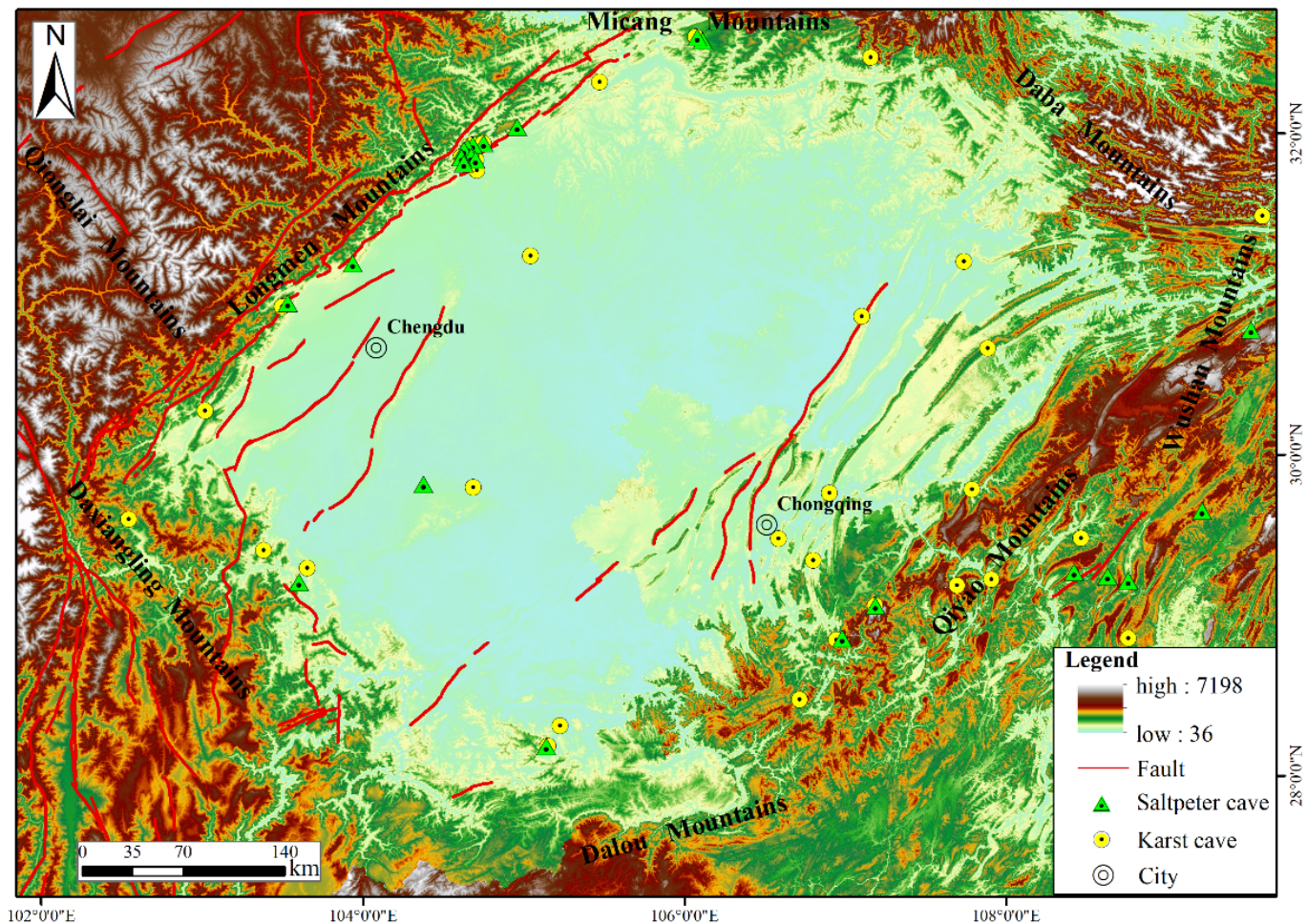


Figure 1

Topographic and geomorphologic map of the Sichuan Basin.

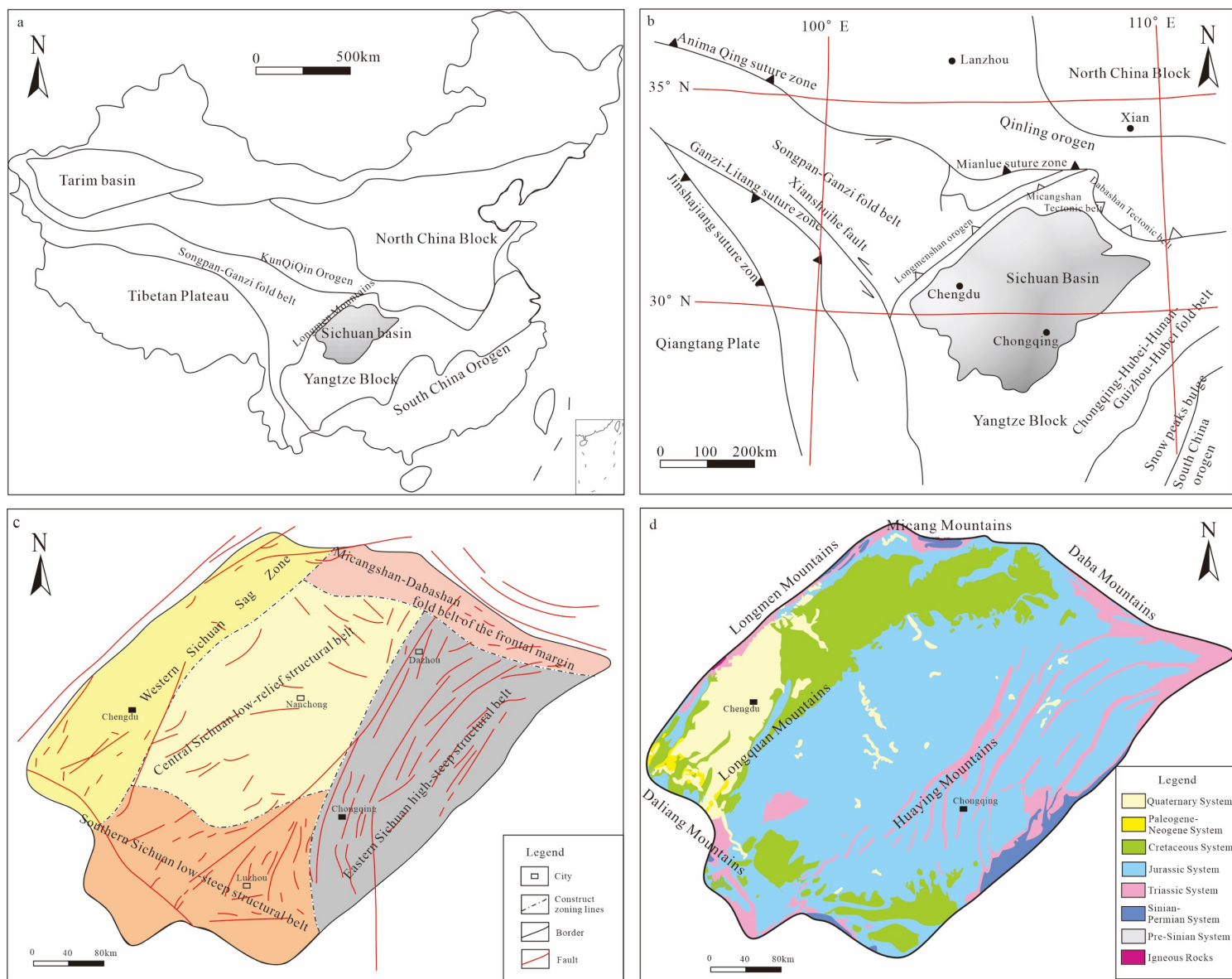


Figure 2

Tectonic unit zoning of the Sichuan Basin (Meng 2011; Zhang, 2016; Li, 2019).

(a) The location of the Sichuan Basin within China. (b) The tectonic zone where the Sichuan Basin is located. (c) The map of the tectonic unit zoning of the Sichuan Basin. (d) A sketch map of the geology of the Sichuan Basin and its periphery.

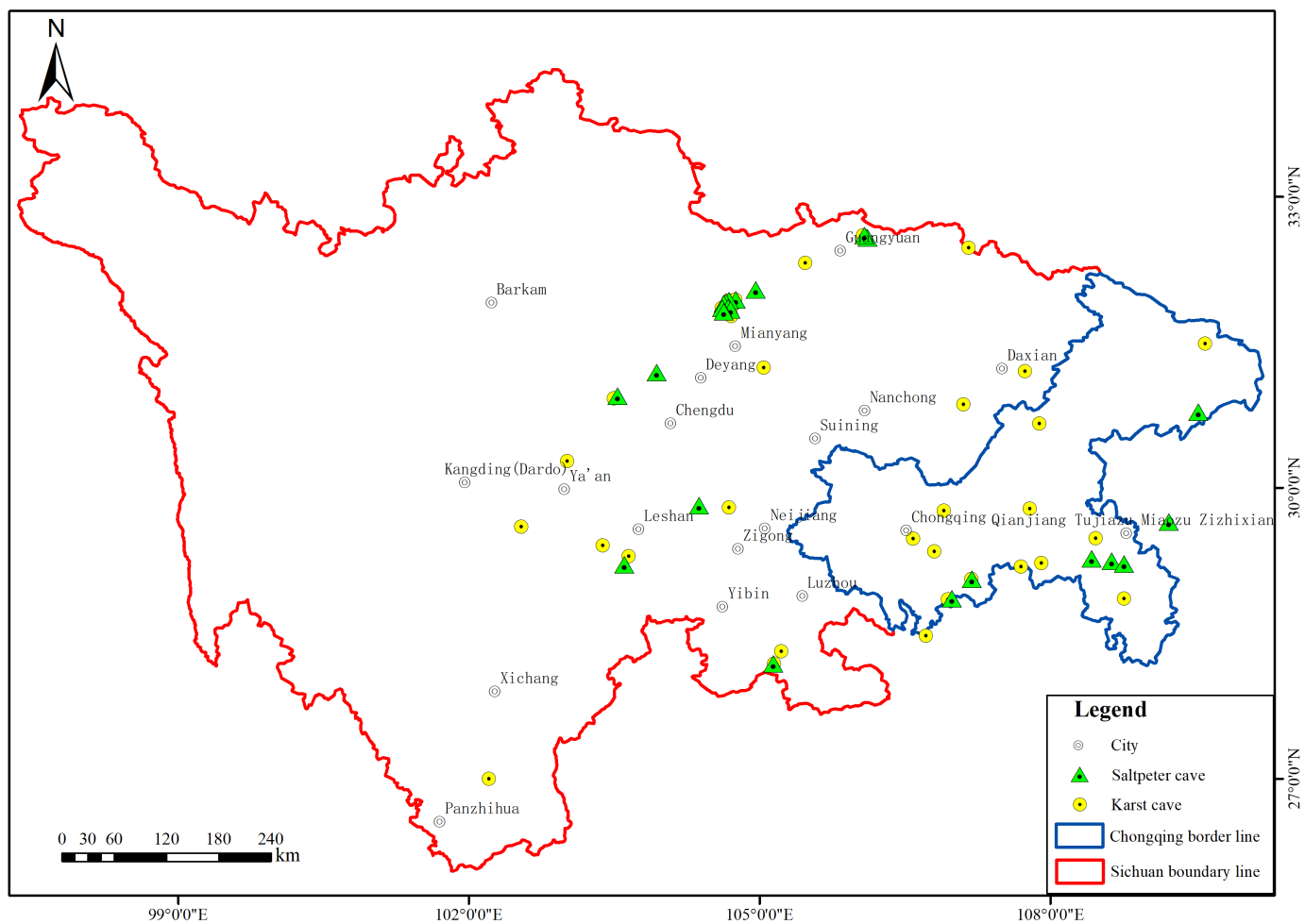


Figure 3

Distribution map of karst caves and saltpeter caves around the Sichuan Basin.

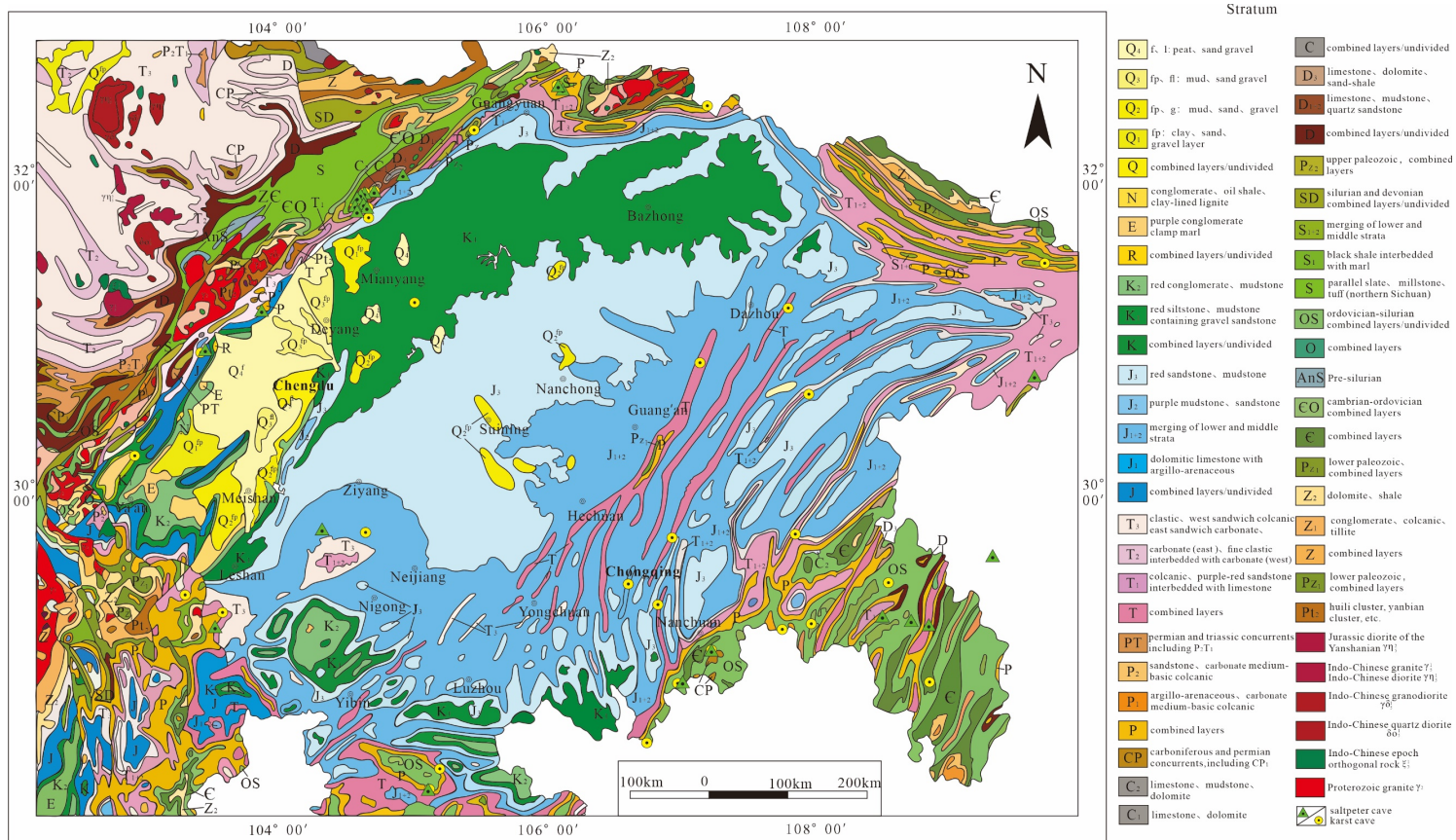
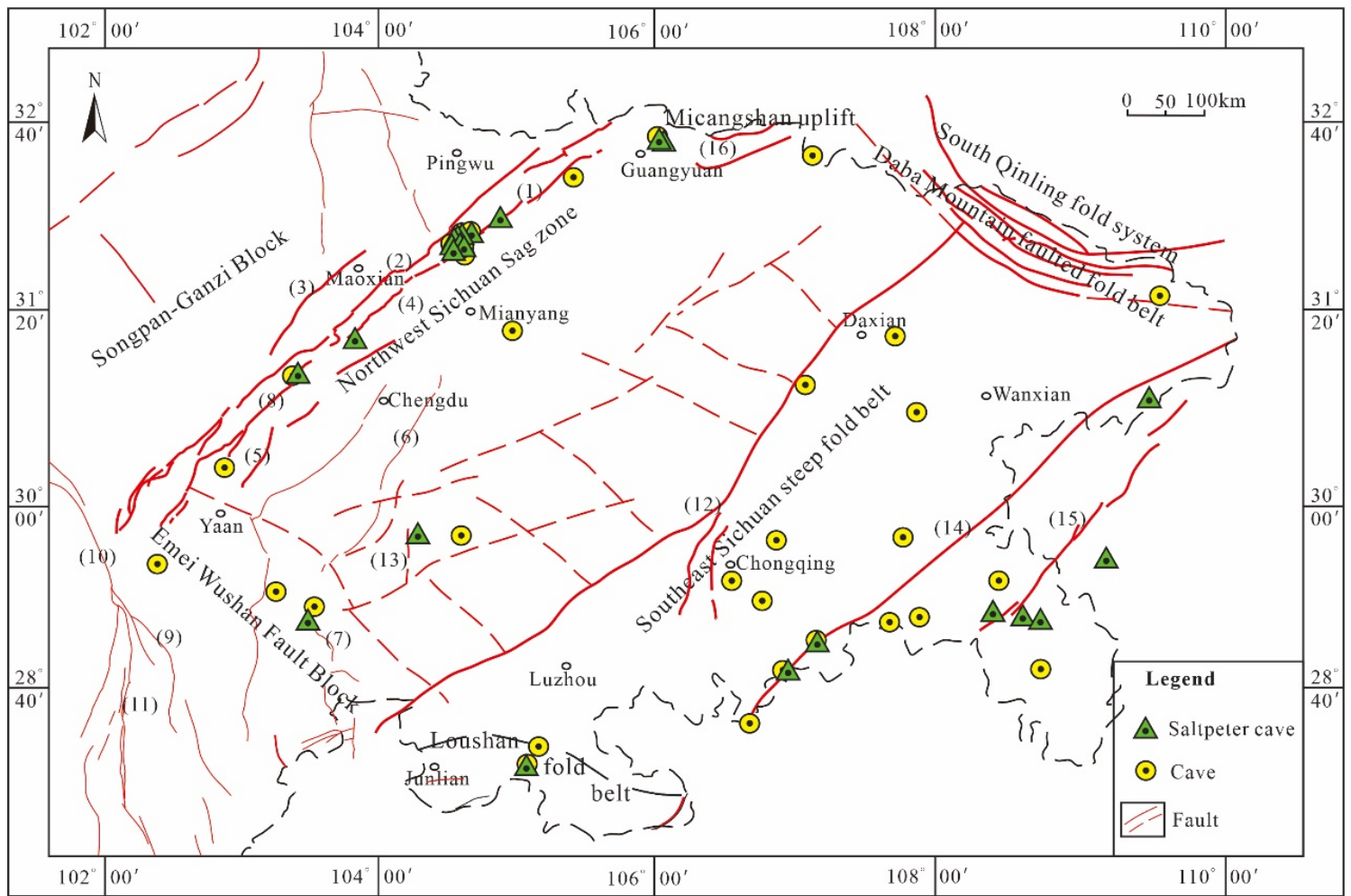


Figure 4

Geologic map of karst caves and saltpeter caves around the Sichuan Basin (Yao et al., 2002).



- | | | | |
|-------------------------------------|-----------------------------|--------------------------------|---------------------------|
| (1) Guanxian-Jiangyou fault | (5) Dayi fault | (9) Daliangshan fault zone | (13) Jingyan fault |
| (2) Beichuan-Yingxiushen fault zone | (6) Longquanshan fault | (10) Xianshui River fault zone | (14) Qiyaoshan fault zone |
| (3) Wenchuan-Maowen deep fault | (7) Mabian fault | (11) Anning River fault zone | (15) Qianjiang fault |
| (4) Longmenshan fault zone | (8) Shuangshi-Dachuan fault | (12) Huayingshan fault zone | (16) Guanba-Shuimo fault |

Figure 5

Fracture structure distribution map of karst caves and saltpeter caves (Yang, 2013).

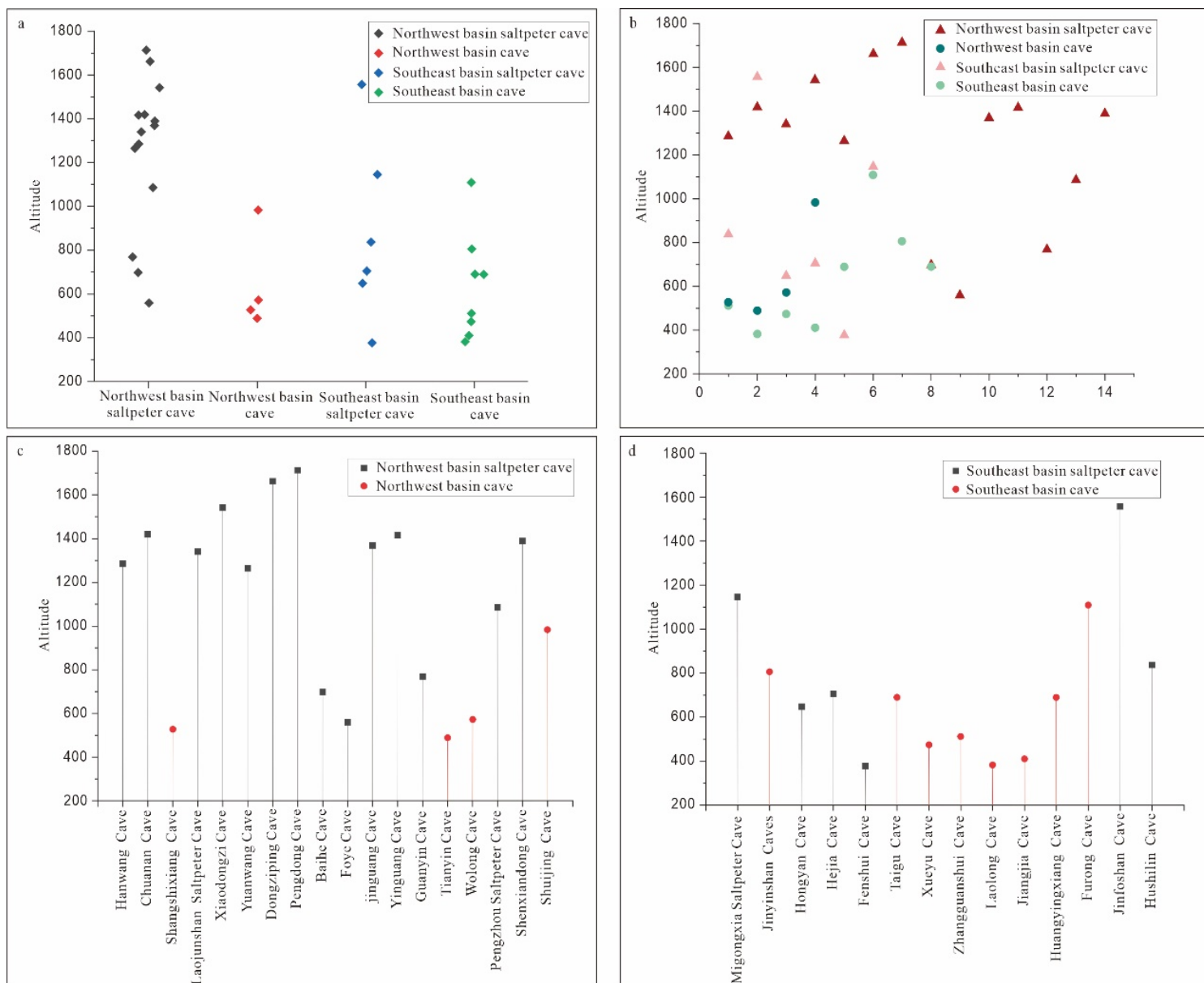


Figure 6

Elevation distribution map of karst caves and saltpeter caves.

(a–b) Elevation Scatter Plot of Sichuan Basin. (c) Elevation plumb line in the northwest of the Sichuan Basin. (d) Elevation plumb line in the southeast of the Sichuan basin.

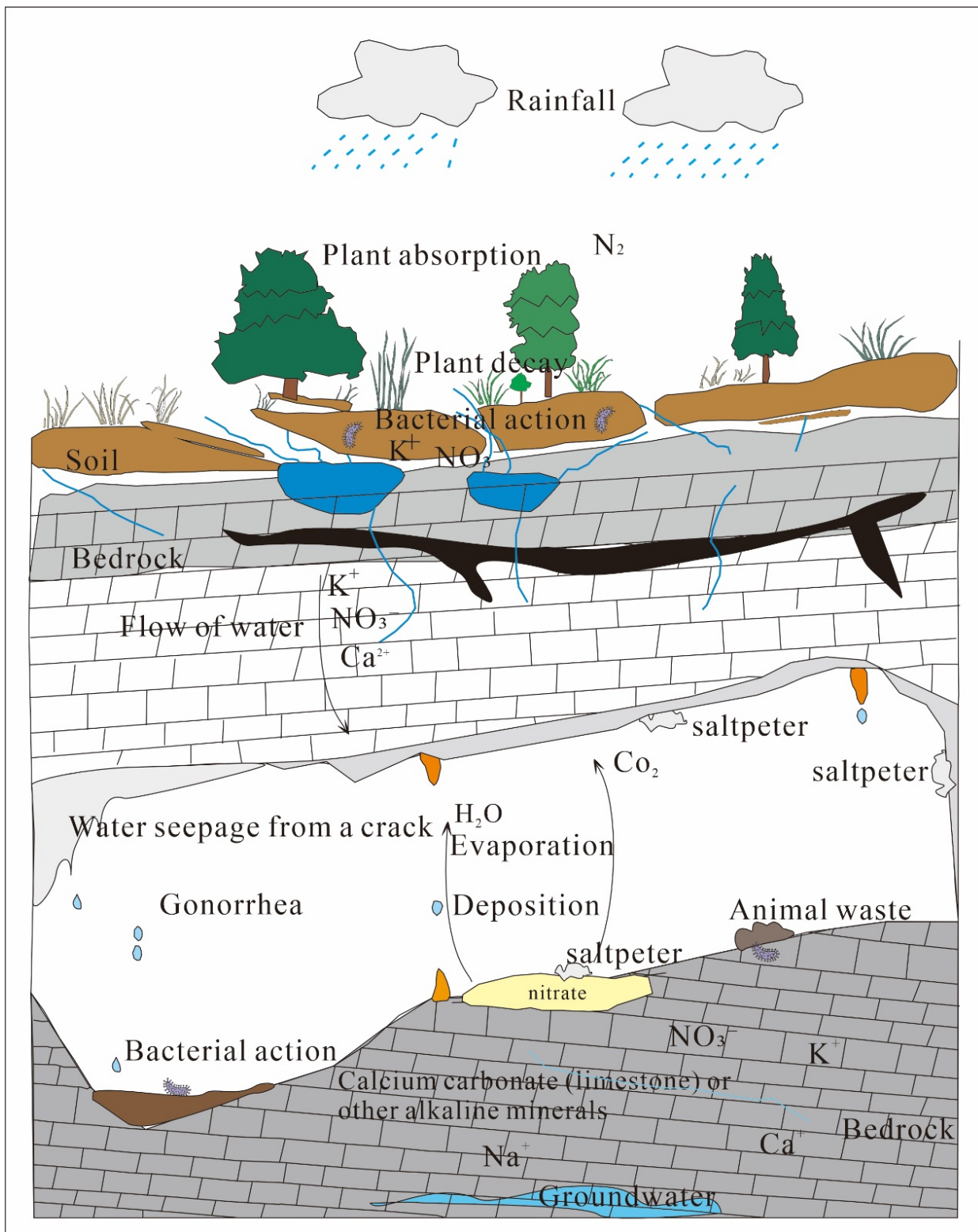


Figure 7

Diagram of saltpeter genesis patterns (Su , 2024; Hill , 1978).