Study on the tufa Thickness and Formation Age of Dyke at Sparkling Lake, Jiuzhaigou Scenic Area, Sichuan Province

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Abstract. Jiuzhai Valley earthquake occurred on August 8, 2017 has resulted in significant impact at Jiuzhai Valley Scenic Area. Some geological landscapes were damaged to different degrees, and the most destroyed landscape at Jiuzhai Valley was the failure of Sparkling Lake’s Dyke, with the shimmering scenery of Sparkling Lake being wiped from the map. Although the earthquake led to the disappear of landscape, it also provides an unusual opportunity to study the formation and evolution of the Sparkling Lake’s Dyke. The author has the honor to participate in the study on the post-earthquake geological changes and reconstruction countermeasures of Jiuzhai Valley World Natural Heritage Site. After conducting comprehensive study on the Sparkling Lake’s Dyke, such as large-scale geological survey, geological profile survey, dronestagram, implementation of minor-caliber backpack drill and formation age, the author finds that the tufa thickness of the Sparkling Lake’s Dyke is 8m-22.78m, with glacial till at the under layer, the age of tufa via carbon-14 dating method (14C) is up to 4.3ka-27ka, and the rate of deposition of tufa is 2.25mm/a-9.35mm/a. The findings that deposition sequence of the Sparkling Lake’s Dyke cannot be attributed to simple bottom-up overlaying relation and no sequential deposition for the deposition of tufa at Jiuzhai Valley area since the very beginning can serve as the complete and accurate scientific basis for ecological restoration of the Sparkling Lake’s tufa dyke.

1. Overview
Situated in the west of Jiuzhai Valley County in Aba Tibetan and Qiang Autonomous Prefecture of Sichuan and bordered with Napping, Songpan and Pingwu counties, Jiuzhai Valley (103°45′-104°05′east longitude and 32°53′-33°20′northern latitude), also known as “nine villages gully”, is famous for the composition of nine Tibetan villages in the Gully. It covers an area of 651.35km².

Located in the northeast of Qinghai-Tibet Plateau, Jiuzhai Valley is the transitional zone of two geomorphic units falling from Qinghai-Tibet Plateau to Sichuan Basin, the pre-scarp topographic transition zone of 1st terrain ladder in Chinese topography and mountain area at the periphery of Basin according to Sichuan Geomorphological Map.
Jiuzhai Valley, third level gully of Baishui River, refers to the "Y" shaped three gullies of Shuzheng, Rize and Zechawa, and is high in south and low in north and high is west and low in east, forming significant topographic relief, with the average relative height difference being 1,600m and maximum relative height difference being 2,768m. In the Jiuzhai Valley Scenic Area, the peaks rise one above the other in the distance, lakes vary totally different, the vertical wall amounts to one thousand miles, and snow mountains are towering. Such extraordinary sight of Jiuzhai Valley with water mirroring green plants and forests reflected in the water attracts great attention, and therefore is honored as “fairyland on earth”, “fairy tale world” and “the best waterscape”.

Situated in the transitional zone of Northern Subtropical Qinling-Bashan Humid Region and Bowo-Western Sichuan Humid Region, the overall climate pattern is expressed as cold and dry monsoon climate, with distinct vertical zoning. The annual average temperature within the Gully is 5.5℃, the frost-free period throughout the year lasts about 100 days, the extreme maximum temperature in July is 32.6℃, the extreme minimum temperature is -20.2℃, the mean annual precipitation amounts to about 761.8mm, and the annual evaporation from water surface is 571.3mm.

The surface water in the drainage basin generally runs from south to north, and main water source comes from atmospheric precipitation and groundwater recharge. The stream flow of rivers within Jiuzhai Valley Scenic Area on the whole is divided into the dry season (or low water season) lasting from November to the following March, the mean flow season lasting from April to May and October to November, and high flow period lasting from June to September. Due to the adequate groundwater recharge, the overland runoff remains relatively stable.

Numerous bead-like mountain lakes, called "haizi" (sea or son of sea) dot in the Jiuzhai Valley drainage basin, with the total area being 2.85km², wherein, Long Lake, located at the upstream of Zechawa Gully, occupies the largest area, with the water area being 0.928km² and storage capacity being 46,740,000m³.

The vegetation in the Jiuzhai Valley drainage basin develops well, with the forest coverage rate up to 63.5% and vegetation coverage rate 85.5%. There is rich diversity of plant communities and distinct vertical zonation.

Jiuzhai Valley Scenic Area is 438km away from Chengdu, 42km from Jiuzhai Valley County, and 90km from Jiuzhai Huanglong (Zhangla) Airport, with Grade II asphalt road of Jiuzhai Valley Circular Highway passing through from the north side of Jiuzhai Valley Scenic Area. There are highways within the scenic area such as Gully Entrance to Nuorilang to Long Lake, Nuorilang to Virgin Forest, as well as highways connecting villages. The Scenic Area is adjacent to Jiuzhai Huanglong Airport in the west, enjoying convenient site access.

2. Geological background

Jiuzhai Valley is located at the zone-link area between Songpan-Ganzi orogenic belt and West Qinling orogenic belt, bordered by Tazang tectonic belt in the north, Minjiang fault zone in the west, snow mountains fault zone in the south, and western frontier of Mongtianling lot of Huysa fault zone in the east (shown in figure 1). It consists of carbonate rocks and clastic rocks of Paleozoic Eraethem and Mesozoic Eraethem, and the thickness of carbonate rocks amounts to about 4,300m, laying the material foundation for the formation of karst landscape in Jiuzhai Valley area. Since it is located at the special geotectonic position, rocks herein have been influenced by the tectonic action at different time and different directions, then formed the northwest to southeast fold structure, and developed four groups of fault structure from north to east, from north to west, from north to south and from east to west, which creates excellent access conditions for the water circulation system and development of karstification within Jiuzhai Valley Scenic Area.
Figure 1. Jiuzhai Valley Scenic Area's geotectonic background image.

Jiuzhai Valley Scenic Area boasts for having well developed Quaternary deposits, which are mainly distributed in the main gullies and branches on both sides, as well as the planation surface, hillside and U-valley bottom of glaciers. The genetic types mainly include glacial drift, tufa, alluviation, proluvial, colluviation and many others.

3. Distribution characteristics of tufa in Jiuzhai Valley

3.1. Overall distribution characteristics of tufa in Jiuzhai Valley

Though extensively distributed in Jiuzhai Valley Scenic Area, the distribution of tufa in the core scenic spot stretches from 2,200m to 2,900m, with the highest up to 3,134m, and the lowest extending to nearby Zharu Bridge with the elevation being 2,020m. The tufa, covering an area of 2.4km², is mainly dotted in the gullies from Grass Lake (the highest elevation) to Reed Lake (the lowest elevation). However, there is no tufa visible on the surface from Nuorilang Waterfall to Rhino Lake’s water entrance. In addition, tufa is also scattered in Heijiao Gully, Zangma Longli Gully and other places.

There are many types of tufa in the Jiuzhai Valley Scenic Area. For example, in terms of the morphology, it mainly include tufa lake (Shuzheng Lakes, Nuorilang Lakes, Five Flower Lake, Arrow Bamboo Lake, Caohai Lake), tufa waterfall (Shuzheng Waterfall, Nuorilang Waterfall, Pearl Shoal Waterfall, Panda Lake Waterfall <high-altitude waterfall>, Arrow Bamboo Lake Waterfall), tufa shoal (Bonsai Shoal, Pearl Shoal), dry tufa shoal or tufa terrace (Eagle Claw Cave, Heijiao Gully, Zangma Longli Gully) and others (as shown in table 1).

Table 1. Statistics of Jiuzhai Valley Main Scenic Area’s tufa distribution area.

| Type of tufa     | Subgroup of tufa                        | Area (m²)     | Distribution                                                                 |
|------------------|-----------------------------------------|---------------|------------------------------------------------------------------------------|
| Tufa lake        | at the bottom of the lake                | 1,528,260     | Swan Lake, Arrow Bamboo Lake, Panda Lake, Five Flower Lake, Small Golden Bell Lake, Big Golden Bell Lake, Mirror Lake, Nuorilang Lakes, Rhino Lake, Tiger Lake, Princess Lake, Shuzheng Lakes, Sleeping Dragon Lake, Sparkling Lake (disappeared in the “8.8” earthquake), Double Dragon Lake |
| Tufa lake        |                                          | 485,819       | Caohai Lake, Swan Lake, Arrow Bamboo Lake Swamp, Mirror Lake Swamp, Rhino Lake Swamp, Reed Lake |
| Tufa lake        | Swampy tufa accumulation                | 19,790        | Eagle Claw Cave Dry Tufa Lake, Heijiao Bridge Spring, Double Dragon Lake Tufa Lake |
Tufa, usually in faint yellow, yellowish-brown, gray white, light gray and grayish yellow, will become brown or black plaques after long-term dehydration and oxidation. Tufa develops well-cemented and solid bottom and loose and porous powder-like surface. It consists of calcite and aragonite, main mineral elements, accounting for over 85%-95%, as well as 15%-5% clay and dolomite and a small amount of quartz and limonite. They are in microcrystalline structure and micritic structure, with intergranular - intercrystalline porosity as well as karst caves and geodes developed, and form the layered structure, crusty structure and concentric structure.

3.2. Characteristics of tufa of the Sparkling Lake’s Dyke

3.2.1. Comprehensive profile characteristics of tufa of the Sparkling Lake’s Dyke. The profile of tufa of the Sparkling Lake’s Dyke starts from Quaternary residual slope deposits inside of the western road of the Sparkling Lake’s Dyke in the west to the Quaternary colluvial deposits inside of eastern trestle road along cliff of the Dyke in the east (as shown in figure 2). It can be attributed to four genetic types according to the lithological association features:

1. Artificial backfill (Qhs)
   Located in the western of the profile, consisting of reinforcement, cement, gravels and concrete used for building 13m-wide sightseeing road, contact with underlying Quaternary residual slope deposits being erosional unconformity.

2. Colluviation (Qhcol)
   Located at the eastern side of the Sparkling Lake’s Dyke, being colluvial mud and gravel accumulation layer, mixed and accumulated with 30%-45% gravels and 55%-70% mud. Angular and subangular gravels are about 12-50cm, with the largest size being over 150cm, without separation. The main element of gravels is gray-black limestone. In the colluvial accumulation area, vegetation well develops, mainly being tall trees and bushes, as well as a small amount of rocks collapsed during the earthquake. Contact with underlying Quaternary tufa or glacial till remains erosional unconformity.

3. Residual slope deposits (Qheld)
   Located at the western side of the Sparkling Lake’s Dyke, being mud and gravel accumulation layer of residual slope deposits, mixed and accumulated with 15%-40% gravels and 85%-50% mud. Angular and subangular gravels are about 2.9cm, with the largest size being over 13cm, without separation. In the accumulation area of residual slope deposits, vegetation well develops, mainly being tall trees and bushes. Contact with underlying bed rock or tufa remains erosional unconformity.

4. Tufa (Qhch)
   The tufa at the Sparkling Lake’s Dyke is about 330m long and 35m long at the breaking point caused by earthquake. In terms of lithology, being earthy yellow, gray white and black gray tufa, with intergranular - intercrystalline porosity as well as karst caves and geodes developed, in microcrystalline structure and micritic structure, and forming the layered structure, crusty structure and concentric structure. The strike of tufa varies widely, some being inclining inside of the dyke, some inclining outside of the dyke and some being nearly horizontal. Its inclination is closely related to the original microtopography and water flow direction. Based on the thickness of tufa at the breaking point of the dyke and depth of tufa detected by the drill, the thickness of tufa at the Sparkling Lake’s Dyke is 21.8-22.78m and its contact with underlying glacial till remains erosional unconformity.
3.2.2. Characteristics of tufa at the vertical section of the Sparkling Lake’s Dyke. In order to study the structural issues and characteristics of tufa at the vertical section of the Sparkling Lake’s Dyke, namely, study the material composition, structure, tectonics, thickness and formation age of tufa, material composition of the under layer, and contact relationship between the tufa and the under layer, to provide scientific basis for ecological restoration of the Sparkling Lake’s tufa dyke, after being approved by the Jiuzhai Valley Scenic Area Administration, the author, following the principle of minimal impact on the environment and combining the existing geological research findings of Jiuzhai Valley Scenic Area, predicts that the thickness of tufa at the Sparkling Lake’s Dyke is about 25m and the thickness of tufa exposed at the breaking point is approximate 13m, and validates that the minor-caliber backpack drill (model: Tanaka TED-270PFDH, pore diameter: 2cm, drilling capacity in ideal conditions with uniform dielectric: 15m) can effectively detect the thickness of tufa layer of the dyke. As a result, the author drilled total four holes, namely ZK01, ZK04, ZK02 and ZK03, at the lower part of steep cliff in the western of breaking point of the Sparkling Lake’s Dyke, at the lower part of steep cliff within 100m scope in the eastern of the breaking point, dry tufa terrace outside of the western dyke, and dry tufa terrace outside of the eastern dyke (as shown in figure 3 and figure 4).

Figure 2. Profile of tufa of the Sparkling Lake’s Dyke, Jiuzhai Valley, Sichuan Province.

ZK01 (N33°12′25.53″, E103°54′0.87″) is located at the lower part of steep cliff in the western of the breaking point of the Sparkling Lake’s Dyke, being 1m above the level of Double Dragon Lake, 9.8m in depth. This hole is drilled through the tufa layer to collect the under layer rock core, which can be divided into four layers from top to bottom, namely: ④ gray white tufa, 1.20m in thickness; ③ gray white hydrous and loose tufa, with tufa crystallization in good shape and coarse grain, 4.20m in thickness; ② gray white hydrous and loose tufa, with tufa crystallization in good shape and coarse grain, severely shrunk during the drilling, the contact between tufa and under layer’s glacial till remains erosional unconformity, 4.38m in thickness; ① glacial grovel-mud layer, with the main element of grovels being limestone, no end detected, its thickness is more than 0.02 m. The thickness of tufa controlled by the drill is 9.78m, which combines with 13m-thick tufa cliff at the breaking point to form a complete tufa profile. The thickness of dyke is 22.78m, and the thickness of tufa below the water detected by this drill is 8.78m.
Figure 3. Location of Drill Holes.

ZK02 (N 33°12′25.53″, E 103°54′0.87″) is located at the dry tufa terrace outside of the western dyke, being 0.5m above the level of Double Dragon Lake, 8.00m in depth. This hole is drilled through the tufa layer. No rock core can be drilled due to the solid under layer rock (speculate to be moraine). It can be divided into four layers from top to bottom, namely: ④ gray white porous and solid tufa, 3.00m in thickness, ③ gray white loose tufa, 4.20m in thickness, ② gray white loose tufa, with a small amount of black clay, 0.60m in thickness, ① gray white loose tufa, with a large amount of sediments and shrinkage during the drill, 0.02m in thickness. The thickness of tufa controlled by the drill is 8m, and the under layer is solid moraine, so the author speculates that the contact between tufa and under layer’s glacial till remains erosional unconformity. The thickness of tufa below the water detected by this drill is 7.5m.

ZK03 (N 33°12′21.83″, E 103°54′5.74″) is located at the dry tufa terrace outside of the eastern dyke, being 3m above the level of Double Dragon Lake, 10.8m in depth. Due to poor power of the drilling machine, the author fails to drill through the tufa layer. It can be divided into ten layers from top to bottom, namely: ⑩ gray white porous and solid tufa, 2.40m in thickness, ⑨ gray white tufa with a small amount of porous and solid tufa and black clay, 0.60m in thickness, ⑧ gray white tufa with a small amount of porous and solid tufa, 0.60m in thickness, ⑦ gray white tufa, 0.60m in thickness, ⑥ gray white porous and solid tufa, 0.60m in thickness, ⑤ gray white tufa, 0.60m in thickness, ④ gray white tufa with a small amount of porous tufa, as well as shrinkage during the drilling, 0.60m in thickness, ③ gray white porous and solid tufa, 0.60m in thickness, ② gray white tufa with a small amount of porous and solid tufa, 0.60m in thickness, ① gray white loose tufa, with a large amount of sediments and shrinkage during the drill, no end detected. The thickness is more than 3.6m. The thickness of tufa below the water of this drill is 7.8m.
Figure 4. Composite columnar section of tufa of the Sparkling Lake’s Dyke of Jiuzhai Valley Scenic Area.

ZK04 (N 33°12′22.12″, E 103°54′3.16″) is located at the lower part of steep cliff within 100m scope in the eastern of the breaking point, being 1.5m above the level of Double Dragon Lake, 10.8m in depth. This drill has passed through the tufa layer, but the under-layer rock is too solid (speculate to be moraine), the author fails to collect the rock core. It can be divided into ten layers from top to bottom, namely: ⑩ gray white tufa, 1.20m in thickness; ⑨ gray white porous and solid tufa, 0.60m in thickness; ⑧ gray white hydrous and loose tufa with a small amount of porous and solid tufa, shrinkage during the drill, 0.60m in thickness; ⑦ gray white loose tufa, 2.40m in thickness; ⑥ gray white loose tufa with a small amount of black gray clay, 0.60m in thickness; ⑤ gray white loose tufa, with partial being solid tufa, as well as tufa crystallization in good shape and coarse grain, 1.20m in thickness; ④ gray white loose tufa with a small amount of porous and solid tufa, 0.60m in thickness; ③ gray white loose tufa, 0.60m in thickness; ② gray white loose tufa with a small amount of porous and solid tufa, 0.60m in thickness; ① gray white loose tufa, with a large amount of shrinkage during the drill, 0.60m in thickness. The thickness of tufa controlled by the drill is 10.8m, which combines with 11m-thick tufa cliff inside the dyke to form a complete tufa profile. The thickness of dyke is 21.8m-22.78m, and the thickness of tufa outside the dyke is 8.00m. By setting the water level of Double Dragon Lake as the base level, the thickness of tufa below the water level is 7.5m, 8.78m and 9.3m, which means that before the tufa sediment of the Sparkling Lake’s dyke, the side close to Double Dragon Lake in its initial form was higher than the other side close to the Sparkling Lake. This result reflects the
characteristics of terminal moraine, and then proves that Jiuzhai Valley’s tufa landscape is developed and evolved on the basis of earlier glacial action.

3.3. Characteristics of tufa around Jiuzhai Valley

In terms of the geographical distribution, the open-air tufa is mainly distributed along the high chilly alpine region in the eastern Qinghai-Tibet Plateau as banded extension. It can arrive the Baishuitai, Zhongdian, Yunnan to the south, and respectively Yulongxi Landscape in Kangding County, Kalong Valley in Heishui County, Mouni Valley in Songpan County [9], Songpan Zhangla Area, Huanglong Scenic Area in Songpan County, Shenxianchi Scenic Area in Jiuzhaigou County to the northeast. Most of these landscapes have become important tourist attractions or scenic area in China, with the main characteristics and parameters in table 2.

Table 2. Comparison of characteristics of tufa landscape in High Chilly Alpine Region in the eastern Qinghai-Tibet Plateau.

|                             | Yulongxi Landscape in Kangding County | Baisnuta, Yunnan | Kalong Valley in Heishui County | Mouni Valley in Songpan County | Shenxianchi Scenic Area in Jiuzhaigou County | Huanglong Tufa |
|-----------------------------|---------------------------------------|------------------|---------------------------------|--------------------------------|-----------------------------------------------|---------------|
| Altitude and area           | Altitude: 3890 m-4250m; Area: 1,373,173m² | 2520m-2600m; Total area: 500,000m² | 3120m-3640m | 2940m-3400m | 2920 m-3280m | 2920 m-3280m |
| Landscape combination       | Fountain, rimstone dam colorful pond, Tufa Shoal, Tufa Waterfall | Tufa Fountain, rimstone dam colorful pond, Tufa Shoal, Tufa Waterfall | Tufa Fountain, rimstone dam colorful pond, Tufa Shoal, Tufa Waterfall | Tufa Fountain, rimstone dam colorful pond, Tufa Shoal, Tufa Waterfall | Tufa Fountain, rimstone dam colorful pond, Tufa Shoal, Tufa Waterfall | Tufa Fountain, rimstone dam colorful pond, Tufa Shoal, Tufa Waterfall |
| Formation Age               | 13860-49810a | 2500a | 72900-10900a | 17590-20190a | 17430-23540a | 12730-35000a |
| Temperatur and flowing status of tufa spring | Temperature: 12-15°C; pH: 6.20-6.25; a rising fountain; Height of blowout: 1.6-20m, with a strong smell of hydrogen sulfide | Separation from residual slope deposits; no outstanding spring opening | Pearl Spring, Temperature: 25°C; A rising fountain; With a strong smell of hydrogen sulfide | Tufa fountain is a rising spring, exposed from the tufa mass | Tufa rising spring, Temperature: 6°C, with stable flow |
| Quantity of rimstone dam colorful pond | Three groups of rimstone dam colorful ponds, consisting of over 200 colorful ponds | Six groups of large rimstone dam colorful ponds | Five large-scale tufa collapse lakes | Five groups of large rimstone dam colorful ponds | Eleven groups of large rimstone dam colorful ponds Consisting of more than 3,400 colorful ponds |
| Scale and color of tufa shoal | Length: 1300m; Width: 10-175m; Floating white, light-gray white, light-gray yellow | Multiple algal banks | Six sections of tufa shoals in small scale | The largest tufa shoal is 80m wide and several hundred meters long, white and light yellow | Golden Sand Pavement is 867.5m long and 131.5m wide to the most, light yellow to golden yellow |
| Scale of tufa waterfall     | Width: 80m; Height: 10-15m | Maximum height: 80m; consisting of three levels | Height 93.2m | Width of waterfall: 167m; Altitude difference: 20m |

The whole tufa deposition in the eastern Qinghai-Tibet Plateau was developed and formed since the last glacial period (35000a). Dawan-Zhangjiagou and Zhangla tufa have completely degraded, while, the Yulongxi, Mouni Valley and Kakong Valley, as a whole, are at the early stage of degradation and
decay. In the contrast, Huanglong Valley is at the growth and equilibrium period during the geological history, while Shenxianchi, Jiuzhai Valley and Baishuitai (Yunnan) are in general at the growth stage.

To sum up, the development and evolution of tufa and tufa landscape, rather than being determined by the formation age, is closely related to the stability of its geological background and tufa spring controlled by the water circulation system.

4. Study on the formation age of tufa of the Sparkling Lake’s Dyke of Jiuzhai Valley Scenic Area

4.1. Ways for measuring the age of tufa

During this study, total 36 tufa samples have been collected from the Sparkling Lake’s Dyke, and common carbon-14 dating (14C) method has been applied to detect the age of tufa. These samples were measured by Karst Geological Resources Environmental Monitoring & Testing Center affiliated to Ministry of Land and Resources, by taking sugar and carbon content as the national standard materials of carbon-14 dating method, and adopting the Ultra-Low Level Liquid Scintillation Spectrometer-Quantulus 1220 produced by perkin-elsmer (an American company), and obtained 33 dating data (as shown in table 3).

Table 3. List of results of carbon-14 (14C) dating method on tufa of the Sparkling Lake’s Dyke of Jiuzhai Valley Scenic Area.

| Test number | Sample number | Name of rock | Sampling location | Sampling time Position (m) | Age-dating (a) (half-life 5730) Note |
|-------------|---------------|--------------|-------------------|--------------------------|-----------------------------------|
| T2018-228-6336 | ZK01-01 | Tufa | The steep cliff in the western of the breaking point of the Sparkling Lake 'Dyke' | +13 | 4340±180 |
| T2018-228-6335 | ZK01-02 | Tufa | The lower part of steep cliff in the eastern of the Sparkling Lake 'Dyke' | -1.2 | 7270±80 |
| T2018-228-6344 | ZK01-03 | Tufa | The steep cliff within 100m scope in the eastern of the Sparkling Lake 'Dyke' | -4.8 | 7300±80 |
| T2018-228-6348 | ZK01-04 | Tufa | The lower part of steep cliff within 100m scope in the eastern of the Sparkling Lake 'Dyke' | -4.8 | 7300±80 |
| T2018-228-6349 | ZK01-05 | Tufa | The steep cliff within 100m scope in the eastern of the Sparkling Lake 'Dyke' | -4.8 | 7300±80 |
| T2018-228-6350 | ZK01-06 | Tufa | The steep cliff within 100m scope in the eastern of the Sparkling Lake 'Dyke' | -4.8 | 7300±80 |
| T2018-228-6351 | ZK01-07 | Tufa | The steep cliff within 100m scope in the eastern of the Sparkling Lake 'Dyke' | -4.8 | 7300±80 |
| T2018-228-6352 | ZK01-08 | Tufa | The steep cliff within 100m scope in the eastern of the Sparkling Lake 'Dyke' | -4.8 | 7300±80 |
| T2018-228-6353 | ZK01-09 | Tufa | The steep cliff within 100m scope in the eastern of the Sparkling Lake 'Dyke' | -4.8 | 7300±80 |
| T2018-228-6354 | ZK01-10 | Tufa | The steep cliff within 100m scope in the eastern of the Sparkling Lake 'Dyke' | -4.8 | 7300±80 |
| T2018-228-6355 | ZK01-11 | Tufa | The steep cliff within 100m scope in the eastern of the Sparkling Lake 'Dyke' | -4.8 | 7300±80 |
| T2018-228-6356 | ZK01-12 | Tufa | The steep cliff within 100m scope in the eastern of the Sparkling Lake 'Dyke' | -4.8 | 7300±80 |
| T2018-228-6357 | ZK01-13 | Tufa | The steep cliff within 100m scope in the eastern of the Sparkling Lake 'Dyke' | -4.8 | 7300±80 |
4.2. Age of tufa of the Sparkling Lake’s Dyke of Jiuzhai Valley Scenic Area

According to the drilling results of backpack drill at ZK01, ZK02 and ZK04 this time, the tufa of the Sparkling Lake’s Dyke at Jiuzhai Valley Scenic Area develops at the earlier U-shaped glacial landform, with the contact between the bottom margin and glacial till being erosional unconformity, 8-22.78m in thickness (figure 2).

The age of tufa at the western cliff of the breaking point of the Sparkling Lake’s Dyke extends from 4340±180a to 7900±80a, with the age of tufa getting older from top to bottom from the surface to 0-3m underground at the tufa deposition rate of 2.25mm/a, as well as tufa at 3-13m underground getting older; the age of tufa at ZK01 hole below the western cliff of the breaking point extends from 7060±80a to 7650±100a, mainly between 7260±90a and 7360±90a.

The age of tufa at the cliff within 100m scope in the eastern of the breaking point of the Sparkling Lake’s Dyke extends from 5840±80a to 6910±70a, and the tufa gets older from top to bottom, with the tufa thickness being 10m and tufa deposition rate of 9.35mm/a, the age of tufa at ZK04 hole below the cliff within 100m scope in the eastern of the breaking point of the Sparkling Lake’s Dyke extends from 4950±260 to 27030±280a, mainly between 6070±100 and 6760±90a. The tufa sample with the oldest age obtained via carbon-14 dating method was drilled at 3.6m, which is the oldest dating result of Jiuzhai Valley Scenic Area since 1987 when the tufa dating started.

4.3. Age of tufa at other core scenic spots of Jiuzhai Valley

Once, researchers had carried out dating at the dry tufa terrace of Zangma Longli Valley of Jiuzhai Valley, dry tufa terrace of Eagle Claw Cave of Jiuzhai Valley, Panda Lake Waterfall of Jiuzhai Valley, Jialijiage Spring in the western of Rhino Lake of Jiuzhai Valley, the dry tufa terrace of Heijiao Valley of Jiuzhai Valley and other places respectively in 1987, 2000, 2004 and 2005, and had obtained abundant dating results of tufa via carbon-14 dating, U-series dating and other different dating methods (as shown in table 4 and table 5).

Table 4. List of results on tufa age of other core scenic spots of Jiuzhai Valley Scenic Area via carbon-14 ($^{14}$C) dating method.

| Test number | Sample number | Name of rock | Sampling location | Sampling time | Age-dating (a) (half-life 5730) | Note |
|-------------|---------------|--------------|-------------------|--------------|-------------------------------|------|
| 012059      | ZK04-9$^{14}$C | Tufa         | Lake’ Dyke        | 6760±90      |                               |      |
| 012059      | ZK04-10$^{14}$C| Tufa         | ZK04              | 6560±80      |                               |      |
| 012059      | ZK04-11$^{14}$C| Tufa         |                    | 5480±70      |                               |      |
| 012059      | ZK04-12$^{14}$C| Tufa         |                    | 8700±80      |                               |      |
| 012059      | ZK04-13$^{14}$C| Tufa         |                    | 8460±80      |                               |      |
| 012059      | ZK04-14$^{14}$C| Tufa         |                    | 7900±80      |                               |      |
| 012059      | ZK04-15$^{14}$C| Tufa         |                    | 7880±80      |                               |      |
| 012059      | ZK04-16$^{14}$C| Tufa         |                    | 7260±70      |                               |      |
| 012059      | ZK05-17$^{14}$C| Tufa         |                    | 7260±70      |                               |      |

Note: These samples were detected by Karst Geological Resources Environmental Monitoring & Testing Center affiliated to Ministry of Land and Resources.
| Test number | Sample number | Name of rock | Sampling location | Sampling time | Age-dating (a) (half-life 5730) | Note |
|-------------|---------------|--------------|-------------------|---------------|--------------------------------|------|
| 2364        | PZang5U1      | Tufa         | Zangma Longli Valley of Jiuzhai Valley |              | 21080±580                      |      |
| 2365        | JD1029U1      | Tufa         | The bottom of Panda Lake Waterfall of Jiuzhai Valley |              | 6660±300                       |      |
| 2366        | JD1029U2      | Tufa         | The Panda Lake Waterfall of Jiuzhai Valley |              | 8770±180                       |      |
| 2381        | PYing1\(^{14}\)C1 | Tufa       | The dry tufa terrace of Eagle Claw Cave of Jiuzhai Valley | 2000        | 600±160                        |      |
| 2382        | PYing3\(^{14}\)C1 | Tufa       | The dry tufa terrace of Eagle Claw Cave of Jiuzhai Valley |              | 5660±190                       |      |
| 2383        | PYing4\(^{14}\)C1 | Tufa       | The dry tufa terrace of Eagle Claw Cave of Jiuzhai Valley |              | 5570±150                       |      |
| 2384        | PYing5\(^{14}\)C1 | Tufa       | The dry tufa terrace of Eagle Claw Cave of Jiuzhai Valley |              | 6290±240                       |      |
| 2385        | PYing6\(^{14}\)C1 | Tufa       | The dry tufa terrace of Eagle Claw Cave of Jiuzhai Valley |              | 7300±230                       |      |
| 2386        | PYing7\(^{14}\)C1 | Tufa       | The dry tufa terrace of Eagle Claw Cave of Jiuzhai Valley | 2004        | 6030±190                       |      |
| 2387        | PYing9\(^{14}\)C1 | Tufa       | The dry tufa terrace of Eagle Claw Cave of Jiuzhai Valley |              | 5630±190                       |      |
| 2388        | PYing10\(^{14}\)C1 | Tufa      | The dry tufa terrace of Eagle Claw Cave of Jiuzhai Valley |              | 4710±130                       |      |
| 2389        | PYing10\(^{14}\)C2 | Tufa      | The dry tufa terrace of Eagle Claw Cave of Jiuzhai Valley |              | 4550±190                       |      |
| 2367        | PJia4U1       | Tufa         | The dry tufa terrace of Eagle Claw Cave of Jiuzhai Valley |              | 7800                           |      |
| 2375        | PJia1\(^{14}\)C1 | Tufa       | The dry tufa terrace of Eagle Claw Cave of Jiuzhai Valley |              | 7490                           |      |
| 2376        | PJia2\(^{14}\)C1 | Tufa       | The dry tufa terrace of Eagle Claw Cave of Jiuzhai Valley |              | 2000                           |      |
| 2377        | PJia3\(^{14}\)C1 | Tufa       | The dry tufa terrace of Eagle Claw Cave of Jiuzhai Valley |              | 2000                           |      |
| 2378        | PJia6\(^{14}\)C1 | Tufa       | The dry tufa terrace of Eagle Claw Cave of Jiuzhai Valley |              | 2000                           |      |
| 2379        | PJia8\(^{14}\)C1 | Tufa       | The dry tufa terrace of Eagle Claw Cave of Jiuzhai Valley |              | 2000                           |      |
| 2380        | PJia9\(^{14}\)C1 | Tufa       | The dry tufa terrace of Eagle Claw Cave of Jiuzhai Valley |              | 2000                           |      |
| 86219       | J-1           | Tufa         | The dry tufa terrace of Eagle Claw Cave of Jiuzhai Valley | 1987        | 7810±130                       |      |
| 2367        | PZang5U1      | Tufa         | The dry tufa terrace of Eagle Claw Cave of Jiuzhai Valley | 1987        | 380±130                        |      |
| 2375        | JD1016\(^{14}\)C1 | Tufa    | The dry tufa terrace of Eagle Claw Cave of Jiuzhai Valley | 2000        | 3600±160                       |      |
| 2378        | JD1016\(^{14}\)C1 | Tufa    | The dry tufa terrace of Eagle Claw Cave of Jiuzhai Valley | 2000        | 3600±160                       |      |
| 796          | JPX1\(^{14}\)C1 | Tufa       | The dry tufa terrace of Eagle Claw Cave of Jiuzhai Valley | 2000        | 18300±360                      |      |

Note: Samples were detected via Former Laboratory of Institute of Karst Geology, Chinese Academy of Geological Sciences (via carbon-14 dating and U-series dating method).
### Table 5. Results on tufa age of other scenic spots of Jiuzhai Valley Scenic Area via U-series dating method.

| Test number | Sample number | Name of rock | Sampling location | Sampling time | Uranium content (Ug/g) | Age-dating (Ka) | Calibrated age-dating (Ka) |
|-------------|---------------|--------------|-------------------|---------------|------------------------|----------------|--------------------------|
| 2363        | PZang1U       | Tufa         | The dry tufa terrace of Zangma Longli Valley of Jiuzhai Valley | 2004          | 0.706                  | 9.3±1.3        | 7.1±1.1                  |
| 2364        | PZang3U       | Tufa         | 0.490             | 6.3±0.5       | 5.3±0.4               |
| 2365        | JD1029U       | Tufa         | The bottom of Panda Lake Waterfall of Jiuzhai Valley | 2004          | 0.180                  | 15.4±1.9       | 7.3±0.8                  |
| 2366        | JD1029U       | Tufa         | The Panda Lake Waterfall of Jiuzhai Valley | 0.530         | 8.7±0.7               | 8.3±0.6       |
| 2367        | PJia4U        | Tufa         | The Jialijia Spring in the western of Rhino Lake of Jiuzhai Valley | 0.291         | 26.2±3.4              | 24.9±3.2       |

Note: Samples in the table were tested via former Laboratory of Institute of Karst Geology, Chinese Academy of Geological Sciences.

According to the results on tufa age of Jiuzhai Valley Scenic Area via the carbon-14 (\(^{14}C\)) dating method since 1987, these scenic spots can be ranked from old to young formation in the following sequence: tufa of the Sparkling Lake's Dyke (from 4340±180a to 27030±280a), tufa of Zangma Longli Valley (from 14390±500a to 21080±580a), tufa in the western Rhino Lake (from 5960±860a to 11290±220a), tufa of Eagle Claw Cave (from 600±160a to 7300±180a), Panda Lake Waterfall (from 6660±300a to 8770±180a) and tufa of Heijiao Valley (3600±160a).

In addition, the tufa age of JP Xi \(^{14}C\), measured via U-series dating method and ICPMSU (Geology and Geophysics Department Minnesota University MN55455 USA), are respectively 11400a and 9036a, which are both younger than that measured via carbon-14 dating method.

In conclusion, tufa in the Jiuzhai Valley Scenic Area, some were formed at the late Pleistocene Epoch, and some at the Holocene Epoch. In addition to the tufa at Zangma Longli Valley, tufa at the core scenic spots formed at the Holocene Epoch as a whole.

### 5. Discussion on the overlaying relation of tufa of the Sparkling Lake's Dyke, Jiuzhai Valley Scenic Area

Based on the Macro-Features of tufa of the Sparkling Lake's Dyke, newly drilled surface is mainly in earthy yellow and gray white, with a small amount of gray black, with intergranular - intercrystalline porosity as well as dissolved pores and geodes developed, in microcrystalline structure and micritic structure, well-constructed openings, and well-cemented into the stratiform-like structure, crusty structure and concentric structure, or poorly-cemented into loose structure, with both structures distributed staggered or at large segments.

Tufa minerals mainly consist of calcite (72-95%), clay (5-15%) and dolomite (0-16%), wherein, the most of the calcite are micrites with the grain size less than 0.004mm-0.03mm and some being micro-crystal with clump-like or dotted recrystallization, clay is cryptocrystalline in light yellow and uniformly scattered and distributed. Pores grow and develop in the rocks in the irregular and elliptical shape, and relatively uniformly distributed, (pores account for 20-40%). Sand cutting may grow in some pores, and the main element is irregular and strip micrites, with poor psephicity, angular and subangular shape, and form olitic caves or dot-type caves, which mainly consists of 1-3 layers, with the size being 0.2-7mm. Among the four tufa drill holes, there are all 1-3 layers of gray black clay bands growing, as well as one layer of 0.5m thick gray-black clay bed growing in the profile of tufa of
Eagle Claw Cave, Jiuzhai Valley Scenic Area. All these evidences can prove that the deposition in Jiuzhai Valley Scenic Area is not consecutive, with interruption from time to time, and the interruption frequency and duration at different parts vary.

According to the tufa age of the drilling holes obtained via the carbon-14 ($^{14}$C) dating method, the tufa of the Sparkling Lake’s Dyke does not deposit following the simple top-bottom overlaying relation since the tufa age at 3.6m depth of ZK04 hole is about 27ka, which is the oldest tufa deposition found in Jiuzhai Valley Scenic Area, and can be attributed to the late Pleistocene Epoch. In the contrast, the tufa age below is 5.9-8.7ka, belonging to the Holocene Epoch, thus presenting a getting younger tendency from bottom to top as a whole, while the tufa age above is 5-6.9ka, presenting a getting old tendency from bottom to top as a whole. The oldest tufa dating data on the cliff of the dyke above the drill hole is 6.9ka, which is located at the bottom of the cliff, while the youngest tufa dating data is 5.8ka, which is located at the very top, thus presenting a getting younger tendency from bottom to top.

The tufa age of ZK01 hole via the carbon-14 ($^{14}$C) dating method is 7.1-7.7ka, not getting older from bottom to top, with the oldest tufa at 1.6m depth of the hole, and the youngest tufa at 0.6m depth of the hole; the oldest tufa age on the cliff of the dyke above the drill hole obtained via the dating method is 4.3-7.9ka, with the oldest tufa not located at the bottom of the scarp, but at the 5m depth, and the youngest tufa located at the top of the scarp.

As to why the tufa age does not grow from old to young when depositing from bottom of the dyke to the top, the reason can be summarized as below:

First, it is closed related to the formation status of the tufa. According to the on-site inspection, some tufa of the Sparkling Lake’s Dyke inclines inward, some outward (as shown in figure 5), some nearly horizontal, some vertical and some arc-shaped. But in practice, no one can distinguish the formation status of tufa samples.

Second, tufa will undergo a series of sedimentation, corrosion, collapse and other geological processes after formation, so the tufa samples from the deep bottom of ZK04 hole may not be the earliest formed tufa at the Sparkling Lake’s Dyke.

6. Conclusion

According to this study, the author finds out the spatial distribution, material composition, structure, tectonics, thickness and formation age of tufa, material composition of the under layer, and contact relationship between the tufa and the under layer, which can provide accurate and detailed scientific basis for ecological restoration of the Sparkling Lake’s Dyke.

(1) After detailed geological survey on the Sparkling Lake’s Dyke, the author finds out that the Sparkling Lake’s dyke extends from northwest to southeast in an arc shape, stretching for 330m long, 130m wide in the east end and 125m wide in the west, with the narrowest being the middle of the dyke, namely, the breaking point of Jiuzhai Valley earthquake on August, 8, with the breaking width being 20-27m and breaking length being 35m.

(2) After carrying out the validation via minor-caliber backpack drill on the Sparkling Lake’s Dyke, the author confirms that the Sparkling Lake’s Dyke consists of tufa layer and moraine layer, with their contact being erosional unconformity. The maximum thickness of the tufa layer can be up to 22.78m, and the minimum thickness 8m. By taking the water level of Double Dragon Lake as the base level, the thickness of tufa layer below the water is 7.5m-9.3m, which means that before the tufa sediment of the Sparkling Lake’s dyke, the side close to Double Dragon Lake in its initial form was higher than the other side close to the Sparkling Lake. This result reflects the characteristics of terminal moraine, and then proves that Jiuzhai Valley’s tufa landscape is developed and evolved on the basis of earlier glacial action.
A Characteristics of tufa in the western profile of the breaking point of the Sparkling Lake’s Dyke, Jiuzhai Valley Scenic Area

B Characteristics of tufa of inner walls in the west of the breaking point of the Sparkling Lake’s Dyke, Jiuzhai Valley Scenic Area, presenting inward inclination of tufa

C Earlier collapse of outside tufa in the west of the breaking point of the Sparkling Lake’s Dyke

Figure 5. Characteristics of tufa at different sections of the Sparkling Lake’s Dyke, Jiuzhai Valley Scenic Area.

(3) Based on the study on the tufa age of the Sparkling Lake’s Dyke via carbon-14 ($^{14}$C) dating method, the author obtains abundant age data (4.3-27ka). The age of 27 ka is the oldest tufa age found in Jiuzhai Valley Scenic Area till now, with the rate of deposition being 2.25 mm/a-9.35mm/a, and 5.19mm/a higher than that in the adjacent Huanglong Scenic Area in terms of the maximum rate of deposition.

(4) The deposition in Jiuzhai Valley Scenic Area is not consecutive, with interruption from time to time, and the interruption frequency and duration at different parts vary.

(5) The tufa of the Sparkling Lake’s Dyke does not deposit following the simple top-bottom overlaying relation. The deposition sequence depends on the original micro topography, water flow direction, flow rate, flux, calcium ion concentration in water and other comprehensive factors, and is the result of a series of sedimentation, corrosion, collapse and other complex geological processes.

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