U-series dating of the travertine depositing near the Rongma hot springs in northern Tibet, China, and its paleoclimatic implication

Jing Gao, Xun Zhou, Bin Fang, Ting Li, Liwei Tang

Abstract

High resolution age data obtained by travertine dating is necessary for the reconstruction of paleoclimate and palaeohydrology near Rongma hot springs in northern Tibet. U-series dating of a travertine cone depositing in the study area was used. The results show that the U contents of the travertine samples range from 0.298 to 1.363 ppm, and the 234U/238U is in the rage of 1.475–1.700, indicating that the deposition of travertine near the Rongma hot springs is stable and continuous. The age of the travertine samples ranges from 11,500 to 4600 a, corresponding to the first stage of MIS 1. Combination of the first stage of MIS with the effect of monsoon climate of the Indian Ocean in the same period implies a warm and humid climate during the deposition of the travertines in the study area. The U-series age range in the Rongma hot springs area is coincident with that of the travertine in southern Tibet. The age data detected from travertine cone help in understanding the evolution of hydrogeology of the hot spring area. High resolution age data must be acquired before travertine can be confidently used as a paleoclimatic archive.

1. Introduction

Studies of continental records have previously been focused on corals, trees, lacustrine sediments, ice cores, loess and paleosols, and stalagmites, which can record changes in paleoclimatic and can help to reconstruct the paleoenvironment. Tufa or travertine has been used as an archive of climate for the studies of paleoclimate and paleoenvironment, and a number of researches on this subject have been carried out by previous researchers. Although there are significant differences in the usefulness of tufa and travertine in paleoclimatology, they have some features as proxies of high-resolution terrestrial records: (1) deposition of the tufa or travertine lasts for a relatively long time, ranging from several thousands of years to nearly a million years (Dramis et al., 1999), (2) tufa is more sensitive (Liu et al., 1995), (3) the distribution of tufa or travertine is relatively extensive and they can be easily sampled, (4) the deposition rate of tufa is greater than that of stalagmites, and it can be as high as 20 mm y\(^{-1}\) (Sun et al., 2008). Lamination of tufa is abundant, and the thickness and extent width of the laminations satisfy the requirements of sampling for analyses of isotopes and trace elements. Tufa or travertine can be used for the studies of paleoclimate and paleoenvironment with seasonal, monthly and weekly resolution (Liu et al., 1995; Ihlenfeld et al., 2003; Kano et al., 2003, 2004).

Ford and Pedley (1996) defined tufa and travertine as: (1) tufa is the product of calcium carbonate precipitation under ambient temperature water and typically contains the remains of micro- and macrophytes, invertebrates and bacteria, and (2) travertine which is thermal and hydrothermal calcium carbonate deposits dominated by physico-chemical and microbial precipitates, and invariably lacks in situ macrophyte and animal remains. According to the origin of the carrier carbon dioxide, Pentecost (1993) separated the travertines to two classes: (a) the meteogene travertines (the carrier CO\(_2\) originates in the soil and epigean atmospheres forming deposits primarily in limestone terrains), and (b) the thermal (thermogene) travertines (the carbon dioxide comes from a range of sources including hydrolysis and oxidation of reduced carbon, decarbonation of limestone or directly from the upper mantle, mainly in areas of volcanic activity) (Pentecost and Vile, 1994). In addition, thermal travertine is formed as massive deposition with relatively high sedimentation rates.

Travertines are morphologically diverse and have been divided into multiple classifications (Chafetz and Folk, 1984; Pentecost and Viles, 1994; Pentecost, 1995). Chafetz and Folk (1984) recognized thermal travertine as five forms: mounds, cascades, fissure ridge,
lake-fill and terraces. *Pentecost and Viles (1994)* proposed autochthonous and allochthonous morphological classifications, subdivided into nine categories. Travertine bridges are a distinct morphology that has been described by *Bayari (2002)*. Mounds corresponding to thermogene travertine have been reported in different regions (Bargar, 1978; Hancock et al., 1999; Akdim and Julià, 2005; Liu et al., 2012).

In China, most research has focused on tufa (Liu et al., 1995; Tian and He, 2000; Dai and Liu, 2003; Hu and Huang, 2008; Yan and Liu, 2011), and travertine deposited in hot springs are seldom examined (Liu et al., 2006; Chai and Zhou, 2007). Research results on travertines have been obtained based on the following aspects: (1) indication of evolution of climate and environment (Frank et al., 2000; Kele et al., 2006; Sierralta et al., 2010), (2) relationship between travertine deposition and fault zones and the effect of earthquake on travertine deposition (Hancock et al., 1999; Uysal et al., 2007; Zentmyer et al., 2008; Brogi and Capezzuoli, 2009), (3) reconstruction of paleoclimatic and paleoenvironment (Soligo et al., 2002; Facenna et al., 2008; Liu and Wang, 2011), (4) application of travertine deposition to archaeology (Bischoff et al., 1988; Zhang and Li, 1983), optically stimulated luminescence (OSL) (Zhang and Li, 1994) have been applied for dating travertine. However, optically stimulated luminescence (OSL) dating is generally not applicable to thermogene travertines due to the presence of acid-insoluble impurities, particularly those containing Mn, where its reliable age is limited to 30,000 BP (Grün and Stringer, 1991). The U-series method, which ranges from 5000 a to 350,000 a(Ivanovich et al., 1992) and with an upper limit of 500 a(Bargar, 1978; Hancock et al., 1999; Sturchio et al., 1980; Schwarcz, 1980; Srdoc et al., 1994; Sturchio et al., 1994) have been applied for dating travertine. However, optically stimulated luminescence (OSL) dating is generally not applicable to travertine, and electron spin resonance (ESR) dating seems to be unsuitable for many epigean travertines due to the presence of acid-insoluble impurities, particularly those containing Mn, where there may be difficulties in obtaining a stable signal (Pentecost, 2005). Theoretically, the upper limit of 14C dating is 50,000 BP, but its reliable age is limited to 30,000 BP (Grün and Stringer, 1991). The U-series method, which ranges from 5000 a to 350,000 a(Ivanovich et al., 1992) and with an upper limit of 500–600 ka, may be a better choice for thermogene travertine (Hall and Henderson, 2001).

In Tibet, China, previous researches on travertines included: (1) the color, texture and carbon and oxygen isotopes of Zabuye travertine were examined and the preliminary 14C age of two travertine samples were also given (Zheng et al., 2007; Zhao et al., 2010), (2) the 85Sr/86Sr and U-series ages of 6 samples of the Nielamu travertine in southern Tibet were analyzed (Zentmyer et al., 2008), (3) geochemical features of spring-depositing travertines in eastern Tibet were discussed (Yokoyama et al., 1999; Hoke et al., 2000), (4) age of the travertine in Dingri of Tibet was detected as 100 ka (Sweeting et al., 1991). In this study the age dating of travertines in central-northern Tibet is discussed, which is of importance in providing information on the environmental evolution of the area. This work focuses on: (1) paleoclimatic and paleoenvironmental reconstruction of the studied area, and (2) providing information for the evolution of hydrogeology and encouraging future research in the Rongma hot springs area.

## 2. Geological setting and site description

The Rongma hot springs are located southeast of Rongma town and southwest of Yibuchaka (32°54′30″N; 86°34′18″E, elevation 4900 m) and lies in the middle-lower reaches of the Qingshuizi river. The Rongma geothermal area is located to the north of the Bangongcuo–Anduo–Nuijiang–Lancangjiang active fault belt. The Rongma hot springs occur in a NW-trending fault valley. Two set of faults occur in the study area. The NW-trending faults control the basin of Lake Chaka, and the NE-trending faults are later than the former. Near the Rongma hot springs region, Carboniferous–Permian metamorphic rocks crop out including white epizonal sandstone and siltstone, with chlorite schist and sericite schist to the south of the spring region and diabase near the mouth of the valley. This set of strata trend in a NE—SW direction and dip in a SE direction. On top of the mountains on both sides of the valley the metamorphic rocks are covered discordantly by Cretaceous—Paleogene red sandstone and conglomerate (Tong et al., 2000).

Hydrothermal activity occurs at the bottom of the river valley. The river valley extends 110°–125°. The river valley near the springs is V-shaped and becomes wider towards the lower reaches near Yibuchaka lake. The hot springs region is 680 m long and 100 m wide in average and has an area of 68,000 m². About 100 hot spring vents occur on the two sides of the red valley of the Qingshuizi river, and massive travertine deposits occur near the hot springs (Tong et al., 2000) (Fig. 1). These hot springs are of low-to-medium temperature, ranging from 39.5 to 72°C. On the northern side of the river, springs are relatively small, the discharge of the springs is low, and several travertine cones occur. In contrast, geothermal activity on the southern side of the river valley is relatively strong and the temperature of the hot water is relatively high, up to a maximum of 72°C. Three levels of travertine platform have developed. The first level rests on the hill slope, travertine is deposited along the slope, and a travertine cascade of 10 m high can be found. No active geothermal features were observed on this platform. The second level of travertine platform is situated lower than the first one and geothermal activities are concentrated on this platform. A 40 m long and 20 m wide hot spring pool occurs in this platform, in which more than 10 spring vents effervesce and continuously discharge hot water (temperature = 50.2°C). Thirty-seven travertine cones of 0.5 m—13 m height are present (Fig. 1). Some of the travertine cones and towers are still active and white travertine is being precipitated on the tops. The third level of travertine platform is located southeast of the second one and is situated 1 m—2 m lower than the second one. Some travertine deposits are found on this platform. In the toes of the southern slope of the valley (Fig. 1, T1—T4), a continuous layer of gravel cemented by travertine occurs and dried-up spring vents can be seen. In the southern part of the valley (T2, T3, elevation 4722 m), travertine was deposited on slate and traces of previous flowing water are observed. At site T5, gravels were cemented by travertine and a cascade 5 m high has developed. Previous channels are present below the cascade (Fig. 2).

### 3. Materials and methods

#### 3.1. Sample gathering and selection

Water samples were collected in polyethylene bottles at the hot spring pond near the sampling site in July 2010. The bottles were previously cleaned and rinsed in the hot spring. Electrical conductivity, pH and temperature of the water were measured in situ. Hydrochemical data of the water samples were determined at the Laboratory of Beijing Institute of Geological Engineering based on standards of natural mineral drinking water in China (GB/T 8538-1995). Saturation index for calcite was calculated based on the hot spring chemical data using the program PHREEQC (Fig. 3).

A travertine cone of about 5 m high near the thermal basin was selected at the second travertine platform in the study area. Using
a small diesel drill, one specimen was sampled from the bottom of the travertine cone. Unfortunately, pulverized particulate matter hung down. Therefore, use of a geological hammer was substituted. Eight travertine specimens were successively sampled from bottom to top. Specimens were carefully put in individual canvas bags and numbered consecutively RM01–RM08 (Fig. 4). One travertine specimen numbered RM10 was collected from the third travertine platform of the bank of the Qingshuihe river using a small diesel drill. Determinations of the U and Th isotopes of the travertine samples were performed in the Uranium-series Geochronology Laboratory of the Institute of Geology and Geophysics of Chinese Academy of Sciences. The measuring instrument was an Octête plus...
alpha-spectrometer with a vacuum of 20 mT and an energy resolution (FWHM) of about 30 keV at 5.15 MeV, measuring alpha spectra of U and Th isotopes were corrected by multiple factors (Ma et al., 2010).

3.2. 230Th age estimation of the travertine samples

In natural water, U and CO₃⁻ form the uranium milling complex anions (UO₂(CO₃)₃⁴⁻ and UO₂(CO₃)₃³⁻), easily soluble in water. In contrast, Th⁴⁺ is easy to hydrolyze, precipitate or adsorb on clay particulate matter. Calcium carbonates usually contain traces of uranium, and Th contents can be ignored at the time of formation. 230Th is a daughter product of 234U with a half-life of 75.2 ky in the 238U → 234U → 230Th radioactive decay system. Assuming that travertine deposition proceeded in a close system, the initial 230Th is zero, and the age of travertine can be calculated from the ratios of 230Th/234U and 234U/238U. The age of the carbonates can be obtained from the extent of disequilibria between 230Th and 234U and between 234U and 238U by the following equation (Kaufman and Broecker, 1965):

\[
\frac{230\text{Th}}{234\text{U}} = \frac{238\text{U}}{234\text{U}} \left(1 - e^{-\lambda_{234}t}\right) + \frac{\lambda_{230}}{\lambda_{234}} \left(1 - \frac{238\text{U}}{234\text{U}}\right) \left[1 - e^{-\left(\lambda_{234} - \lambda_{230}\right)t}\right] \tag{1}
\]

Where \(\lambda_{230}\) and \(\lambda_{234}\) are decay constants of 230Th and 234U, respectively, \(\lambda_{230} = 2.8263 \times 10^{-6}/\text{a}\) and \(\lambda_{234} = 9.1577 \times 10^{-6}/\text{a}\) (Cheng et al., 2000), and \(t\) is the age of the sample which can be calculated with iteration procedure.

Generally, travertine contains aluminosilicate and limestone particles as well as organic matter. These contaminants often carry large amounts of uranium compared to the calcite itself and do not reflect radioactive disequilibrium related to the time of carbonate formation (Mallick and Frank, 2002). Thus any contaminants will seriously affect the accuracy of the dating. In addition, weathering causing the dissolution and re-precipitation of carbonate is still difficult to handle. Typically, if a 230Th/232Th ratio is greater than 20, the influence of initial detrital 230Th is negligible, and an uncorrected age estimate is almost acceptable. 230Th/234U ages require significant correction for detrital contamination if the value of 230Th/234U ratio is less than 20 (Schwarz, 1980; Bischoff et al., 1994; Auler and Smart, 2001).

Detrital 230Th can be corrected by using the following correction methods: leachate–leachate (L/L) method (Schwarz and Latham, 1989), leachate–residue (L/R) method (Ku and Liang, 1984; Herczeg and Chapman, 1991; Sturchio et al., 1994; Liu and Ma, 1998) and total-sample dissolution (TSD) method (Bischoff and Fitzpatrick, 1991; Luo and Ku, 1991; Rihs and Condomines, 2000; Auler and Smart, 2001). The first two methods give the same age only if there is no differential isotopic fractionation (DIF) of U or Th during the partial dissolution of the residue. If DIF occurs but is uniform for all leachates, the L/L method gives the true age of the deposit, but the L/R age will generally be in error (Schwarz and Latham, 1989). The L/L method is also simpler than methods requiring total dissolution of the detrital component. Kaufman...
(1993) compared these leaching methods and the results indicated that the L/L method yielded valid ages in contrast to leachate–residue procedure. If the travertines are simply binary mixtures of carbonate and a single detrital component, TSD scheme is the most appropriate to measure their age (Bischoff and Fitzpatrick, 1991). An important prerequisite for these correction methods is that no U–Th isotopic fractionation occurs when the sample is dissolved (Ma et al., 2010).

3.3. Experimental procedures

Nine solid samples were ground to powder (<100 mesh) after being cleaned. About 10 g of the sample were baked in an oven at 600 °C for 2 h and then dissolved in 2 M HNO3. HNO3 + HF + HClO4 were added in the solution to remove insoluble material. The insoluble residue was separated from the solution by centrifugation, and about 2 g tracer 228Th–232U and 10 ml Fe3+ was then added and heated to boiling. Subsequently NH4OH was added to co-precipitate the U–Th isotopes. The solution and sediment were centrifuged with 8 M HCl then transferred to a separatory funnel. Briefly, evaporated sample was dissolved in 8 M HCl, and injected into an anion exchange column (BIORAD AG1 × 8, 100–200 meshes, 10 × 1 cm) to isolate Th. Iron and ammonia were washed off the column with 8 M NH4NO3–0.1 M HNO3 after 8 M HCl, then U was eluted with 0.1 M HNO3. Isolated Th was evaporated to dryness, dissolved in 7 M HNO3, and added to an anion exchange column washed with 7 M HNO3. Th was eluted off the anion exchange column with 8 M HCl. The purified U and Th were evaporated to dryness and leached with 0.1 M HNO3. U and Th were extracted with a mixture solution of 0.4 M TTA-benzene at pH of 1–1.5 and 3–3.5. After centrifugation, the upper solution was dropped on stainless steel planchets and heated. The planchets were burned with an alcohol burner before final instrumental measurements.

For the requirements of the measurement accuracy, the National Standard Reference Material (CRM) (GBW04412 and GBW04413) were analyzed. The results show that the analyses coincide with the average value of 26 laboratories from nine countries in the Uranium-Series Intercomparison Project II (abbreviated as USIP-II) (Ivanovich and Warchal, 1981), meaning the measurement process would be reliable.

4. Results

Na-HCO3 water of the hot spring pool discharges mainly from seven spring orifices at the second level of travertine platform with an altitude of 4712 m. The hot spring pool is characterized by temperature, pH, and electrical conductivity values of 50.2 °C, 6.47 standard units and 10,320 μS cm⁻¹, respectively. The measured flow rate is about 5 l s⁻¹ and the TDS is 5180 mg/L. Hydrochemical data (Table 1) shows that the travertine is a formation of moderate temperature geothermal system with high mineralization. Na2+ is the first major cation accounting for 70.4% equivalent to the sum of cations and Ca2+ only accounts for 13.5%. HCO3 is the major anion and the milliequivalent percentage is 77.7%. The hot spring water is supersaturated with respect to calcite.

The mineral composition of travertine in Tibet is mostly calcite. Aragonite is secondary in travertine. The tall and large sinter pillars in the Rongma hot spring region are composed of calcite and aragonite. Those carbonates are all composed of fine needle-shaped calcite minerals with good crystallization (Tong and Zhang, 1981; Zheng, 1988).

Isotopic ratios and ages of the 9 samples are listed in Table 2. U contents of the samples range from 0.298 to 1.363 ppm, and 234U/238U with values from 1.462 to 1.700, which indicate that the sediments of U is mainly authigenic and major loss and migration in U isotopes do not occur.

The ages of 8 travertine samples RM01–RM08 obtained from the second travertine platform ranged from 4600 ± 200 a to 11,500 ± 400 a. Basal sample RM01 yielded the oldest age of 11,500 ± 400 a, and the uppermost sample, RM08, yielded an age of 6300 ± 300 a (Fig. 4). However, the youngest age was, unexpectedly, obtained from RM04 in intermediate position of the travertine cone. Furthermore, two of the samples yielded younger ages (RM05 = 5700 ± 200 a, RM07 = 5300 ± 200 a, respectively, Fig. 4). In the third travertine platform, the age of the RM10 sample is 6100 ± 400 a.

5. Discussion

5.1. Paleoclimatic implications

Travertine deposition is frequently associated with warm and humid climate (Frank et al., 2000; Rihs and Condaminres, 2000; Soligo et al., 2002). Many of the U-series ages (4600 ± 200 a, 5300 ± 200 a, 5700 ± 200 a, 6300 ± 300 a, 7000 ± 300 a, 7700 ± 400 a and 8700 ± 400 a) of the travertine cone from the Rongma geothermal field fall within the time interval between 4500 and 10,000 a. This time period is characterized by generally high δ18O values in the Hulu Cave stalagmites and in Guliya ice cores, respectively, reflecting a period of persistently warm and wet climate. The Vostok ice core in East Antarctica providing a wealth of climate information reveals that the Holocene, which has already lasted 11 ka, is, by far, the longest stable warm period recorded in Antarctica (Petit et al., 1999). The age of 4600 ± 200 a for the most
Corresponds to the termination of the Younger Dryas (YD) at Hulu Cave (11,473 ± 100 a, Wang et al., 2001). Zentmyer et al. (2008) have shown that travertine deposits (5400 ± 950–11,600 ± 1000 a) near Nyalam in Tibet existed in the same period with the Rongma hot spring travertines (4600 ± 200–11,500 ± 400 a). The period corresponds to a time of higher intensity in the Indian Ocean monsoon (Sirocko et al., 1993), which could have elevated spring flow in Tibet, and thus increased the volume and/or rate of travertine precipitation (Zentmyer et al., 2008).

Characteristics of a warm and humid climate of early to mid-Holocene were disclosed in the research on pollen and diatom at the Taicuo ancient lake of Tibet (Liu et al., 2004, 2011). Holocene were disclosed in the research on pollen and diatom at the Taicuo ancient lake of Tibet (Liu et al., 2004, 2011). At the same time, the Qinghai–Tibet plateau was influenced by a strong summer monsoon, the climate of the Holocene was warmer than today’s, and the temperature was 2–4°C higher than current average value (Gasse et al., 1991; Auvac et al., 1996; Shi et al., 1999).

The influence factors are less documented for the reduction and cease of thermogene travertines. Three main inferences have been revealed: the first states the effects of climate change (Frank et al., 2000), the second is related to climate and fault activities (Faccenna et al., 2008), and the third invokes anthropic causes (Dilsiz, 2002). The Rongma hot spring area of Tibet is uninhabited. Thus, the travertine deposition is hardly affected by human activity, and the stop of travertine deposition at the Rongma hot springs of Tibet could be related to climatic change to some extent.

### 5.2. Geological and geomorphological implications

The distribution of most natural hot springs is closely related to fault activities, and most travertine deposits accumulate close to active fault traces (Hancock et al., 1999; Uysal et al., 2009). This is because faulting plays a key role in the transport of hydrothermal fluids (Sibson, 1996). Hot springs usually occur in the fault crushed zones of fault valleys and piedmont regions or nearby areas and the cross composite part of active faults in different directions. The active belt of hot springs with high temperature and the active belt of violent earthquakes sometimes have excellent corresponding relationships in space, which shows that it is an important performance pattern of crustal activity (Wu, 2004). The Rongma hot springs emerges at the potential connection part of the Yibu-chaka controlling faults or their secondary faults in the study area. Geothermal water discharges though the extension line of NW-trending faults at the bottom of the valley. In the Rongma hot springs area, travertines are formed as massive deposition with various landforms. In addition to the conventional morphotypes (cascades, terraces, mounds), there are other depositional morphologies, for example, travertine bridges and towers, and

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**Table 2**

Results of U-series dating of the travertines in the Rongma hot springs.

<table>
<thead>
<tr>
<th>Sample number</th>
<th>$^{238}$U (ppm)</th>
<th>$^{238}$U ($\text{mBq/g}$)</th>
<th>$^{232}$Th ($\text{mBq/g}$)</th>
<th>$^{232}$Th/$^{238}$U</th>
<th>$^{230}$Th/$^{232}$Th</th>
<th>$^{230}$Th/$^{234}$U</th>
<th>Uncorrected age (ka)</th>
<th>Corrected age (ka)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RM-01</td>
<td>0.748 ± 0.008</td>
<td>9.240 ± 0.219</td>
<td>1.555 ± 0.045</td>
<td>0.160 ± 0.011</td>
<td>1.532 ± 0.037</td>
<td>9.713</td>
<td>0.110 ± 0.004</td>
<td>12.6 ± 0.4</td>
</tr>
<tr>
<td>RM-02</td>
<td>1.237 ± 0.040</td>
<td>22.552 ± 0.644</td>
<td>1.766 ± 0.055</td>
<td>0.107 ± 0.005</td>
<td>1.475 ± 0.048</td>
<td>16.460</td>
<td>0.081 ± 0.003</td>
<td>9.2 ± 0.4</td>
</tr>
<tr>
<td>RM-03</td>
<td>1.363 ± 0.040</td>
<td>24.839 ± 0.649</td>
<td>2.294 ± 0.109</td>
<td>0.763 ± 0.049</td>
<td>1.476 ± 0.046</td>
<td>3.087</td>
<td>0.092 ± 0.005</td>
<td>10.5 ± 0.5</td>
</tr>
<tr>
<td>RM-04</td>
<td>1.100 ± 0.028</td>
<td>20.742 ± 0.467</td>
<td>0.965 ± 0.038</td>
<td>0.145 ± 0.010</td>
<td>1.526 ± 0.038</td>
<td>6.634</td>
<td>0.047 ± 0.002</td>
<td>5.2 ± 0.2</td>
</tr>
<tr>
<td>RM-05</td>
<td>1.138 ± 0.022</td>
<td>24.000 ± 0.366</td>
<td>1.262 ± 0.034</td>
<td>0.035 ± 0.006</td>
<td>1.462 ± 0.018</td>
<td>23.736</td>
<td>0.035 ± 0.001</td>
<td>5.9 ± 0.2</td>
</tr>
<tr>
<td>RM-06</td>
<td>0.487 ± 0.013</td>
<td>9.268 ± 0.267</td>
<td>0.663 ± 0.027</td>
<td>0.112 ± 0.007</td>
<td>1.542 ± 1.044</td>
<td>5.909</td>
<td>0.072 ± 0.003</td>
<td>8.0 ± 0.4</td>
</tr>
<tr>
<td>RM-07</td>
<td>0.410 ± 0.009</td>
<td>7.692 ± 0.153</td>
<td>0.368 ± 0.016</td>
<td>0.001 ± 0.000</td>
<td>1.518 ± 0.038</td>
<td>287.454</td>
<td>0.048 ± 0.002</td>
<td>5.3 ± 0.2</td>
</tr>
<tr>
<td>RM-08</td>
<td>0.298 ± 0.008</td>
<td>6.155 ± 0.141</td>
<td>0.347 ± 0.014</td>
<td>0.006 ± 0.003</td>
<td>1.700 ± 0.002</td>
<td>1.780</td>
<td>0.006 ± 0.003</td>
<td>6.3 ± 0.3</td>
</tr>
<tr>
<td>RM-10</td>
<td>0.390 ± 0.008</td>
<td>9.410 ± 0.178</td>
<td>0.476 ± 0.025</td>
<td>0.014 ± 0.001</td>
<td>1.678 ± 0.004</td>
<td>8.742</td>
<td>0.072 ± 0.003</td>
<td>8.0 ± 0.4</td>
</tr>
<tr>
<td>GBW04412(1)</td>
<td>0.700 ± 0.015</td>
<td>212.416 ± 0.063</td>
<td>122.089 ± 2.473</td>
<td>0.857 ± 0.037</td>
<td>122.089 ± 2.473</td>
<td>122.089</td>
<td>0.575 ± 0.011</td>
<td>85.9 ± 2.2</td>
</tr>
<tr>
<td>GBW04412(4)</td>
<td>0.342 ± 0.182</td>
<td>219.341 ± 3.859</td>
<td>125.921 ± 2.415</td>
<td>0.900 ± 0.036</td>
<td>950 ± 2.2</td>
<td>219.341</td>
<td>0.574 ± 0.010</td>
<td>85.6 ± 2.1</td>
</tr>
</tbody>
</table>

Notes: (1) All the isotopic ratios reported are radioactivity ratios. (2) Uncertainties are ±1σ of all data listed in Table 1.

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Fig. 5. Orange bars encompass ±1σ error range of ages of the travertines from Rongma hot springs, and high resolution paleoclimate records δ18O of Hulu Cave stalagmites (Wang et al., 2001; Uysal et al., 2009) (purple) and Guliya Ice Core (Yao, 2000) (blue) and Marine Oxygen Isotope stage (MIS) (Martinson et al., 1987) (black), respectively. Gray bands indicate Younger Dryas (YD) (Wang et al., 2001). Numbers indicate Marine Isotope Stages. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
rare landforms of wall-like travertine. The hydrochemical conditions (for example, concentrations of $\text{Ca}^{2+}$, $\text{HCO}_3^-$, and $\text{CO}_2$) are the first necessary condition for travertine sedimentation. The factors of hydrodynamic conditions as flow rate and turbulent fluid, and biological effect (e.g. bacteria, algae and plants) influence travertine sediment rate. However, the formation of travertine cones needs numerous advantageous factors. Linares et al. (2010) found that a flat topography is necessary for the origins of mounds to make carbonate-precipitating waters form a pool around spring vents. Pentecost (2005) also hypothesized that the relative carbonate saturation of spring waters plays an important role in the geometrical characteristics of mounds, e.g. high calcite saturation produces high steep mounds, and flat round mounds reflect spring waters approximately in equilibrium.

U-series dating provided reliable age data, helping to better understand the development process of travertine deposition. Further, it helps in study of the characteristics of hydrogeology and geomorphology and paleoclimatic information. The values of $^{230}\text{Th}/^{234}\text{U}$ are less variable, indicating a relatively stable depositional environment with no growth discontinuities. The age of RM01 measured at second travertine platform is the oldest, and RM02 at the bottom end of the travertine cone is second oldest, but there are some young dates (e.g. RM04, RM05, RM07). The samples show younger upward dates, except for these three samples. Generally the cones are younger upward, but this is not always the case. If the water discharges on top, the precipitating travertine can cover the whole surface of the cone. In case of water level decrease, water can discharge at different (lower) parts of the cone.

For the third travertine platform with low terrain, the age of RM10 at the edge of the modern river course is much younger than that of RM01, and it is within the error range with RM08 at the bottom end of the travertine cone. They present very good consistency, and the results show that the travertine deposition stopped in the same period (Fig. 4). Field observations show that most of the travertine cones in study area were not growing and had serious weathering. They were retained within water channels and the huge spring orifices in the swamp. More than 100 spring vents occur on the sides of the river. It can be postulated that the previous geothermal activities of the Rongma hot springs were fierce, and the discharge of geothermal water has reduced considerably.

6. Conclusion

Humid conditions of early to mid-Holocene led to the concentration of groundwater flowing through bedrock and eventually emerging as a series of springs. The Rongma hot springs occur in the form of spring groups with temperatures of 39.3–72 °C, pH 5.85–6.47, 3490–5370 mg/L TDS and $\text{HCO}_3$-Na type water. The total flow is about 100 l s$^{-1}$. Dozens of travertine cones and/or towers with heights ranging from 0.5 to 13 m formed in the Rongma hot springs group, a 680 m long and 100 m wide geothermal area. The $\text{HCO}_3$–rich water, in which $\text{Ca}^{2+}$ is the major cation, is a factor controlling whether travertine can occur. In addition, mound construction requires several complex factors, including artesian flow, hydrostatic head, spatial and temporal of springs, supersaturated water and favorable topography. A well-dated travertine cone in Rongma provides a window into the Holocene geomorphic and climatic processes. Uranium-series ages of travertine deposition range from 4600 a to 11,500 a consisting with travertine deposits of southern Tibet-Nyalam. The range of U-series ages coincides with a higher precipitation and warmer climate associated with greater intensity of the Indian monsoon. RM10 and RM08 have a similar age, suggesting that travertine deposition followed the water table decline and flow reduction. Travertine cones are fossil features related to former palaeohydrological conditions linked to past wetter and warmer periods. Thus, the massive travertine deposits of the Rongma hot springs could serve as an archive of past climatic changes and geomorphology and paleohydrology.

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