

Article

Travertines of the South-Eastern Gorny Altai (Russia): Implications for Paleoseismology and Paleoenvironmental Conditions

Evgeny V. Deev ^{1,2,*} , Svetlana N. Kokh ^{1,3}, Yuri Dublyansky ^{1,4}, Ella V. Sokol ³, Denis Scholz ⁵ , Gennady G. Rusanov ⁶ and Vadim N. Reutsky ^{1,3} 

¹ Department of Geology and Geophysics, Novosibirsk State University, 2 Pirogov Street, Novosibirsk 630090, Russia

² A.A. Trofimuk Institute of Petroleum Geology and Geophysics, Siberian Branch of the Russian Academy of Sciences, 3 Acad. Koptug Avenue, Novosibirsk 630090, Russia

³ V.S. Sobolev Institute of Geology and Mineralogy, Siberian Branch of the Russian Academy of Sciences, 3 Acad. Koptug Avenue, Novosibirsk 630090, Russia

⁴ Institut für Geologie, Leopold-Franzens-Universität, Innrain 52, A-6020 Innsbruck, Austria

⁵ Institute of Geosciences, Johannes Gutenberg-Universität Mainz, J.-J.-Becher-Weg 21, 55128 Mainz, Germany

⁶ Gorno-Altai Expedition JSC, 15 Sovetskaya Street, Maloyeniseiskoe Village, Altai Territory 659370, Russia

* Correspondence: deev@ngs.ru

Abstract: The south-eastern Gorny Altai is one of the most hazardous seismogenic area in the north of Central Asia. We present a synthesis of field, ²³⁰Th-U geochronological, mineralogical and geochemical data collected on seven Quaternary travertines. All travertines occur within the zones of active faults that border the Chuya and Kurai intermontane basins. Travertine cement mainly comprises calcite (with minor amounts of aragonite), which cements alluvial, alluvial fan, and colluvial deposits. The results of ²³⁰Th-U dating suggest that deposition of the travertines was triggered by large paleoearthquakes in the last eight thousand years. Several stages of travertine formation with ages 9–11 ka BP correspond to the known period of strong paleoseismicity in the region (8–16 ka BP). The 123 ka BP travertine resulted from a slip triggered by the Middle Pleistocene deglaciation, while that of 400 ka BP represents seismic motions likely associated with the main Cenozoic orogenic phase. All travertine forming events fall within warm and wet climatic phases (interglacials). Large earthquakes activated faults and caused a rapid rise along them of ambient-temperature bicarbonate groundwater, which was previously sealed in deep-seated Upper Neoproterozoic–Paleozoic limestone-dolostone aquifers. Rapid CO₂ degassing of the spring water was the most important control of calcite or aragonite precipitation. Such travertines represent an important tool for paleoseismological research in seismically active regions.

Keywords: large paleoearthquake; active fault; travertine; paleoenvironmental conditions; ²³⁰Th-U dating; Gorny Altai



Citation: Deev, E.V.; Kokh, S.N.; Dublyansky, Y.; Sokol, E.V.; Scholz, D.; Rusanov, G.G.; Reutsky, V.N. Travertines of the South-Eastern Gorny Altai (Russia): Implications for Paleoseismology and Paleoenvironmental Conditions. *Minerals* **2023**, *13*, 259. <https://doi.org/10.3390/min13020259>

Academic Editors: Francesca Giustini, Mauro Brilli and János Haas

Received: 19 December 2022

Revised: 4 February 2023

Accepted: 7 February 2023

Published: 12 February 2023



Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The term ‘travertine’ refers to a large group of freshwater carbonate rocks that precipitate to form bicarbonate water upon or near the surface. As authors of many overviews note [1–3], there is no unified classification system for the calcareous fresh-water spring deposits, and differentiation between travertine and tufa is problematic. Pedley [4] and Ford and Pedley [5] defined travertines as carbonate precipitates from warm-to-hot hydrothermal water and tufas as precipitates from ambient-temperature water. Pentecost [6] and Pentecost and Viles [7] introduced the term ‘cemented rudite’ to describe surface-cemented rudites, consisting of cemented screes, alluvium, breccia, gravel, etc. We do not use the term ‘cemented rudite’ in our study.

‘Travertine-cemented gravel’ [8,9], ‘conglomerate carbonate cements’ [10], or ‘carbonate cement in gravels’ [11,12] are considered as an independent lithofacies genetically

related to a travertine-deposition system. This carbonate cement precipitated from ascending bicarbonate waters discharged into the permeable colluvium, till, alluvium, and mixed debris sediments. This process leads to the deposition of variably inclined large bodies (up to several square kilometres). Obviously, erosion is the reason why we often are dealing with the remnants of the originally large bodies and have not found travertine lithofacies associated with vent or slope environments, feeding channels along active faults, calcite veins associated with fractures, fluid escape features, etc. The incorrect definition of the 'travertine-cemented gravel' lithofacies leads to the loss of a huge archive of paleoseismological and paleoclimatic information on mountainous areas. According to Pentecost [1], the term 'travertine', in its broadest sense, refers to all chemically precipitated continental carbonate precipitates formed in or near seepages, springs, along streams, rivers, and occasionally in lakes. It is in this way that the term 'travertine' is applied for both travertine and tufa fossil deposits by Claes et al. [13,14]. In our study, the term 'travertine' is always used in its broadest sense.

Travertines can be classified according to several criteria, the most important being the stable isotope composition, geochemistry, fabric and morphology, and the depth at which the travertine-forming fluids circulated [1,7,14–16]. Pentecost [1] divided travertines into 'meteogene' and 'thermogene' according to the carrier of CO₂ incorporated in travertine formation. The CO₂ involved in 'meteogene' travertine precipitation has meteoric origin (vegetation, soil, and atmosphere). Waters of 'meteogene' travertines are often characterized by ambient temperatures. The CO₂ for 'thermogene' travertines originates from deeply seated thermal processes (magmatic CO₂, decarbonation of sedimentary calcareous parent rocks during regional and contact metamorphism). Travertines of thermogenic origin are enriched in ¹³C. 'Thermogene' travertines often precipitated from hot spring water, but thermogene source waters are not necessarily hot [1]. According to Crossey et al. [15] waters containing deeply derived CO₂ (regardless of temperature) are classified as 'endogenic'.

The origin of travertine-forming fluids is frequently associated with different source rocks dissolved in non-hydrothermal superficial ('epigean') or hydrothermal deep ('hypogean') hydrogeological systems. The classification of travertines as 'epigean' or 'hypogean' was based on the stable isotope composition of CaCO₃ [16]. The Ba/Sr ratio was used in the reconstruction of source rock lithology prevailing in the hydrogeological or paleo-hydrogeological reservoir. In this study, the travertine classification is based on Teboul et al. [16].

Travertines may be relevant for paleoclimate studies, providing information on, e.g., the climate-controlled temperature of groundwater; provenance of atmospheric precipitation, recharging groundwater; characteristics of soils and intensity of biological activity in them; etc. [17–22]. Numerous studies on Quaternary travertines worldwide have demonstrated the close link between the circulation of travertine-forming fluids and active faulting [23–41]. Attempts have been made to link the mobilisation of CO₂-rich fluids to seismic triggers, to use travertines, which source fluids have deep origin, to determine the age and recurrence periods of paleoearthquakes, and to estimate slip rates and coseismic slip along seismogenic faults [42–49]. These travertines are also used for the estimation of the CO₂ flux from tectonically active regions in the Earth's atmosphere, necessary to understand the global geological carbon cycle [50].

Gorny Altai (49–52° N, 82–90° E) represents the northern end of the fan of the Mongolian Altai structures, and together with the latter is part of the system of intracontinental Cenozoic orogens in northern Central Asia, formed as a far-field response to the India–Eurasia convergence and collision [51]. The neotectonic crustal deformation and mountain growth in the Gorny Altai, especially intensified during the Quaternary period, produced 6 km of structural relief (between high mountain ranges and the bottoms of the large intermontane basins), based on the displacement of the Mesozoic pre-orogenic erosion surface [52–55]. They were accompanied by strong seismicity and occurred at times of significant climate change [56–62].

To date, several dozen travertine deposits have been documented in various areas of the Gorny Altai [63,64]. Importantly, in the south-eastern part of the Gorny Altai (Figure 1) all known travertine deposits are spatially associated with zones of active faults [41,48,65,66]. The goals of this study are: (1) the generalization of the available data on the structures of travertine deposits of the south-eastern part of the Gorny Altai, and their petrographic, mineralogical and geochemical features and ^{230}Th -U geochronology; (2) the correlation of episodes of travertine formation with movements along active faults, including the ages of paleoearthquakes; (3) the evaluation of the possible connection between travertine formation and the climate.

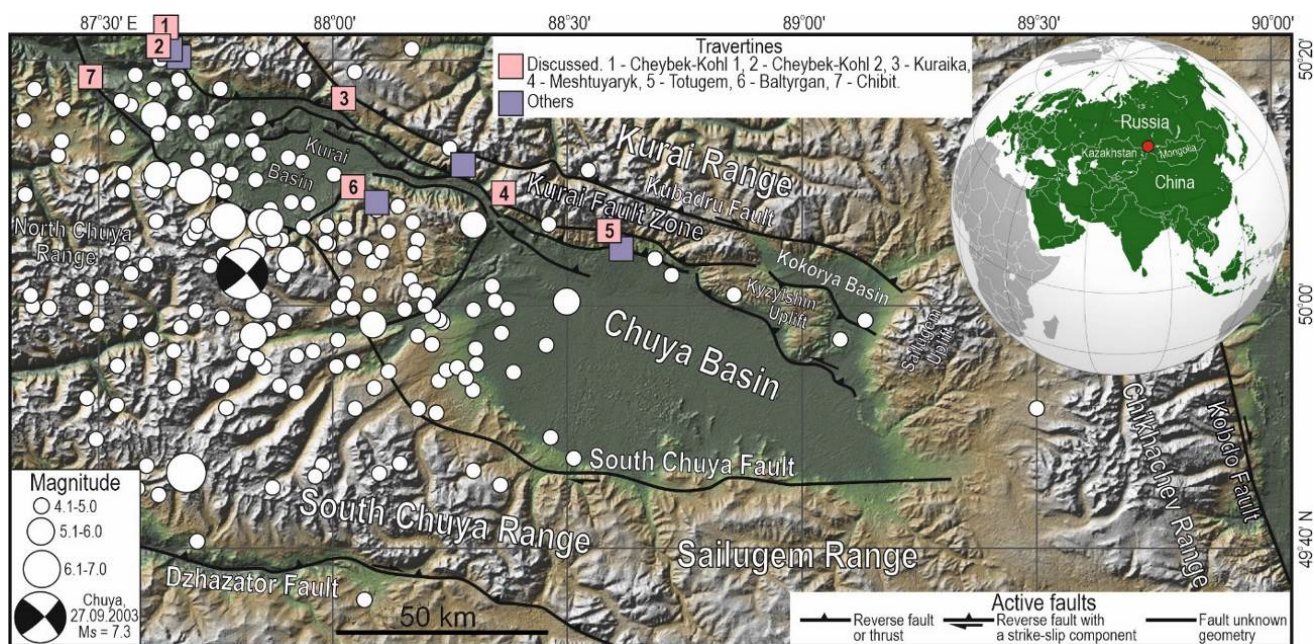


Figure 1. Main active faults, earthquakes, and travertines in the south-eastern Gorny Altai. Base map was made from GeoMapApp (<http://www.geomapp.org>, accessed on 5 December 2022) [67].

2. Geological Setting

2.1. Morphostructures of the South-Western Gorny Altai

The main morphostructures in the south-western Gorny Altai are mountain ranges with altitudes of 3000–4000 m a.s.l.: North Chuya, South Chuya, Sayluygem, Chikhachev, and Kurai ranges. The ranges frame the Chuya (70 × 35 km), Kurai (35 km × 20 km), and Kokorya (23 km × 9 km) intermontane basins (Figure 1). The Chuya and Kurai basins are separated from each other by the Chagan Uplift (2900 m a.s.l.), and the Chuya and Kokorya basins by the Kyzylshin Uplift (2560 m a.s.l.).

Cenozoic siliciclastic infill of the basins overlies the deformed Late Neoproterozoic–Carboniferous and Jurassic volcanogenic, siliciclastic, and carbonate rocks (Figure 2) as well as relics of the Late Cretaceous–Paleogene weathering crust [68]. Controlled-source resistivity results show that the thickness of the infill reaches 1.0–1.6 km [53,54,56,69]. The basins were formed in the Paleogene–Neogene period as pull-apart structures, in which 600–800 m of fine-grained lacustrine (in the central parts of the basins) and coarser near-shore lacustrine and alluvial (closer to basin margins) sediments have accumulated [53,54,70,71]. In the Early to the earliest Middle Pleistocene period the main phase of the Cenozoic orogenesis and the growth of mountain ranges occurred. At that time the pull-apart structures transformed into basins bounded by thrusts and reverse faults. Up to 300 m of coarse brown intermountain molasse have accumulated in the basins [52–54,71]. The upper part of the sedimentary fill of the basins comprises Middle Pleistocene–Holocene glacial, fluvioglacial, alluvial, limnic, mud-debris, colluvial, and aeolian sediments [53,56,63,72].

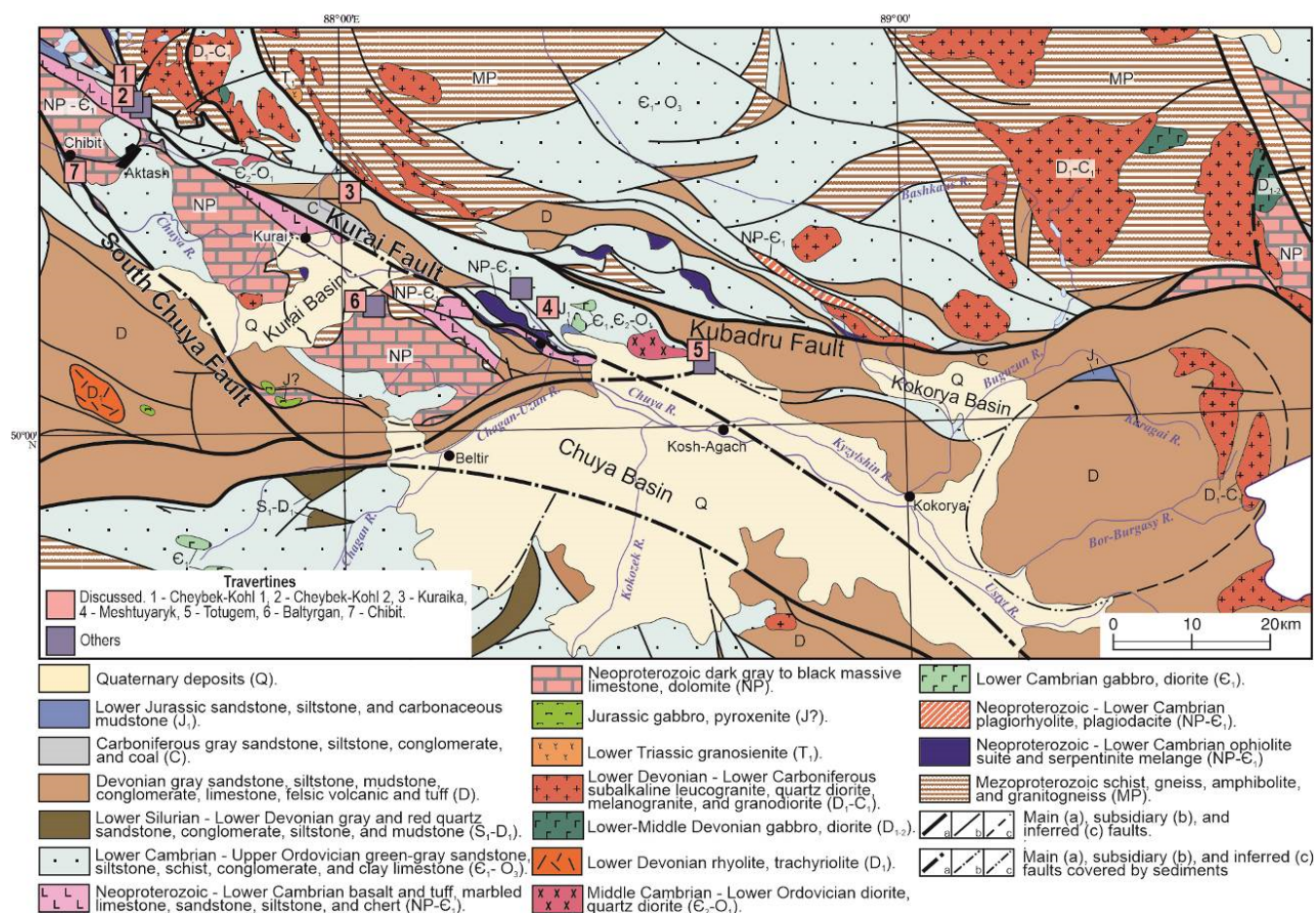


Figure 2. Geological map of the south-western Gorny Altai (simplified from [73]), showing locations of travertine occurrences.

2.2. Active Faults and Seismicity

The Kurai and Chuya basins are bordered to the south by the active South Chuya Fault (Figure 1), separating them from the North- and South Chuya ranges [74,75]. The Chuya (the Altai) earthquake (27 September 2003; $M_s = 7.3$, $I = IX$) with its epicenter at the back of the Chagan Uplift, the largest of the historic and instrumental Gorny Altai earthquakes, was associated with the South Chuya Fault (Figure 1). Its largest aftershocks occurred on 27 September 2003 ($M_s = 6.4$) and 1 October 2003 ($M_s = 6.6$). The main shock and the largest aftershocks had a dextral strike-slip focal mechanism with a NW trending plane [76]. The earthquake caused the formation of surface ruptures exceeding 70 km in length. In the vast areas of the Chuya and Kurai basins, multiple secondary seismic deformations, triggered by this large seismic event, have been detected [77,78].

The structure at the northern margin of the Chuya, Kurai, and Kokorya basins (Figure 1) is controlled by the active Kurai Fault Zone (KFZ). The positive flower structure of the KFZ with the Kubadru master fault is the result of transpression [52,71,74]. The Kubadru Fault dips towards the N-NE reverse fault with a dextral strike-slip component. To the south, there is a series of sub-parallel reverse faults and thrusts along which the Kurai Range thrusts over the basins. The backthrusts with a southern dip are pinnate to them. The displacements along the two fault systems lead to the growth of forebergs at the ridge front. Forebergs separate narrow (from a few meters to a few kilometres) negative morphostructures from the Chuya, Kurai, and Kokorya basins [57,71,74,79,80]. The regional seismological catalogues contain records only $M \leq 5$ instrumental and historic events along the KFZ. Morphostructural and seismological data also indicate that the faults associated with the Chagan and Kyzylshin uplifts are still active [48,71,80].

Numerous fault scarps and large landslides known in the area indicate that abundant large Late Pleistocene–Holocene paleoearthquakes are associated with the South Chuya Fault and the KFZ [57,74,77]. Trenching studies, supported by radiocarbon, optically stimulated luminescence, and infrared-stimulated luminescence dating revealed that at least 12 large paleoearthquakes with Mw of 6.6 to 7.6 occurred along the Kurai faults over the past 16 thousand years [49,57,71,74,79,81].

2.3. Climate, Permafrost, and Hydrogeology

The south-eastern Gorny Altai is characterized by a sharp continental climate and desert-steppe landscapes. The mean temperatures in January are from -26 to -30 °C, and in July 10 to 14 °C; the mean annual temperature is -6 °C. The areal distribution of precipitation is heterogeneous: the annual amounts range from 67 to 300 mm in the intermontane depressions and 600 to 800 mm on the slopes of the mountain ranges [82].

The Chuya and Kurai depressions and the surrounding mountain ranges are affected by permafrost, whose thickness ranges from 6 to more than 100 m [82,83]. On the surface, permafrost manifests as patterned ground and pingos. Numerous thermokarst lakes are associated with permafrost degradation.

The Chuya and Kurai intermontane basins host the largest artesian basins of the Gorny Altai, whose aquifers are associated with Neogene-Quaternary sediments. Fissure waters are ubiquitous in the bedrock of the basin rim, often associated with fault zones. Such waters discharge as descending low-yield springs, most of which are known in the Kurai Range. Fissure waters are recharged primarily by the infiltration of meteoric precipitation and meltwater. Fresh (salinity up to 0.5 g/L) bicarbonate Ca-Mg, Ca and Ca-Na groundwaters prevail in the area. Bicarbonate-sulphate Ca (0.5–1.0 g/L) and sulphate Na-Mg (up to 1–3 g/L) waters occur locally in the south-east of the Chuya Basin [84].

3. Materials and Methods

3.1. Field Studies and Sampling

Seven travertine occurrences in the south-eastern Gorny Altai were examined and sampled in the course of field expeditions in 2017–2021. The field documentation included the determination of the linear dimensions of travertine bodies, the evaluation of their relationships with the underlying and overlying sediments and rocks, and the mapping of zones of active faults and fracturing. Fifty-five samples of fossil travertines, five samples of modern precipitates, and three samples of spring water were collected. Spring water temperature (T) and pH values were measured in situ with a manual Hanna Instruments PH ORP Combo Meter & Temperature Gauge (HI98121) to a precision of 0.1 °C and 0.1 pH.

3.2. Petrography, Mineralogy and Mineral Chemistry

The petrographic study was assessed by optical petrography on thin sections in both transmitted and reflected light using an Olympus BX51 optical microscope at the Analytical Centre for Multi-Elemental and Isotope Research (Sobolev Institute of Geology and Mineralogy (IGM), Novosibirsk, Russia).

Mineral phases ($\geq 1\%$) were identified by X-ray diffraction analysis (XRD) in powdered samples. All specimens were analysed on a Shimadzu XRD-600 diffractometer (Shimadzu Corporation, Kyoto, Japan) ($\text{CuK}\alpha$ radiation with a graphite monochromator, $\lambda = 1.54178$ Å) at the South Urals Research Centre of Mineralogy and Geoecology (SU FRC MG) Miass, Russia). The scans were recorded from 6 to 60° 2 θ at 0.05° 2 θ increments with a 5 s scanning time per step.

Scanning electron microscopy (SEM) was applied to characterize the phase distribution and to identify minerals based on back-scattered electron (BSE) images, energy-dispersive spectra (EDS), and elemental maps (EDS system). The polished thin sections were sputter-coated with ~15–25 nm carbon films for SEM examination. The measurements were performed on a Tescan Mira 3MLU scanning electron microscope (Tescan Orsay Holding, Brno, Czech Republic) equipped with an Oxford AZtec Energy Xmax-50 microanalyses

system (Oxford Instruments Nanoanalysis, Abingdon, UK), at IGM (Novosibirsk, Russia). An accelerating voltage of 20 kV and 1 nA beam current were used in low- (40–60 Pa) or high-vacuum modes at a 20 s count time.

The chemical composition of minerals was determined by wavelength-dispersive electron microprobe analysis (EMPA) on carbon-coated polished samples (IGM, Novosibirsk). Carbonates were analysed on a Jeol JXA 8100 electron microprobe microanalyzer (Jeol, Tokyo, Japan) at an accelerating voltage of 20 keV, a beam current of 15 nA, and a peak counting time of 10 s. The mineral compositions were estimated with reference to natural and synthetic standards: albite (Na), diopside (Mg, Ca), BaSO₄ (Ba, S), pyrope (Fe), Sr-Si glass (Sr), Mn-almandine (Mn), fluorapatite (P), Y₃Al₅O₁₂ (Y). The detection limits for the elements were (in wt%): 0.02 for P; 0.03 for Na, Fe and Ca; 0.04 for Mn; 0.05 for S and Sr; 0.06 for Y; and 0.08 for Ba (3 σ). The matrix correction using the ZAF algorithm (generalized algebraic procedure; assumes a linear relation between concentration and X-ray intensity) was applied to the raw data prior to recalculation into elements. Analytical accuracy was within 2 rel% for [C] > 5 wt% elements, and ca. 5 rel% for [C] < 2 wt% elements [85].

3.3. Rock Chemistry

Minor and trace elements, including REE, in isolated carbonate fractions from travertine samples were determined with inductively coupled plasma mass spectrometry (ICP-MS) on an Agilent 7700 $\times$ spectrometer (Agilent Technologies, Inc., Santa Clara, CA, USA) at the SU FRC MG (Miass, Russia). Selective dissolution of CaCO₃ followed a modified procedure of Feng et al. [86]. Powdered samples (0.2 g) were rinsed in 50 mL of water (Milli-Q) in an ultrasonic bath. The obtained solutions were centrifuged and the supernatants were carefully decanted to remove any water-soluble salts. Then, the insoluble residues were dissolved in 5% HNO₃ in a centrifuge tube for 2–3 h to isolate the carbonate phase. The solutions were centrifuged and the supernatants were stored for analysis. The analyses were ran in triplicate, and the results differed for <5%. Precision and accuracy were estimated to be 10–15 rel% for all elements. The detection limits for trace elements were in the range 0.01–0.5 μ g/l. The analytical reproducibility was monitored using a BCR-2 standard (U.S. Geological Survey, Denver, CO, USA), in which the measured values were consistent with the certified ones.

3.4. Stable Isotope Geochemistry of Carbonates

For the measurement of C and O stable isotopes in bulk travertine samples (Table S1), 26 powdered carbonate samples were dissolved in 100% phosphoric acid at 50 °C for over 48 h and then analysed on a Gas Bench II instrument coupled with a MAT 253 mass spectrometer (Thermo Finnigan, Waltham, MA, USA) at IGM (Novosibirsk, Russia). All isotope values are quoted in per mill (‰) using δ -notation relative to the Vienna Pee Dee Belemnite (V-PDB), with accuracy of <0.1‰ for $\delta^{13}\text{C}$ and 0.2‰ for $\delta^{18}\text{O}$ (1 σ).

Additionally, the 105 powdered carbonate samples were taken from 17 hand specimens (Table S1). For each specimen, multiple samples were taken across the growth zones of mineral aggregates. Powders were reacted with 99% orthophosphoric acid and analysed using a Delta V Plus isotope ratio mass spectrometer equipped with a Gasbench II (Thermo Fisher Scientific, Waltham, MA, USA) at the Institute of Geology, University of Innsbruck. The results were calibrated against international calcite reference materials and reported relative to the VPDB standard. The long-term precision for $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ was 0.06 and 0.08‰, respectively (1 σ [87]).

3.5. Water Chemistry and Stable Isotope Analysis

Major- and trace-element concentrations in three water samples were measured at the Institute of Geology, Innsbruck University by inductively coupled plasma–optical emission spectrometry (ICP-OES) on an Activa spectrometer (HORIBA Jobin Yvon SAS, Edison, NJ, USA) and by titration. Major cations and trace elements were analysed in 15 water aliquots which were stored separately and then acidified with 0.5 mL of 15 N distilled nitric

acid; anions were determined in another 50 mL aliquot of unacidified water. Oxygen and hydrogen isotope compositions of H₂O were studied at the Institute of Geology, Innsbruck University using a L-2130-i analyser (Picarro, Santa Clara, CA, USA). The results were statistically processed and normalized against the Vienna Standard Mean Ocean Water (V-SMOW). The measurement accuracy was 0.1‰ for $\delta^{18}\text{O}$ and 0.4 for $\delta^2\text{H}$ (1 σ). The PHREEQC software can be used to calculate the saturation index (SI) values of the minerals in water [88].

3.6. ²³⁰Th-U Geochronology

Nineteen samples of travertines were dated by the ²³⁰Th-U method. Thirteen samples were prepared and analysed at the Institute for Geosciences, University of Mainz, Germany, using a Neptune Plus multi-collector inductively coupled plasma mass spectrometer (MC-ICPMS) (Thermo Scientific, Bremen, Germany). Six samples were prepared and analysed at the Max Planck Institute for Chemistry, Mainz, Germany, using a Nu Plasma MC-ICPMS (Nu InstrumentsTM; Nu Instrument Ltd., Wrexham, Wales, UK). Typical sample sizes were 0.3 g. Chemical separation of U and Th in both laboratories was performed as described by Yang et al. [89]. Details of the MC-ICPMS analyses in both laboratories are described by Obert et al. [90], a detailed description of the calibration of the mixed U-Th spike used in both laboratories is given by Gibert et al. [91]. To account for the potential effects of detrital contamination, all ages were corrected assuming an average upper continental crust ²³²Th/²³⁸U mass ratio of 3.8 for the detritus and ²³⁰Th, ²³⁴U and ²³⁸U in secular equilibrium. All activity ratios were calculated using the half-lives of Cheng et al. [92]. Ages are reported in thousands of years before present (ka BP); age uncertainties are quoted at 2 σ -level.

4. Results

4.1. Description of the Travertines

4.1.1. The Cheybek-Kohl 1 Travertines

The Cheybek-Kohl 1 travertine is located at the western flank of the KFZ (Figures 1 and 2), in close proximity to the active Kurai Fault line (Figure 3A). The area of the Kurai Fault in the terrain is expressed by a deep gorge that divides the Kurai and Aygulak ranges. The gorge hosts the Cheybek-Kohl lake, which formed as a result of the Chibitka River being dammed by a debris flow cone. The travertine body is located in the upper reaches of a creek, a left tributary of the Chibitka River, 168 m above the Cheybek-Kohl lake, at 1958 m a.s.l. (50.400556° N, 87.611389° E) (Figure 3A). In the modern relief, only a few remnants of the original large travertine complex have survived. In August 2015, the largest remnant with the size 12 × 6.5 × 2 m was found (Figure 3B). The valley hosts abundant boulders of breccia with travertine cement (Figure 3C). In travertines, calcium carbonate cements grey Holocene colluvium, forming breccias (Figure 3B-E). Carbonate also lines the walls of tensional fissures in underlying shale and/or fill them along with shale clasts (Figure 3F).

4.1.2. The Cheybek-Kohl 2 Travertines

The Cheybek-Kohl 2 travertine crops out 0.5 km west of the Cheybek-Kohl 1 travertines, at the shore of the lake with the same name (Figures 1, 2 and 3A; 50.40144° N, 87.60491° E; 1818 m a.s.l.). Travertine carbonate cements grey colluvium, which predominantly consists of fragments of Devonian shale, forming a breccia (Figure 4A–D). The apparent thickness of the outcrop is 2.5–4.0 m (Figure 4A). The travertine body can be traced for 29 m along the base of the mountain slope. Water seeps are observed in the south-eastern part of the breccia body (Figure 4E). At these discharge sites, fresh carbonate precipitates on the older breccia, forming a white-yellow or brownish laminated travertine crust, not exceeding 1–2 mm in thickness. The surface of the modern precipitates is coated by microbial colonies and algae (Figure 4F).



Figure 3. Location and morphology of the Cheybek-Kohl 1 and Cheybek-Kohl 2 travertines. (A) Active faults, location, and U-Th dates of the Cheybek-Kohl 1 (50.400556° N, 87.611389° E) and Cheybek-Kohl 2 (50.40144° N, 87.60491° E) travertines. (B) Remnant of the breccia with travertine cement capping the colluvium. (C) Boulders of breccia with travertine cement truncated by a creek. (D,E) White-yellow sparry and micritic calcite cementing Lower Devonian shale clasts; druse calcite aggregates are present in voids and small cavities. (F) Tensional fissures, lined with travertine carbonate and hosting shale clasts.

4.1.3. The Kuraika Travertines

The Kuraika travertines are located on the southern slope of the Kurai Range, overthrust along the KFZ on the deposits of the Kurai Basin (Figures 1, 2 and 5A). The spring is located some 770 m above the bottom of the Kurai Depression (50.28034° N, 88.00408° E, 2029 m a.s.l.). The spring discharges from the debris, formed by the destruction of the Lower-Middle Devonian siltstones and sandstones (Figure 5B). At the spring orifice, the ferruginization of debris surfaces is notable. No signs of modern travertine formation were found (Figure 5C). A scree slope of yellowish colour can be traced from the spring down the slope for 200 m (Figure 5B). The colour of the talus is due to the abundance of travertine debris (Figure 5D). These fragments are formed during the destruction of

travertine-cemented breccias. Small outcrops of such breccias can be found locally under the scree.

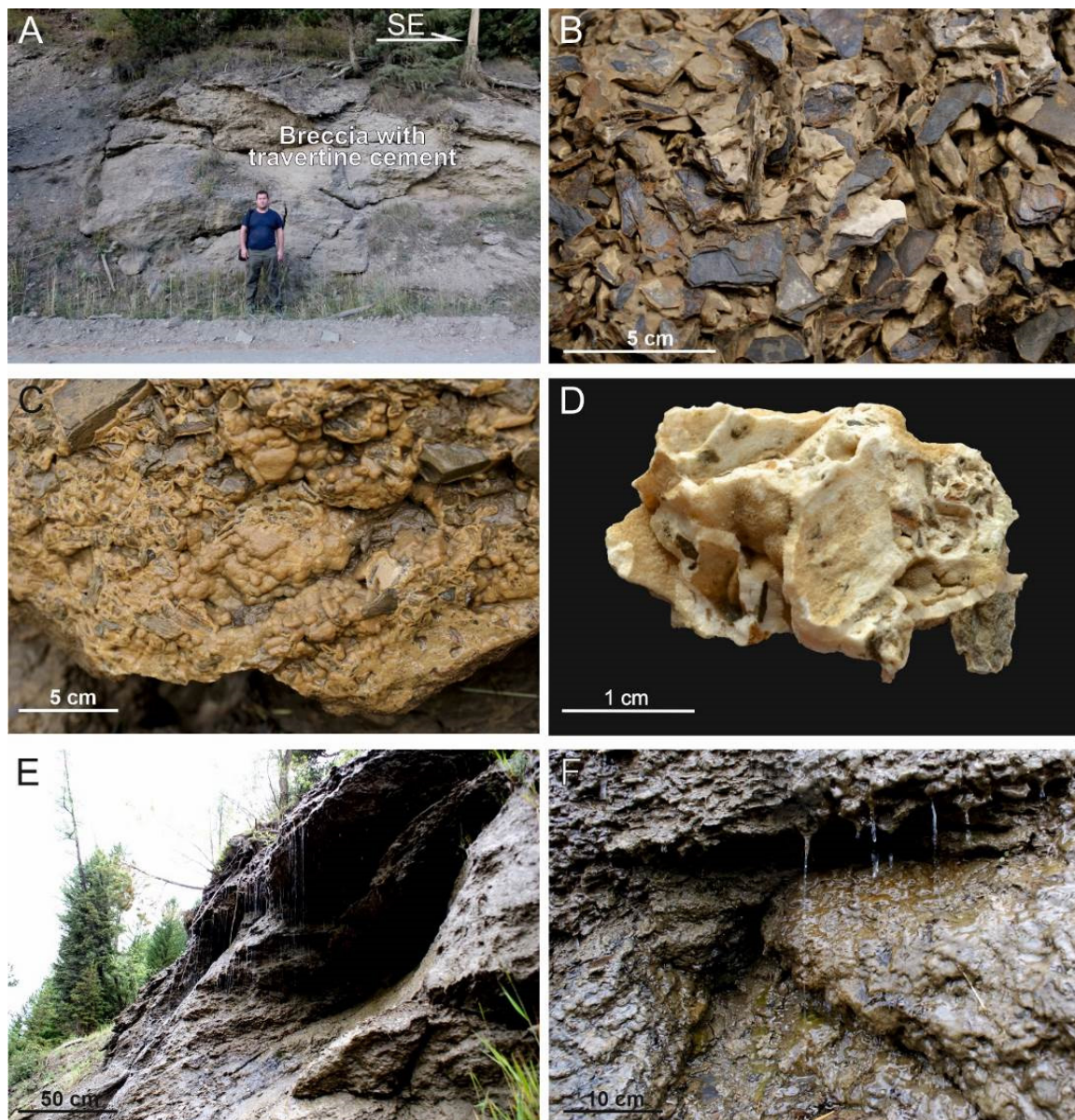


Figure 4. The Cheybek-Kohl 2 travertines. (A) Outcrop of breccia with travertine cement. (B,C) Close-ups: breccia with travertine cement. (D) Travertine crusts lining the inter-clast space. (E,F) Carbonate crusts covered with algae precipitating in the present seepage zone.

4.1.4. The Meshtuyaryk Travertines

The Meshtuyaryk travertines are located on the Kurai Fault line, immediately north-east of the Chagan Uplift (Figures 1, 2 and 6A). They crop out on the right side of the valley of the river with the same name, at the base of one of the triangular facets (50.13817° N, 88.34074° E, 1860 m a.s.l.). The outcrop of coarse-layered breccias with travertine cement is ca. 5 m thick, 15 m wide, and extends 80 m up the slope. The breccia overlies the ferruginous greenschists and phyllites. In the breccia, white, white-yellow and honey-yellow microsparitic-to-sparitic carbonate crusts, 2 cm in thickness, cement sand- to gravel-sized detrital clasts. The layering of breccias is the result of sorting of the colluvial material (Figure 6B–D). Along with greenschist and phyllite debris dominating in the breccias, fragments of dolerites, limestones, and calcite veins were found. There were no obvious

angular unconformities in the body of the breccias that would suggest the presence of travertines of different ages.

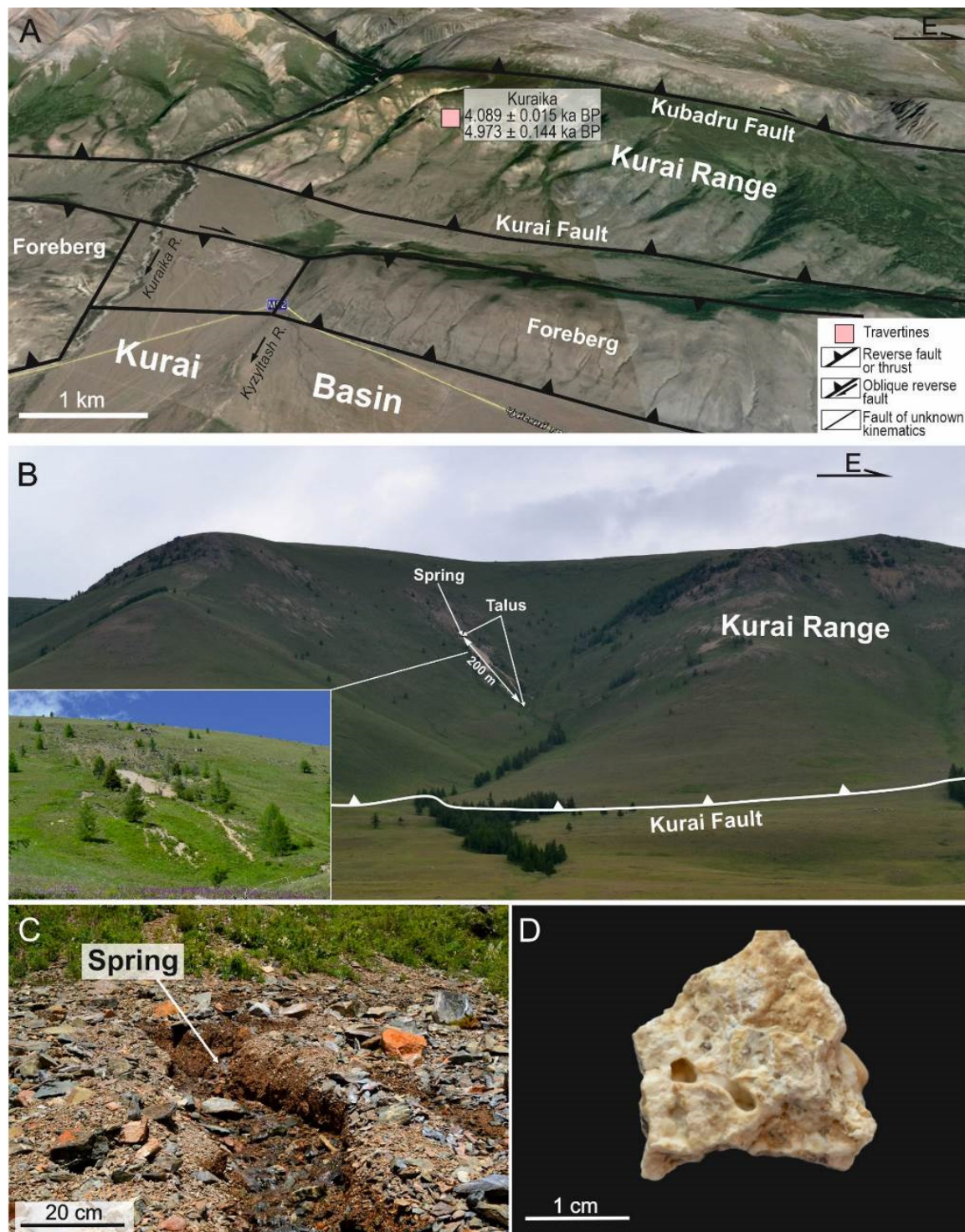


Figure 5. Location and morphology of the Kuraika travertines. (A) Structure of the Kurai Fault Zone and northern part of the Kurai Basin, showing the location and U-Th dates of the Kuraika travertines (50.28034° N, 88.00408° E). (B,C) Emerging spring and scree slope, composed of travertine on the southern slope of the Kurai Range. (D) Travertine fragment.

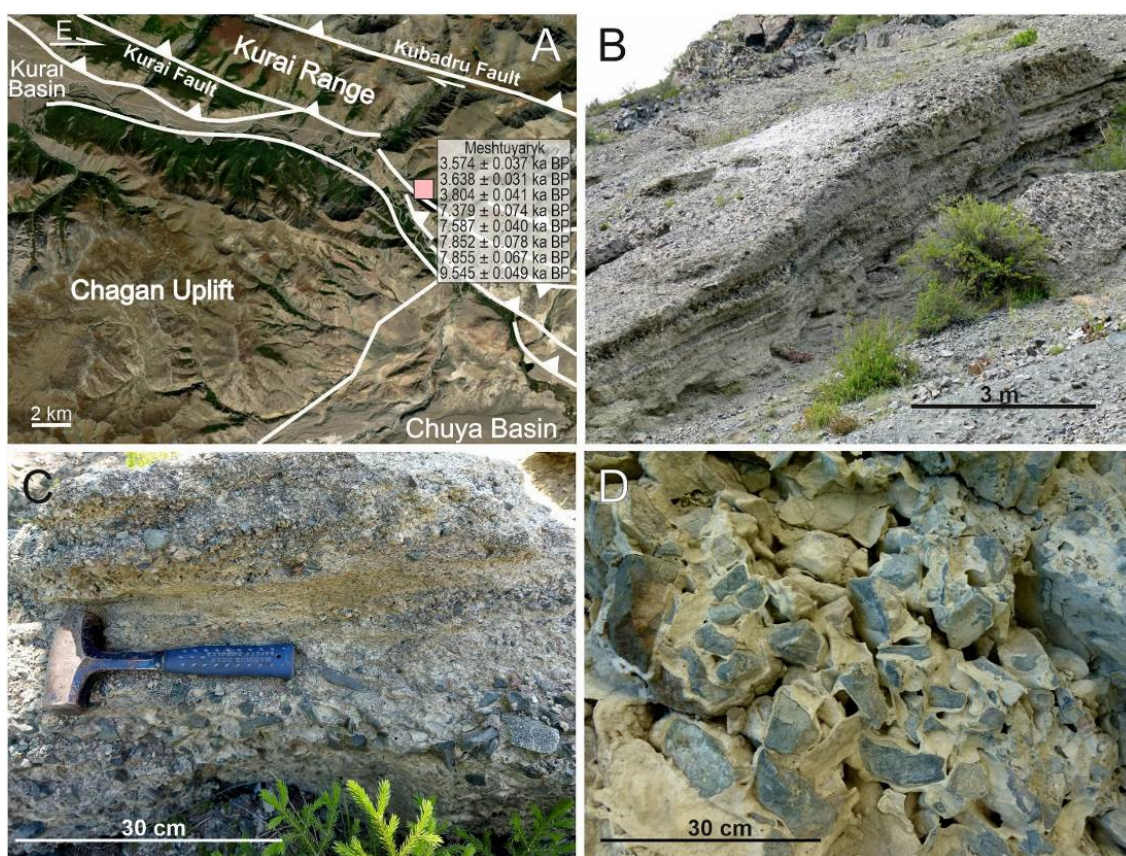


Figure 6. Location and morphology of the Meshtuyaryk travertines. (A) Active faults, location, and U-Th dates of the Meshtuyaryk travertines (50.13817° N, 88.34074° E). (B) Fragment of a layered breccia body with travertine cement. (C) Layered characteristics of travertine-cemented breccia; layering is due to variations in grain sizes of the clastic material. (D) Close-up: breccia with travertine cement.

4.1.5. The Totugem Travertines

The Totugem travertines are located on one of the faults, which is part of the KFZ structure at the junction of the Chuya Basin and the Kurai Range (Figures 1, 2 and 7A; 50.11039° N, 88.60268° E, 2434 m a.s.l.). The thrust crosses the Totugem River valley in its middle part, and forms in its sides a tectonic scarp ca. 300 m in height. During floods, the Totugem River intensively erodes the left side of the valley; as a result, a 6 m high cliff has formed. Its lower part is composed of strongly fissured siltstones (Middle Devonian) with a visible thickness of 3–5 m, overlain by a scree (Figure 7B). The lower part of this talus is cemented by travertine, making a 1–3 m thick and 30 m long breccia body (Figure 7C). The white-yellow carbonate crusts lining the debris surface reaches a thickness of 1.5 cm (Figure 7D).

4.1.6. The Baltyrgan Travertines

The Baltyrgan travertines are exposed within the forberg located north-west of the Chagan Uplift (Figures 1, 2 and 8A; 50.157524° N, 88.023709° E, 1700 m a.s.l.). The asymmetric foreberg is bordered from the south-east by an active thrust and rises above the bottom of the Kurai Depression from the south-west to the north-east from several tens to 100 m. Within the foreberg Middle Pleistocene alluvial fan gravels are involved in the uplift [56]. Late Proterozoic limestones and metamorphosed effusives of the Lower Cambrian age dominate in the debris, ranging in size from 1 cm to 30 cm. Travertine material cements the alluvial fan gravels, transforming them into conglomerate, roughly layered beds which dip towards the Chagan Uplift at 60–70° (Figure 8B). In conglomerates, carbonates line the pore space between clasts, forming crusts up to 0.5 cm thick (Figure 8C).



Figure 7. Location and morphology of the Totugem travertines. (A) Active faults, location, and U-Th dates of the Totugem travertines (50.11039° N, 88.60268° E). (B) Outcrop of the breccia with travertine cement on the left bank of the Totugem River. (C) Breccia with travertine cement. (D) Close-up: travertine cement of breccia.

4.1.7. The Chibit Travertines

Chibit travertines are confined to the north-western flank of the South Chuya Fault (Figures 1, 2 and 9A; 50.31277° N, 87.49337° E, 1187 m a.s.l.). In the erosional ledge of the left bank of the Chuya River valley, 15 m above the river, travertines cement alluvial sand and gravel, creating a 20 m body. The cementation produces sandstones and conglomerates up to 3 m thick (Figure 9B,C). In conglomerates, travertine crusts (several mm to 3 cm thick) coat the gravel surfaces and fill the free space between them. In the lower part of

the outcrop, the seepage of water was observed. At the spring outlet, modern precipitates (crusts up to 0.2 cm thick) have been deposited (Figure 9D). The modern vegetation and soil are partially covered by powdery gypsum (Figure 9E).

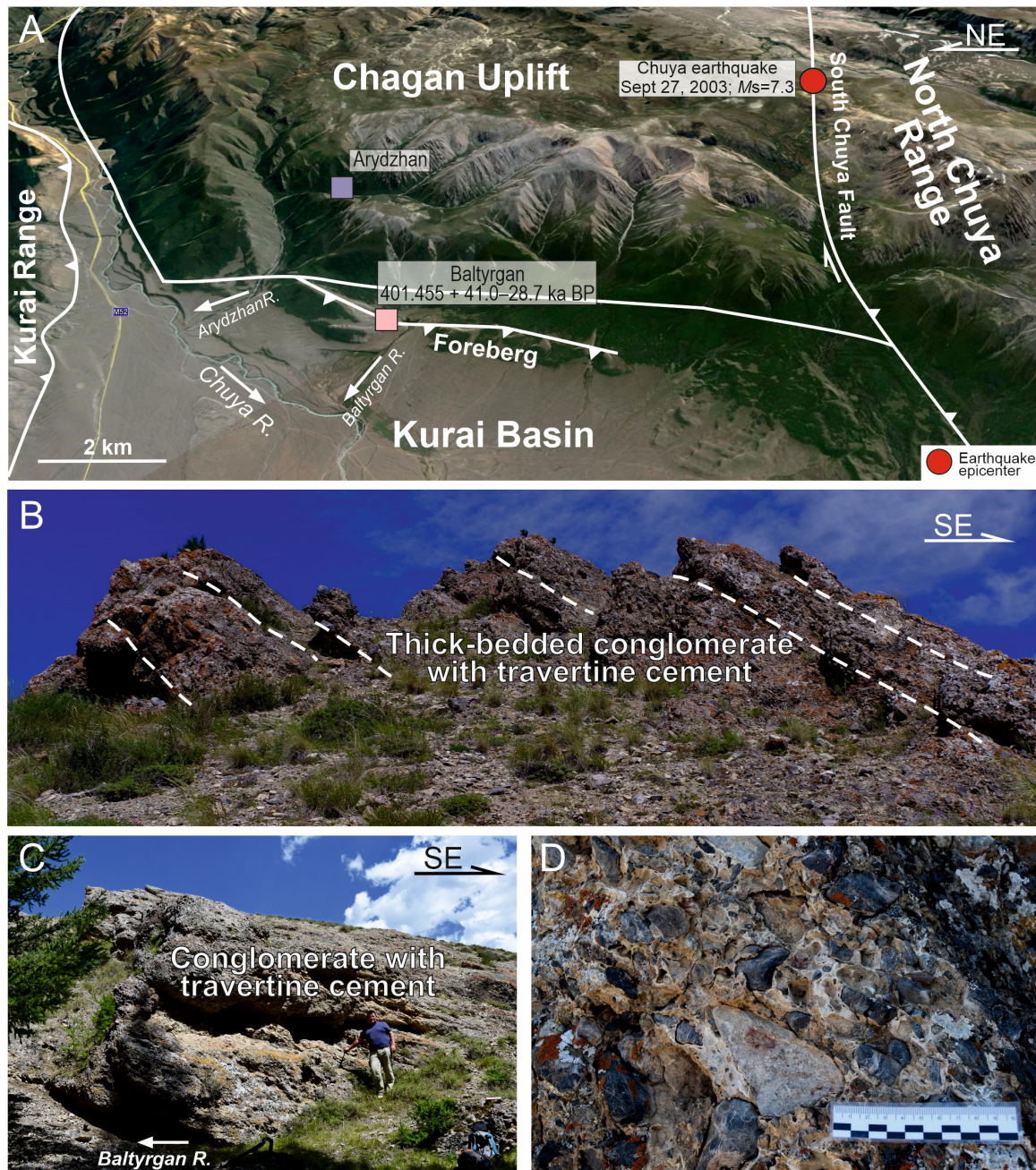


Figure 8. Location and morphology of the Baltyrgan travertines. (A) Active faults, location, and U-Th dates of the Baltyrgan travertines (50.157524° N, 88.023709° E). (B) Inclined thick-bedded conglomerates with travertine cement. (C,D) Conglomerates with travertine cement.

Summarizing, the most common type of fossil travertine in the south-eastern Gorny Altai is represented by carbonate cements that bind the debris clasts of different genesis: colluvial, alluvial, and alluvial fan. Much less common travertines in the south-eastern Gorny Altai are the crystalline flowstone crusts (up to 2 mm thick), forming near the discharge sites of modern springs and seeps.

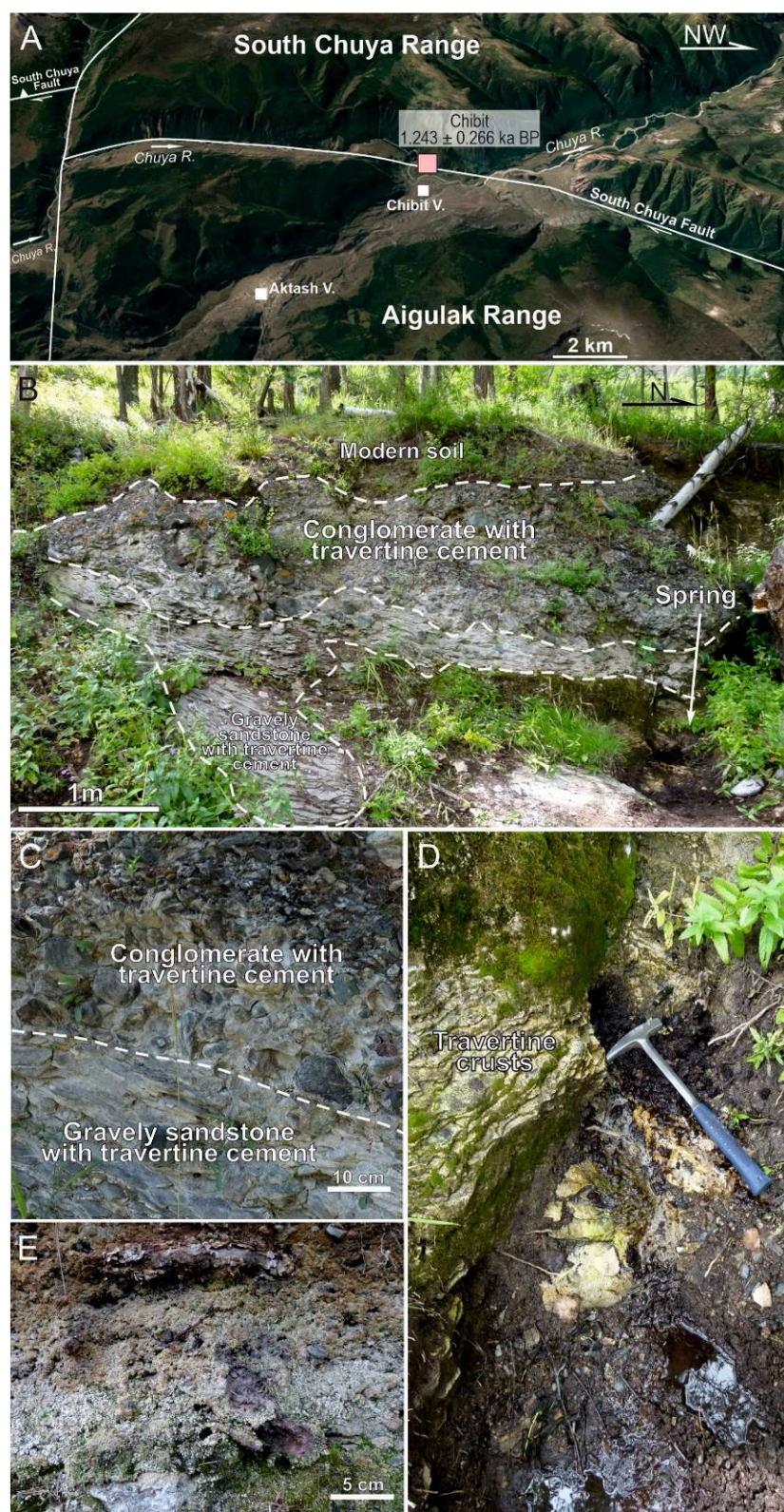


Figure 9. Location and morphology of the Chibit travertines. (A) Active faults, location, and U-Th date of the Chibit travertines (50.31277° N, 87.49337° E). (B,C) Sandstones and conglomerates formed by the cementation of alluvial deposits by travertines. (D) Travertine crusts, formed at the point of discharge of a modern spring. (E) Powdery gypsum aggregates covering modern vegetation and soil.

4.2. Hydrochemical Characteristics of Travertine Spring Water

All waters sampled at the travertine sites were slightly alkaline (pH = 7.9–8.2) (Table 1). The temperature recorded in the Cheybek-Kohl 2 and Kuraika springs were similar (3–4 °C, 3–4 °C, August 2021), water of the Chibit spring was substantially warmer (11 °C, 3–4 °C, August 2021). The TDS (total dissolved solids) values were 1629 mg/L at Chibit, 431 mg/L at Kuraika and 312 mg/L at Cheybek-Kohl 2. The Cheybek-Kohl 2 and Kuraika spring water were of HCO₃-SO₄-Ca-Mg and HCO₃-SO₄-Mg-Ca types, whereas Chibit water was of the SO₄-HCO₃-Mg-Ca type (Figure 10). The SO₄^{2−} content was the highest in the Chibit spring water (733.6 mg/L), whereas 13.6 mg/L and 18.9 mg/L were found at Kuraika and Cheybek-Kohl 2, respectively. Similar to SO₄^{2−}, HCO₃[−] was higher in the Chibit spring water (507 mg/L). The HCO₃[−] concentrations were 330 mg/L at Kuraika and 224 mg/L at Cheybek-Kohl 2. Ca²⁺ and Mg²⁺ were the dominant cations in all the sampled spring waters (mg/L): 35 and 45 at Kuraika, 34 and 28 at Cheybek-Kohl 2, and 211 and 150 at Chibit. All the sampled spring waters showed low concentrations of Na⁺ (3–16 mg/L), K⁺ (1–2 mg/L) and Cl[−] (0.7–1.6 mg/L). Travertine spring water at the Kuraika, Cheybek-Kohl 2 and Chibit sites were characterized with similar anion and cation compositions in 2015 and 2020 (Figure 10). The saturation index values of calcite and aragonite for all the sampled water samples were greater than 0: SI_{calcite} = 0.45 and SI_{aragonite} = 0.29 for Kuraika; SI_{calcite} = 0.09 and SI_{aragonite} = 0.25 for Cheybek-Kohl 2; and SI_{calcite} = 1.00 and SI_{aragonite} = 0.85 for Chibit (Table 1).

Table 1. Chemistry and stable isotope composition of waters of the travertine springs of the south-eastern Gorny Altai.

Spring	Kuraika	Cheybek-Kohl 2	Chibit
Location	50.280503° N 88.00398 °E 2258 m a.s.l.	50.40144° N 87.60491° E 1818 m a.s.l.	50.31277° N 87.49337° E 1187 m a.s.l.
Sample ID	PN-2021/2.1	PN-2021/4.1	PN-2021/5.1
Year of sampling	2021	2021	2021
T (°C)	3	4	11
pH	8.21	8.14	7.92
TDS (mg/L)	431	312	1629
K ⁺ (mg/L)	0.9	1.0	2.5
Na ⁺ (mg/L)	4.9	2.9	15.9
Ca ²⁺ (mg/L)	34.6	34.3	211.4
Mg ²⁺ (mg/L)	44.8	27.9	150.4
Ba ²⁺ (mg/L)	0.009	0.010	0.017
Sr ²⁺ (mg/L)	0.25	0.35	5.14
Al ³⁺ (mg/L)	0.022	0.021	0.051
Cl [−] (mg/L)	0.67	1.59	1.21
SO ₄ ^{2−} (mg/L)	13.56	18.85	733.6
NO ₃ [−] (mg/L)	1.36	0.61	1.66
HCO ₃ [−] (mg/L)	330	224	507
Mg/Ca	1.29	0.82	0.71
δ ¹⁸ O (‰ VSMOW)	−17.4	−15.9	−16.9
δ ² H (‰ VSMOW)	−126.7	−114.6	−125.5
SI _{calcite}	0.45	0.09	1.00
SI _{aragonite}	0.29	0.25	0.85

The Chibit and Kuraika spring waters had similar stable isotope compositions: δ¹⁸O = −16.9 and −17.4‰ and δD = −126 and −127‰, respectively. The heaviest isotopic composition was typical of the Cheybek-Kohl 2 spring water (δ¹⁸O = −15.9‰; δD = −145‰) (Figure 11).

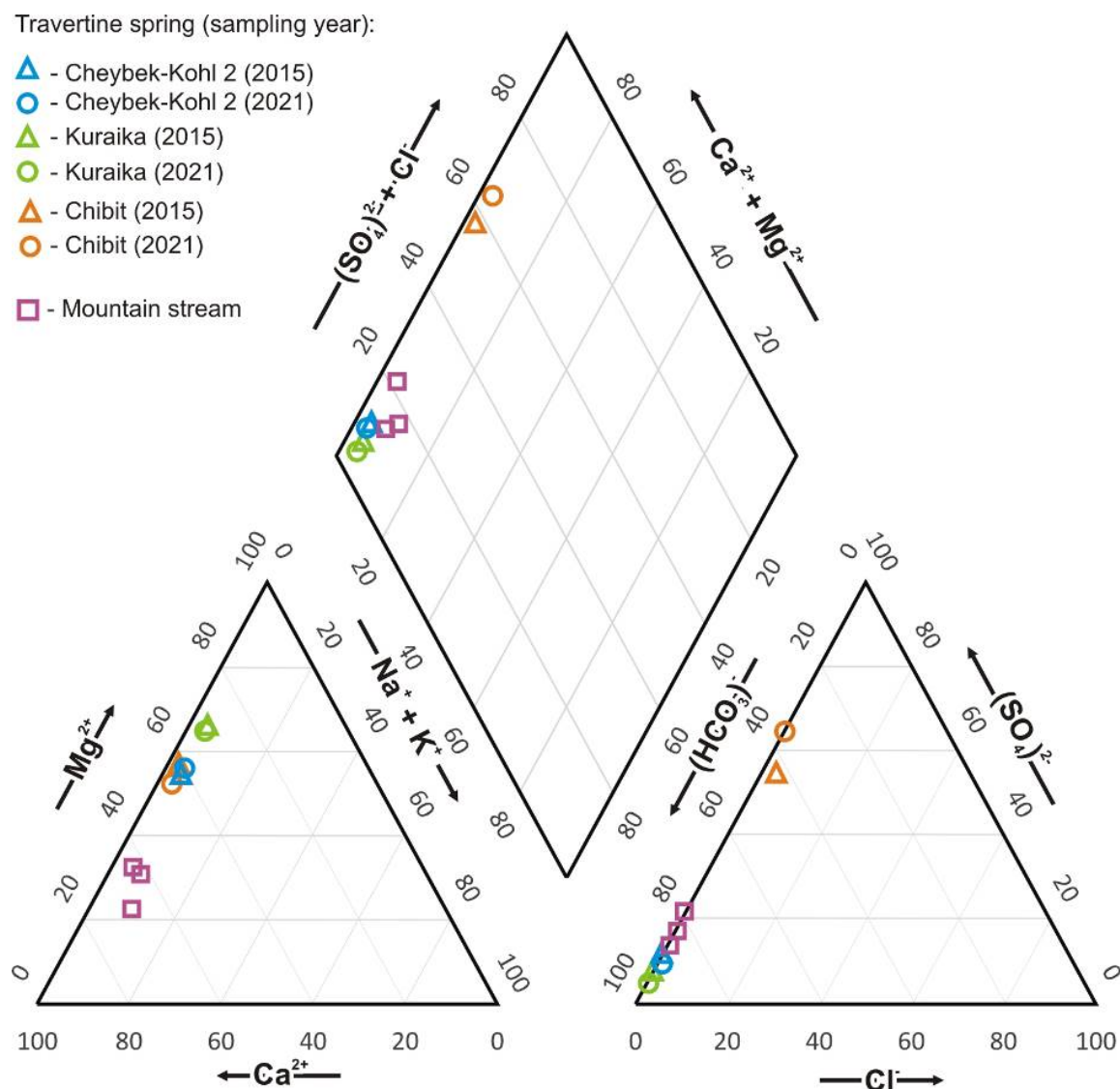


Figure 10. Piper diagram for the travertine spring water (cf. Table 1) and mountain steam water [41] of the south-eastern Gorny Altai.

4.3. Travertine Petrography and Mineralogy

All fossil travertines of Totugem, Baltyrgan, Cheybek-Kohl 1, Cheybek-Kohl 2, Chibit, and most parts of travertines of the Meshtuyaryk were composed of calcite (Table 2, Figures 12 and 13). Sparry and micritic calcite was white-yellow or grey; cementing clasts of different shapes and sizes. Calcite forms multiple layers which rimmed the clasts (Figure 12A–E). The free space of cavities and pores were filled with closely packed elongate crystals, up to 1 mm in size, with rhombohedral terminations. At the base of such aggregates there was a zone usually formed by anhedral calcite. In some cases, a series of druse rhythms alternated. Breaks in calcite precipitation were caused by poisoning by detrital silicate materials (Figure 12E,G–I). Euhedral terminations of calcite crystals displayed evidence of recurrent surface etching and subsequent regeneration (Figure 12F).

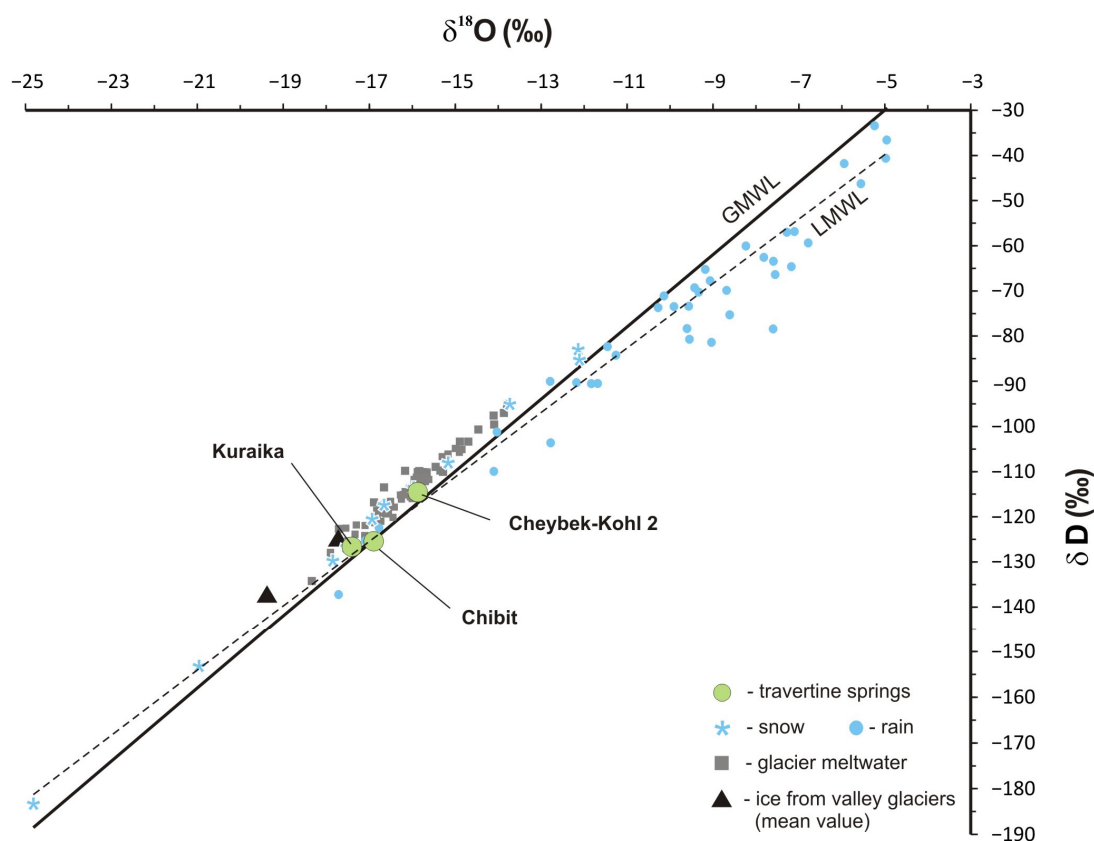


Figure 11. The isotope composition of the travertine water compared with ice and meltwater of the south-eastern Gorny Altai as well as meteoric precipitation. Sources: Glacier meltwater and ice from valley glaciers in Tavan-Bogd and Mongun-Taiga massifs [93,94]. Local meteoric water line (LMWL; $\delta D = 7.1 \cdot \delta^{18}O - 4.3$) [95]. Global meteoric water line (GMWL) [96].

Table 2. Stable isotope composition of CaCO_3 and mineralogy of fossil travertines and modern precipitates from the south-eastern Gorny Altai.

Travertine Deposit	Mineralogy	$\delta^{13}\text{C}$ (‰VPDB)	$\delta^{18}\text{O}$ (‰VPDB)
Fossil travertines			
Cheybek-Kohl 1	calcite	−4.4 to −2.9	−13.8 to −13.0
Baltyrgan	calcite	−2.5 to −2.0	−13.4 to −13.1
Cheybek-Kohl 2	calcite	−2.5 to 1.2	−13.8 to −12.9
Meshtuyaryk	calcite; calcite + aragonite	−1.2 to 1.9	−16.3 to −14.4
Kuraika	aragonite; aragonite + calcite	−0.3 to 0.7	−14.8 to −13.2
Totugem	calcite	0.4 to 2.0	−15.0 to −14.5
Chibit	calcite	1.5 to 4.3	−14.3 to −12.2
Modern precipitates			
Cheybek-Kohl 2	calcite + aragonite	na	na
Chibit	gypsum + calcite + aragonite	na	na

Mineralogy according to XRD and SEM data; na—not analysed.

Kuraika was the only fossil travertine site, where aragonite was the dominant mineral phase (62–98%) and calcite was present as a minor phase. Aragonite formed colourless and white-yellow fan-shaped radiating aggregates up to 2 mm in size, built up of needle-like crystals. Usually such aggregates are formed in the free pore space, where they overgrow with elongated calcite crystals (Figure 13A–D).

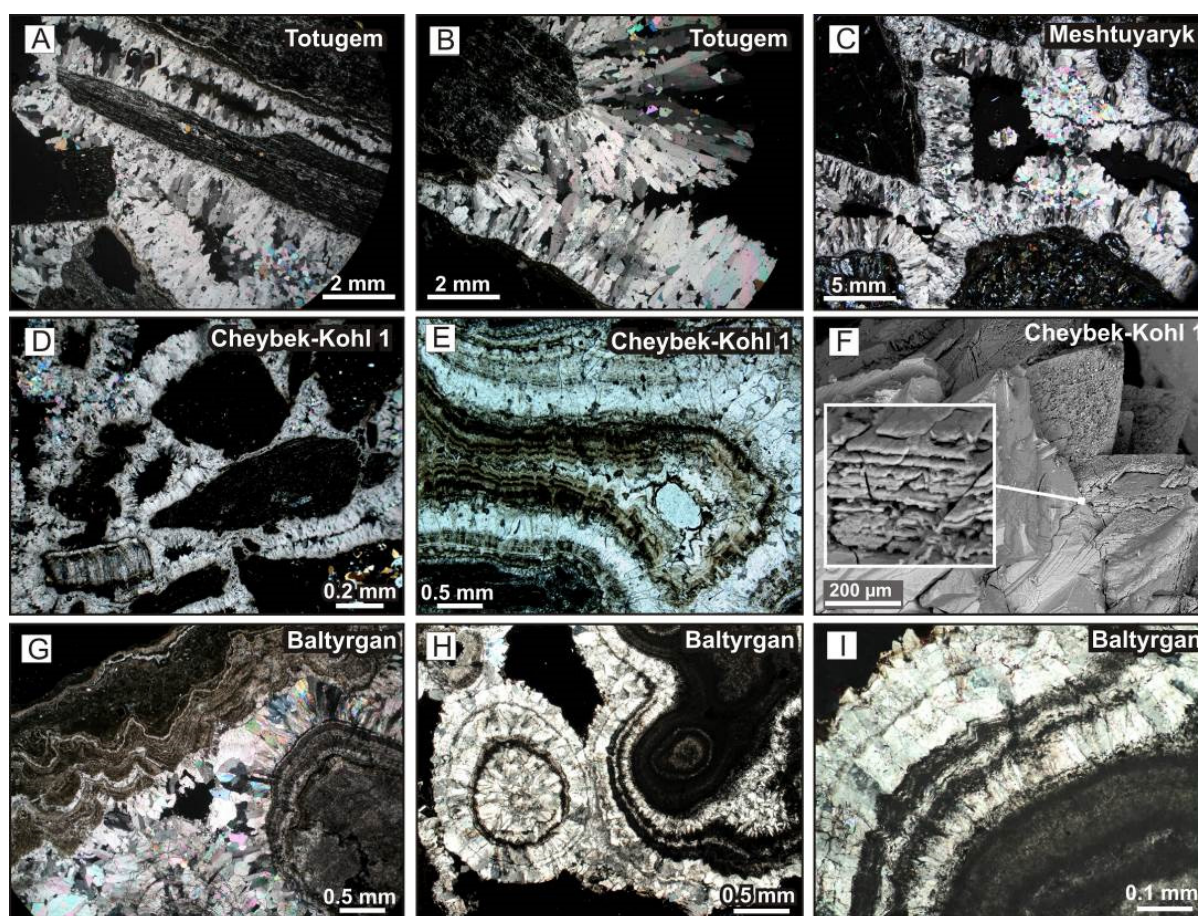


Figure 12. Photomicrographs of the fossil travertine samples composed of calcite. (A–D) Closely packed druse aggregates of elongate calcite crystals covering angular detrital clasts. (E,G–I) Calcite-laminated crusts composed of translucent sparite layers alternating with brown micrite laminae enriched in detrital material. (F) Calcite crystals with evidence of repeated surface etching and regeneration. Cross-polarized light (A–D,G), plane-polarized light (E,H,I), and backscattered electron (BSE) images (F).

In the Meshtuyaryk travertines calcite drusy aggregates sometimes contained aragonite (up to 15%), overgrowing anhedral sparry calcite at the base (Figure 13M–P). Aragonite formed layers of acicular crystals (up to 150 μm long) which grew nearly perpendicularly to the substratum. In some samples aragonite formed thicker layers (up to 1 mm), which overgrew drusy aggregates of calcite, and, in turn, were overgrown by calcite. The fan-shaped radiating acicular aggregates of aragonite originating from a nucleation point (detrital particles or calcite grains) are quite rare.

Samples of modern travertine crusts found only in the active seepage zone at the Cheybek-Kohl 2 and the Chibit sites also contained aragonite as well as calcite (Figure 13E–L). The upper surface of the travertine crust was colonized by algae and moss. Aragonite (5 to 40%) was present only in laminated crusts that grew upon oriented aggregates of elongate calcite crystals, up to 300 μm in length. The laminae of aragonite alternated with layers of brown micrite (<150 μm thick) or, less often, colourless anhedral sparite calcite. Aragonite formed colourless fan-shaped radiating acicular aggregates. The carbonate rhythms were locally separated by thin layers of fine-grained detrital material or organic films. The Chibit travertines contained fossilized moss cushion and algae (Figure 13G). Gypsum was found in the Chibit travertines in association with the active water seepage zone. Gypsum occurred as anhedral grains filling pores between calcite and aragonite or forming thin layers overlying laminated calcite–aragonite aggregates (Figure 13H).

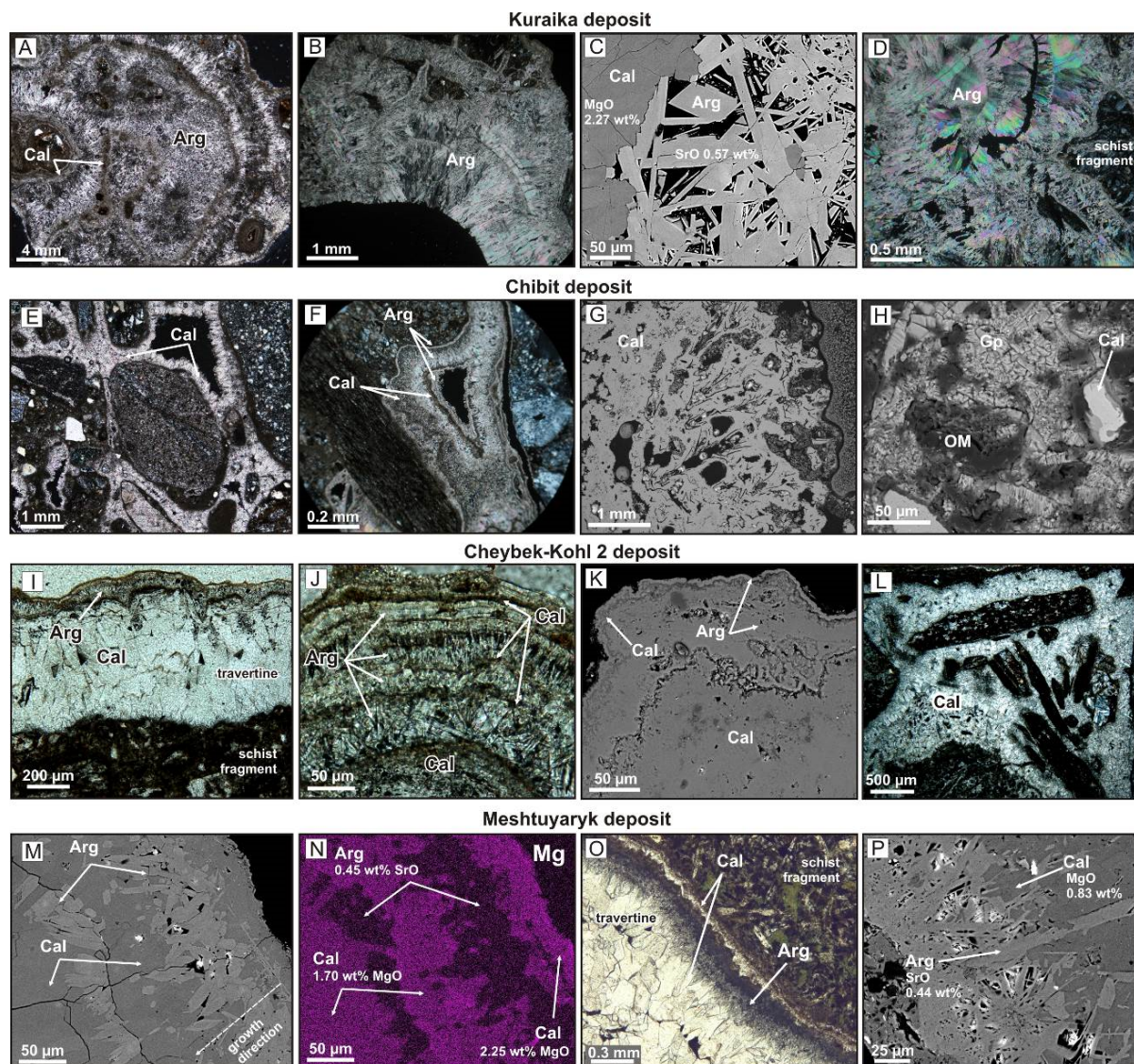


Figure 13. Photomicrographs of the fossil travertine samples and modern precipitates composed of aragonite and calcite. (A,B,D) Fan-shaped radiating and acicular aragonite layers. (C) Porous aggregate of elongated aragonite crystals and monolithic calcite aggregate. (E) Calcite crystals cementing detrital clasts. (F) Calcite–aragonite-laminated crust in void. Present seepage zone. (G) Fossilized moss cushion and algae in calcite precipitated in the present seepage zone. (H) Aggregate of the anhydrous gypsum grains with calcite clasts and organic matter particles. Present seepage zone. (I,J,K) Laminated crust with multiple alternations of micrite calcite and acicular aragonite laminae covering an aggregate of oriented calcite crystals. Present seepage zone. (L) Closely packed calcite crystal-cemented sand particles. (M,N) BSE image and elemental map (Mg) of laminated crust with aragonite layers at the base. (O) Calcite–aragonite crust covering a fragment of schist. (P) Fan-shaped radiating and acicular aragonite in a Mg–calcite matrix. Cross-polarized light (A,B,D,E,F), plane-polarized light (I,J,L,O), and backscattered electron (BSE) (C,G,H,K,M,P) images; Mg elemental map (N). Arg = aragonite, Cal = calcite, Gp = gypsum; OM = organic matter. Fossil travertines (A–E,L–P); modern precipitates (F–K).

4.4. Mineral Chemistry

Calcites from all travertines contained significant amounts of MgO (0.5–5.7 wt%) while FeO, MnO, SrO, and Y₂O₃ were below detection. Aragonite showed SrO contents of 0.2–2.0 wt%, occasionally containing Y₂O₃ (up to 0.5 wt%) and BaO (up to 0.15 wt%). Other impurities (Fe, Mn, Na) in aragonite were negligible.

4.5. Trace Elements

The calcitic and calcite–aragonitic travertines showed contrasting trace-element compositions (Table 3). The calcite travertines were enriched in Mg (4264–7925 ppm) but had low Sr and Ba abundances (235–1515 ppm and 11–41 ppm, respectively). Travertines composed of aragonite and calcite showed low Mg contents (≤ 594 ppm) but higher Sr (3106–4586 ppm) and Ba (up to 138 ppm) contents. The Fe and Mn contents in travertines were variable (18–465 ppm and 1–36 ppm, respectively) due to commonly observed secondary impregnations of cements by Fe³⁺-hydroxides. Kuraika and Cheybek-Kohl 2 travertines were enriched in U relative to other travertines of the south-eastern Gorny Altai (13.9–15.8 ppm vs. 0.6–2.0 ppm). Travertines from Cheybek-Kohl 1, Cheybek-Kohl 2, Totugem, and Baltyrgan deposits had the greatest Zn content (4.9–8.2 ppm). All travertines were depleted in Th (<0.13 ppm) and Rb (<0.5 ppm).

Table 3. Trace-element and REE concentrations (ICP-MS data, in ppm) in carbonate fractions extracted from travertines of the south-eastern Gorny Altai.

Deposit	Cheybek-Kohl 1 *	Baltyrgan	Totugem	Meshtuyaryk	Cheybek-Kohl 2 *	Kuraika	Chibit
Phases	Cal	Cal	Cal	Cal	Cal + Arg	Cal + Arg	Cal + Arg
Li	1.90	3.30	3.35	2.95	1.50	2.86	4.80
Na	93.5	n.a.	146	204	114	141	n.a.
Mg	7049	n.a.	4264	7925	273	594	n.a.
Al	378	107	19.8	25.9	169	45.9	110
P	50.3	n.a.	32.5	n.a.	35.3	8.08	n.a.
K	108	34.7	25.9	13.0	85.7	19.0	237
Mn	35.6	n.a.	1.30	1.60	17.2	2.78	n.a.
Fe	376	89.2	18.4	51.4	465	64.0	183
Co	0.6	0.17	n.d.	0.07	0.50	0.07	0.16
Cu	3.40	0.59	n.d.	5.21	1.00	1.77	4.70
Zn	5.20	4.90	7.47	0.49	8.20	0.69	2.50
Rb	0.50	0.30	n.d.	n.d.	0.40	0.01	0.10
Sr	344	1515	454	235	4586	3817	3106
Y	0.50	3.04	6.90	n.d.	0.40	n.d.	0.12
Ba	11.1	40.8	26.3	20.7	121	138	31.0
La	0.42	2.02	3.41	n.d.	0.25	0.04	0.07
Ce	0.86	2.76	3.14	0.03	0.48	0.07	0.15
Pr	0.11	0.44	0.73	n.d.	0.06	n.d.	0.02
Nd	0.48	1.90	3.20	0.02	0.25	0.02	0.09
Sm	0.11	0.34	0.71	0.01	0.08	n.d.	0.02
Eu	0.02	0.08	0.16	n.d.	0.01	n.d.	0.01
Gd	0.10	0.39	0.96	0.02	0.10	n.d.	0.02
Tb	0.02	0.07	0.13	n.d.	0.01	n.d.	n.d.
Dy	0.13	0.39	0.68	n.d.	0.06	n.d.	0.02
Ho	0.02	0.09	0.15	n.d.	0.02	n.d.	n.d.
Er	0.06	0.27	0.50	n.d.	0.04	n.d.	0.02
Tm	0.01	0.04	0.08	n.d.	0.01	n.d.	n.d.
Yb	0.06	0.22	0.54	n.d.	0.05	n.d.	0.01
Lu	0.01	0.03	0.09	n.d.	0.01	n.d.	n.d.
ΣREE	2.41	9.05	14.49	0.08	1.43	0.13	0.43
Th	0.13	0.12	n.d.	n.d.	0.09	n.d.	n.d.
U	0.60	1.76	3.1	1.96	15.8	13.9	0.79

n.a. = not analysed, n.d. = not detected. Arg = aragonite; Cal = calcite. Phase composition according to XRD data.

* Composition according to [41].

All travertines were markedly depleted in ΣREE (0.08–14.49 ppm) relative to the PAAS (post-Archean Australian shale) value of 83 ppm [97]. The PAAS-normalized REE + Y patterns of all travertines were similar, with a slight enrichment in heavy REEs (Figure 14). Weak negative anomalies for redox-sensitive REEs were observed for travertines Baltyrgan

and Totugem (Ce anomaly) and Cheybek-Kohl 2. Travertine Chibit showed a positive Eu anomaly.

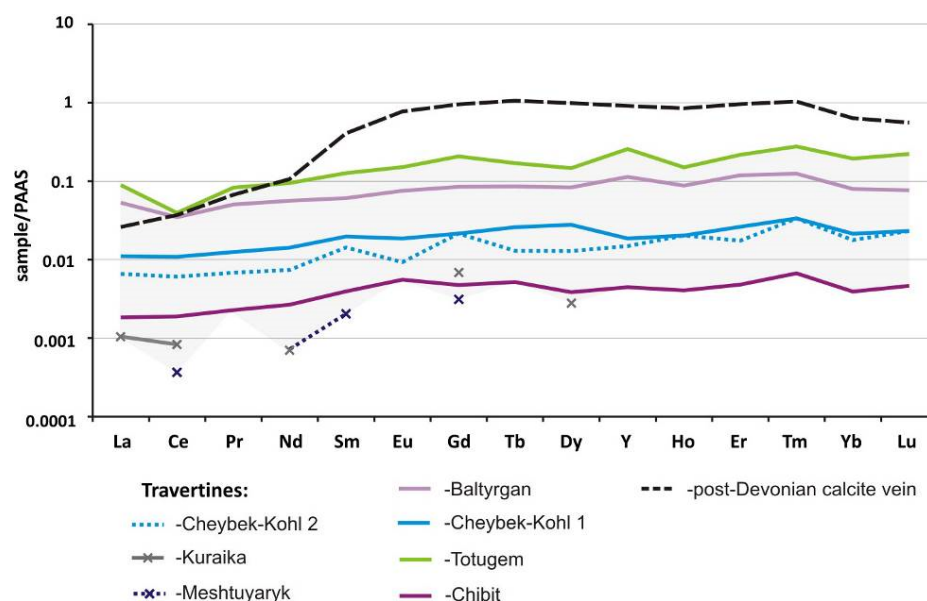


Figure 14. REE + Y patterns of CaCO_3 fractions extracted from travertines of the south-eastern Gorny Altai (cf. Table 3) compared to the post-Devonian calcite vein [41]. Normalized to PAAS [97].

4.6. Stable Isotope Compositions of CaCO_3

The studied travertines slightly differed in their $\delta^{18}\text{O}$ values (-15.8 to -12.2‰) (Table 2, Table S1, Figure 15). The $\delta^{13}\text{C}$ values showed a rather wide range (-4.4 to 4.3‰), with 70% of the data falling within the -1.0 to 2.0‰ range. The CaCO_3 from Cheybek-Kohl 1 and Baltyrgan travertines had a $\delta^{18}\text{O}$ varying between -13.8 and -13.0‰ , and a $\delta^{13}\text{C}$ varying between -4.4 and -2.0‰ . Both positive and negative values of the $\delta^{13}\text{C}$ (-2.5 to 1.9‰) were measured in the Cheybek-Kohl 2, Kuraika and Meshtuyaryk travertines. Calcites from Totugem site were markedly enriched in ^{13}C (0.4 to 2.0‰). The CaCO_3 from Meshtuyaryk and Totugem had the lowest $\delta^{18}\text{O}$ values (-16.3 to -14.4‰). The highest $\delta^{13}\text{C}$ (1.5 to 4.3‰) and $\delta^{18}\text{O}$ -4.3 to -12.2‰ values were observed in CaCO_3 from the Chibit deposits.

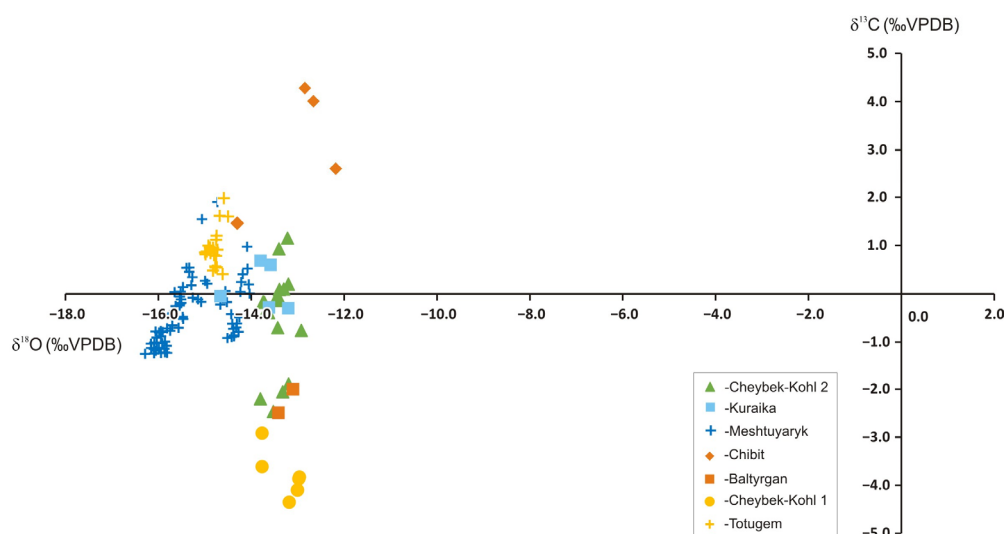


Figure 15. Stable isotope properties of the CaCO_3 from travertines of the south-eastern Gorny Altai (see Table S1).

4.7. Ages of Travertines

We obtained nineteen of ^{230}Th -U age dates [48,49] of travertines from the south-eastern Gorny Altai (Table 4 and Table S2, Figures 3A, 5A and 6A). The oldest Baltyrgan travertine (401,455 +41,000/−28,700 ka BP) is located within the foreberg west of the Chagan Uplift (Figure 8A). The Totugem travertines (ca. 123 ka BP) are located on the eastern flank of the KFZ (Figure 7A). Further to the west, along the active faults of the zone, there are only Holocene travertines, ranging in ages from 11.0 to 3.5 ka BP. The youngest Chibit travertine (1.243 ± 0.266 ka BP) is spatially related to the South Chuya Fault.

Table 4. ^{230}Th -U ages of travertines from the south-eastern Gorny Altai, data from [48,49].

Sample	^{238}U (mg/g)	±	^{232}Th (ng/g)	±	$[\frac{^{234}\text{U}}{^{238}\text{U}}]_{\text{A}}$	±	$[\frac{^{230}\text{Th}}{^{238}\text{U}}]_{\text{A}}$	±
Cheybek-Kohl 1								
20.1-2 +	0.441	0.003	3.0930	0.0245	2.6888	0.0002	0.1715	0.0013
RYALT-15-17-1 ++	0.623	0.005	2.452	0.026	2.687	0.012	0.151	0.001
Cheybek-Kohl 2								
5.12-3 +	36.670	0.246	0.6821	0.0057	2.8820	0.0008	0.2383	0.0011
RYALT-15-16-11 ++	0.886	0.006	33.247	0.339	2.840	0.010	0.278	0.004
RYALT-15-16-8-1 +	0.518	0.015	2.166	0.018	2.846	0.002	0.275	0.002
Kuraika								
15-14-1 +	8.276	0.055	0.2274	0.0019	3.4099	0.0010	0.1258	0.0004
RYALT-13-18-2 ++	12.229	0.238	0.651	0.007	3.385	0.070	0.151	0.003
Meshtuyaryk								
PN 2019/1.1_2 +	1.404	0.008	0.4626	0.0031	1.1687	0.0003	0.0980	0.0005
PN 2019/1.5_1 +	1.561	0.010	0.0170	0.0002	1.1321	0.0004	0.0371	0.0003
PN 2019/1.5_3a +	1.661	0.010	0.0349	0.0003	1.1390	0.0004	0.0367	0.0004
PN 2019/1.5_3b +	2.012	0.013	0.0363	0.0003	1.1391	0.0003	0.0390	0.0004
PN 2019/1.6 +	1.077	0.007	0.7849	0.0055	1.1537	0.0004	0.0802	0.0008
PN 2019/1.10 +	2.160	0.014	0.3897	0.0026	1.1653	0.0003	0.0810	0.0007
PN 2019/1.11 +	1.596	0.010	0.0327	0.0002	1.1587	0.0004	0.0758	0.0007
PN-2019/1.14 +	0.969	0.006	0.0765	0.0011	1.1310	0.0005	0.0760	0.0004
Totugem								
RYALT-13-8.1 ++	2.852	0.037	5.069	0.060	2.345	0.028	1.728	0.023
RYALT-15-12-13-2 +	2.260	0.015	12.689	0.097	2.3237	0.0011	1.7078	0.0067
Baltyrgan								
RYALT-13-7.1 ++	1.519	0.011	12.064	0.138	1.045	0.004	1.034	0.007
Chibit								
RYALT-15-32-1 ++	0.476	0.004	12.746	0.169	1.490	0.003	0.017	0.004
Sample	Age Uncorrected (ka BP)	±	Age Corrected (ka BP)	±	$[\frac{^{234}\text{U}}{^{238}\text{U}}]_{\text{A}}$ Initial ±			
Cheybek-Kohl 1								
20.1-2 +	7.226	0.045	7.152	0.056	0.056	2.7233	0.0020	
RYALT-15-17-1 ++	6.337	0.056	6.296	0.059	0.059	2.7171	0.0124	
Cheybek-Kohl 2								
5.12-3 +	9.340	0.042	9.340	0.043	0.043	2.9324	0.0008	
RYALT-15-16-11 ++	11.484	0.053	11.109	0.168	0.168	2.8992	0.0098	
RYALT-15-16-8-1 +	11.022	0.061	10.981	0.060	0.060	2.9038	0.0016	
Kuraika								
15-14-1 +	4.090	0.015	4.089	0.015	0.015	3.43788	0.0010	
RYALT-13-18-2 ++	4.973	0.140	4.973	0.144	0.144	3.418	0.072	

Table 4. Cont.

Meshtuyaryk						
PN 2019/1.1_2 ⁺	9.553	0.048	9.545	0.049	1.1733	0.0003
PN 2019/1.5_1 ⁺	3.639	0.031	3.638	0.031	1.1335	0.0004
PN 2019/1.5_3a ⁺	3.575	0.036	3.574	0.037	1.1404	0.0004
PN 2019/1.5_3b ⁺	3.804	0.041	3.804	0.041	1.1406	0.0003
PN 2019/1.6 ⁺	7.870	0.079	7.852	0.078	1.1572	0.0004
PN 2019/1.10 ⁺	7.859	0.066	7.855	0.067	1.1690	0.0003
PN 2019/1.11 ⁺	7.379	0.075	7.379	0.074	1.1620	0.0005
PN-2019/1.14 ⁺	7.589	0.040	7.587	0.040	1.1339	0.0006
Totugem						
RYALT-13-8.1 ⁺⁺	122.987	3.652	122.970	3.677	2.904	0.030
RYALT-15-12-13-2 ⁺	122.60	0.80	122.540	0.80	2.8716	0.0006
Baltyrgan						
RYALT-13-7.1 ⁺⁺	401.656	+39.900/ −29.000	401.455	+41.000/ −28.700	1.139	0.011
Chibit						
RYALT-15-32-1 ⁺⁺	1.761	0.067	1.243	0.266	1.4922	0.0025

All measurements are reported with $\pm 2\sigma$ absolute uncertainties. Subscript A denotes activity ratio. U decay constants: $\lambda_{238} = 1.55125 \times 10^{-10}$ [98] and $\lambda_{234} = 2.82206 \times 10^{-6}$ [92]. Th decay constant: $\lambda_{230} = 9.1705 \times 10^{-6}$ [92]. Corrected ^{230}Th ages assume the initial $^{230}\text{Th}/^{232}\text{Th}$ atomic ratio of $4.4 \pm 2.2 \times 10^{-6}$. Those are the values for a material at secular equilibrium, with the bulk Earth $^{232}\text{Th}/^{238}\text{U}$ value of 3.8. The errors are arbitrarily assumed to be 50%. BP stands for “before present” where the “present” is defined as the year 1950 CE. ⁺—Measured on the Neptune Plus at the Institute for Geosciences, ⁺⁺—Measured on the Nu Plasma at the Max Planck Institute for Chemistry, Mainz.

5. Discussion

5.1. Paleofluid Source Rocks

A combination of isotope and elemental analyses can be used to constrain the origin of CO_2 and paleofluid provenance fossil travertine systems [14–16,99]. The carbon and oxygen isotope data of fossil travertines from the south-eastern Gorny Altai plot was within the hypogean travertine (according to Teboul et al. [16]), with CO_2 derived from carbonates or igneous (except carbonatites and ultramafics) source rocks (Figure 16A). The high strontium and low barium contents in the Gorny Altai travertines indicate that the fluids had hypogean origin and were in contact with source rocks consisting of mixed limestones, evaporites and dolostone [16] (Figure 16B). The relatively elevated concentrations of Mg can be related to the interaction of the fluids with the dolomitic limestones or dolostones. Thus, the isotope and trace-element data jointly indicate hypogean origin of the paleofluid from the fossil Gorny Altai travertine system and the dolomitic limestones or dolostones as fluid source rocks. The paleofluid originated from groundwaters subjected to prolonged water–rock interactions with aquifer carbonate rocks, Upper Neoproterozoic to Devonian limestone and dolostone, widespread in the area.

5.2. Calcite–Aragonite Precipitation

Fossil travertine cements in the south-eastern Gorny Altai comprise calcite and aragonite. At different sites, mineral compositions varied from exclusively calcitic (Totugem, Baltyrgan, Cheybek-Kohl 1, Cheybek-Kohl 2, and Chibit) to predominantly calcitic with minor aragonite (Meshtuyaryk) to predominantly aragonitic (Kuraika). The Mg-calcite and Sr-aragonite showed no signs of diagenetic alteration and retained their typical morphological features. This indicates that both CaCO_3 polymorphs were in primary phases, and that calcite was not a replacement of precursor aragonite. As it was shown previously, [1,2,100–104] the precipitation of aragonite and calcite in spring systems is controlled by a number of factors, such as: (1) temperature of the spring water, (2) microbial activity, (3) pCO_2 and the rate of CO_2 degassing, (4) mineral precipitation rates, and (5) Mg/Ca ratio in water. There is not a single or universal control applicable in all situations [102].

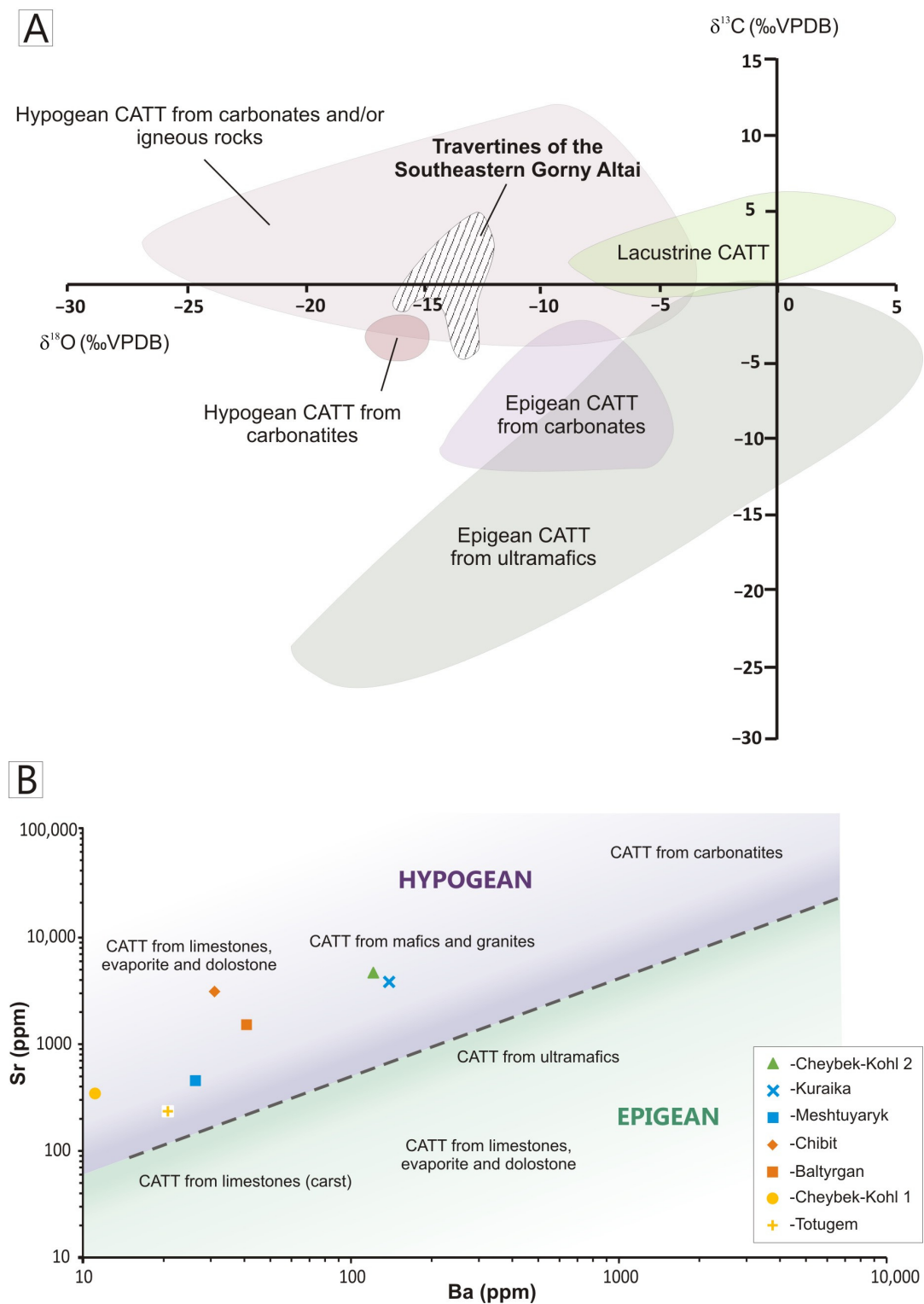


Figure 16. $\delta^{13}\text{C}$ - $\delta^{18}\text{O}$ (A) and Sr-Ba (B) cross-plots of travertines from the south-eastern Gorny Altai overlay on clusters of Teboul et al. [16].

Aragonite precipitation commonly takes place in thermal springs with temperatures of 30–80 °C [1,100,105–108]. Meanwhile, some studies have suggested that temperature does not play any significant role in the precipitation of aragonite or calcite [109–113]. The studied travertine springs in the south-eastern Gorny Altai had temperatures ranging from 3 to 11 °C; yet both calcite and aragonite were deposited in them (Table 2). Stable isotope studies

suggested that fossil travertines were precipitated from ascending ambient-temperature bicarbonate waters [41,48,49,65,66]. Thus, the spring water temperature does not seem to be a controlling factor in aragonite precipitation in the case of the Altai travertines.

It is known that biofilms can affect the precipitation of CaCO_3 polymorphs [1,106,107,113–116]. The Cheybek-Kohl 2 travertine complex provided evidence that microbial activity was involved in the modern calcite–aragonite precipitation, but was suppressed during the formation of fossil travertines [41]. In the case of the Chibit travertine site, limited aragonite precipitation occurred only in present seepage zone featuring abundant microbial mats around the spring orifice; modern precipitates were enriched in organic compounds (Figure S1). Fossil travertines at this site were composed of calcite only. Evidently, at the Chibit site the microbial activity and high $\text{SI}_{\text{aragonite}}$ in water may favour aragonite formation in modern precipitates.

Neither optical microscopy nor SEM analysis on fossil aragonite-rich Kuraika and aragonite-bearing Meshtuyaryk travertines yielded evidence of biological influence on their precipitation. In Particular, weak UV-luminescence of Meshtuyaryk travertines [49] was consistent with the lack of involvement of biological processes in travertine precipitation. In the Kuraika travertines aragonite occurred as fan-shaped radiating aggregates associated with calcite layers in the inner parts of the fossil travertine body. At the fossil Meshtuyaryk travertines aragonite formed thin layers at the base of calcite crusts. The absence of organic compounds corroborates the hypothesis about abiotic precipitation of calcite and aragonite.

Many researchers note, that the precipitation of aragonite is favoured by high Mg/Ca ratios of the spring water (>1), because the Mg inhibits the growth of calcite [117–121]. In water of the south-eastern Gorny Altai travertine springs the Mg content was typically lower than the Ca content (Table 1). Only one water sample from the Kuraika spring had a $\text{Mg}/\text{Ca} = 1.29$. According to Folk [100], such Mg/Ca ratio at low spring temperatures (3°C) should promote the precipitation of aragonite. All calcites from Meshtuyaryk travertines contained appreciable amounts of Mg . The anhedral sparry calcite that coexisted with aragonite at the base of druse had the greatest CaO content (up to 6.0 mol% MgCO_3). There, fine layers of Mg -enriched calcite overgrew the aragonite layers. The Mg/Ca ratio in carbonates of abiotic origin depend on the Mg/Ca ratio in solution [119] and temperature, which affects the distribution coefficient [122]. The Mg/Ca ratio of waters is controlled by the lithology of host rock in zones, where most of water–rock interactions occur. For Meshtuyaryk travertine-forming water, the Paleozoic limestone and dolostone served as the aquifer. It is likely that the water was characterized by a slightly elevated Mg/Ca ratio, favouring aragonite precipitation.

Reviewing calcium carbonate polymorph precipitations, Jones [102] reported abundant evidence of aragonite ($\pm$ calcite) precipitation from spring water with a high CO_2 content and rapid CO_2 degassing. Chafetz et al. [123] also suggested that aragonite precipitates from water with high CaCO_3 supersaturation, whereas low-supersaturation waters tend to precipitate calcite. The formation of travertines in the south-eastern Gorny Altai was triggered by seismic events, which induced the activation of faults and the rapid rise of bicarbonate groundwaters previously sealed in carbonate aquifers. The rapid rise of groundwaters to the surface was accompanied by rapid CO_2 degassing and increased CaCO_3 supersaturation levels, which led to aragonite precipitation. Decreasing overpressure led to the rise in subsequent portions of groundwaters in a quieter mode. The lowering of CaCO_3 supersaturation favoured the precipitation of calcite.

It is likely, therefore, that rapid CO_2 degassing along with elevated Mg/Ca ratios of the travertine-forming water were the primary controls of calcite and aragonite precipitation in the fossil travertines of the south-eastern Gorny Altai.

5.3. Stable Isotopes and Geochemistry of Present-Day Spring Water

The linear distribution of the δD and $\delta^{18}\text{O}$ in spring water along global and local meteoric water lines (Figure 11) strongly suggests its meteoric origin [96]. The stable isotope values of the travertine spring water were lower than that of the summer rainwater

in the south-eastern Gorny Altai [95]. On the contrary, the δD and $\delta^{18}O$ in travertine spring water were plotted close to the meteoric precipitation of cold and transitional seasons (snow) and water from melted glaciers/ice. Bantsev et al. [93,94] showed that precipitation of the transitional seasons (spring-autumn) played the most important role in the recharge of glaciers in the arid parts of the Altai Mountains. Thus, the travertine spring water appeared to be recharged by glaciers meltwater and/or winter precipitation, with isotopically depleted compositions.

The chemistry of groundwater is controlled by many factors, including aquifer rock type, residence time, and geochemical processes along the groundwater flow paths (evaporation–crystallization, flow regime, etc.) [124,125]. Waters from Cheybek-Kohl 2 and Kuraika travertine springs were dominated by HCO_3^- , Ca^{2+} , and Mg^{2+} (Table 1). Such composition is indicative of carbonate aquifers. Mg/Ca ratios depend on the proportion of calcite and dolomite present in the aquifer rock and/or chemical kinetics [126]. The Upper Neoproterozoic fractured limestone and dolostone are the main aquifer rocks for travertine-forming solution within the south-eastern Gorny Altai (Figure 2) [84]. Hence, the Mg/Ca ratios of travertine-forming solutions (and, by extension, of travertine carbonates) was controlled by reactions of water with dolostone-poor or dolostone-rich rocks.

The sulphate, Ag and In contents were low for almost all the travertine spring water samples, except for the Chibit sample, showing the highest values of 733.6 mg/L for SO_4^{2-} , 5 $\mu g/L$ for Ag, and 10 $\mu g/L$ for In (Table 1). Gypsum dissolution or oxidation of sulphides is a common source of sulphate in groundwaters [127,128]. The Mg/Ca ratio was similar in the sulphate-rich Chibit and sulphate-poor Cheybek-Kohl 2 waters. Therefore, gypsum should not be considered as the main source of SO_4^{2-} in the travertine-forming solutions, because its dissolution would increase the Ca^{2+} content and lower the Mg/Ca ratios. Sulphate, In and Ag in Chibit spring water can be sourced from the oxidation of sulphide minerals, which are abundant in Devonian Chibit Cu-sulphide-quartz-carbonate ore deposits and numerous Cu-Au, Ag-Cu-Pb, Cu-Ag, Au-Cu-Ag sulphide ore occurrences [84].

Thus, the studied spring waters were similar to groundwater in the area in their $HCO_3-SO_4-Ca-Mg$ water chemistry. Their isotopic composition suggests the dominant contribution of winter precipitation; chemical characteristics suggest minor water–rock interactions. These waters rarely deposit carbonates. The saturation index values of calcite ($SI_{calcite}$) and aragonite ($SI_{aragonite}$) in Cheybek-Kohl 2 water were 0.09 and 0.25, respectively. In Kuraika water $SI_{calcite}$ (0.45) and $SI_{aragonite}$ (0.29) values were higher. According to Pentecost [1], in freshwater environments the minimum critical $SI_{calcite}$ for calcite precipitation is perhaps around 0.48. In many travertine systems calcite and aragonite precipitation starts significantly after $SI_{calcite}$ exceeds 0.8 (or around one) [104,107,129,130]. In the studied spring waters $SI_{calcite}$ (1.00) and $SI_{aragonite}$ (0.85) values only exceeded 0.8 in the Chibit deposits, where minor amounts of $CaCO_3$ precipitated along with gypsum.

5.4. Comparison of Travertine Ages with Paleoearthquake Ages

The age of the Chibit travertines (1.243 ± 0.266 ka BP) agrees well with the age of the paleoearthquake (Figure 17A) with $M_w = 6.6–6.9$ and intensity IX–X on the ESI-2007 intensity scale, associated with the KFZ. Its surface ruptures can be traced along the zone for 40 km; in the north of the Kurai Basin, they are dated to 1.210 ± 0.07 cal ka BP (IGAN_{AMS7749}; 0.954 probability; this study), 1.240 ± 0.110 cal ka BP (IGAN –3205), and 1.150 ± 0.105 cal ka BP [131], in the north-western part of the Chuya Basin to 1.305 ± 0.015 cal ka BP [57,79]. The western end of the surface ruptures is 30 km east of the Chibit travertine outcrop.

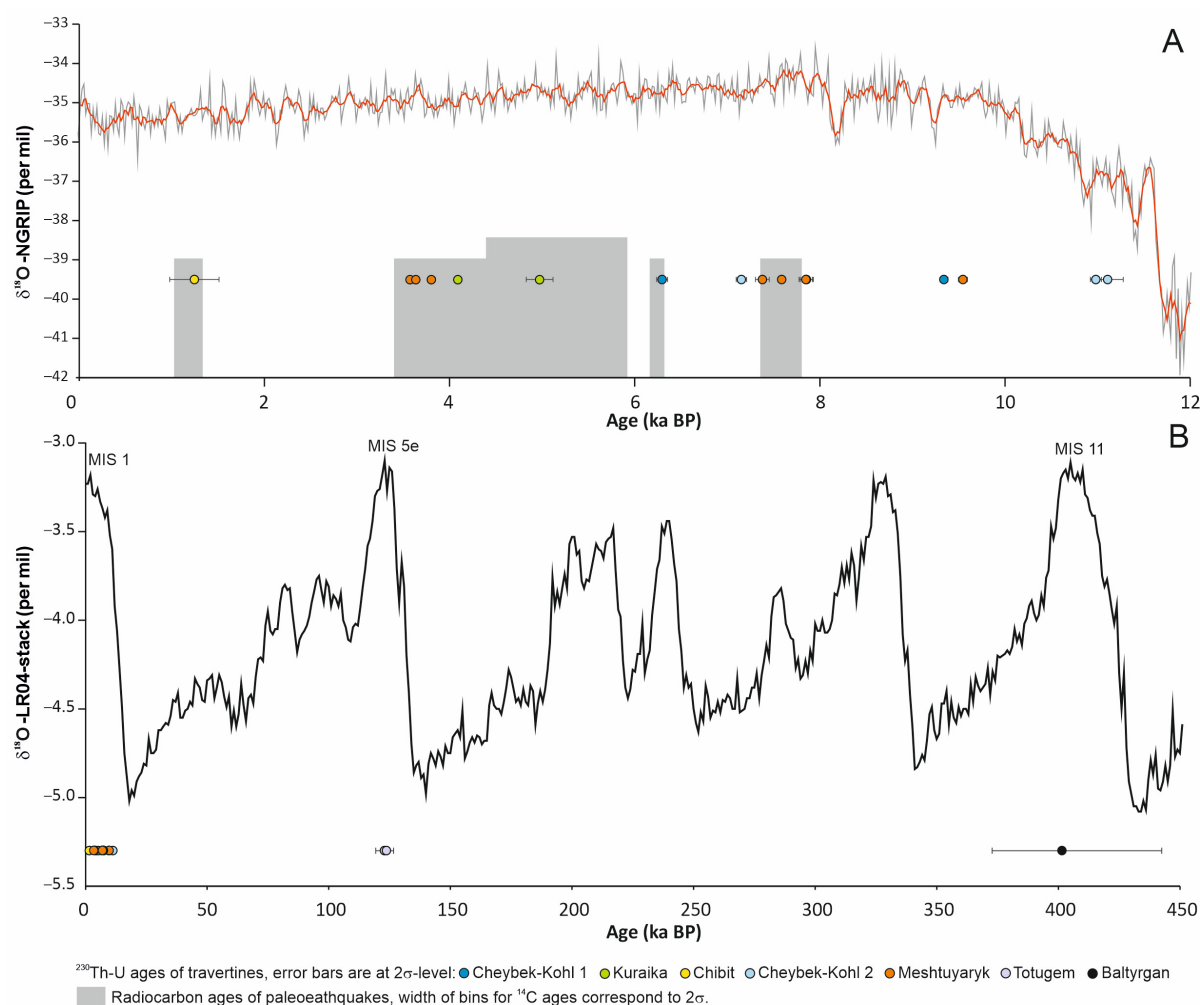


Figure 17. Age dates of the travertines (U-Th) and large paleoearthquakes (^{14}C) in the south-eastern Gorny Altai shown in the context of the paleoclimate proxy records: (A) North Greenland Ice Core Project (NGRIP) $\delta^{18}\text{O}$ [132,133]; grey line—complete data set; red line—5-point moving average. (B) LR04-stack $\delta^{18}\text{O}$ [134].

The youngest age cluster of the Meshtuyaryk travertines (3.574 ± 0.037 , 3.638 ± 0.031 , and 3.804 ± 0.041 ka BP), as well as the age of the youngest Kuraika travertines (4.089 ± 0.015 ka BP) fit into the time frame (Figure 17A) of the surface rupture of the paleoearthquakes: from 4.630 ± 0.120 cal ka BP to 3.420 ± 0.030 cal ka BP [49]. The synchronicity of travertine formation at different locations may indicate that travertine springs began to discharge in the north of the Chuya and Kurai basins as a result of a single seismic event. Consequently, the zones of open fracturing along the faults of the Kurai zone opened up simultaneously at a distance of ca. 30 km. This distance can be used as an analogue of the “surface rupture length” parameter. If so, according to the empirical relationships [135] the paleoearthquakes had a magnitude of $M_w = 6.8$. This value is close to the magnitude estimates (6.5–6.7) obtained from trenching studies.

A series of different-age surface ruptures of paleoearthquakes were identified and dated by us in the north of the Kurai Basin. Thus, the age of the oldest Kuraika travertines (4973 ± 144 yr BP) falls within a relatively wide age range of one of the primary paleoseismic deformations (Figure 17A): from 5.910 ± 0.050 cal ka BP (IGAN_{AMS}7731; 0.954 probability; this study) to 4.550 ± 0.170 cal ka BP (IGAN_{AMS}7715; 0.954 probability; this study). At the same time, the Cheybek-Kohl 1 travertines of 6.296 ± 0.059 ka BP match the age of the surface rupture (Figure 17A), which occurred in the northern part of the Kurai Basin during the 6.3 ka paleoearthquake ($M_w = 6.5$ –6.7, shaking intensity VIII–IX) [57,79].

The age dates of the Meshtuyaryk travertines (7.379 ± 0.074 , 7.587 ± 0.040 , 7.852 ± 0.078 , and 7.855 ± 0.067 ka BP) agree well with the age of the surface ruptures caused by one paleoearthquake (Figure 17A) documented only 3.7 km south-east ($7.850\text{--}7.500$ cal ka BP [49]). A seismic rupture with a similar age at 7.460 ± 0.060 cal ka BP (IGAN 7752; 0.916 probability; this study), was also found in the north of the Kurai Basin. The Cheybek-Kohl 1 travertine 30 km north-west of it was dated to 7.152 ± 0.056 ka BP.

In recent years, there has been much evidence that the removal of glacial loading on continents after the Last Glacial Maximum (LGM) has increased the rate of displacement along active faults and resulted in the overall increase in the seismicity of these areas [136,137]. For example, the glacial deloading during the degradation of the last (Vistulian) glaciation in Fennoscandia between 15 and 9 ka BP was accompanied by fault movements and large earthquakes with $M_w \approx 7\text{--}8$ [138–142].

Similar processes apparently occurred during the degradation of the LGM glaciers in the south-western Gorny Altai. According to Butvilovsky [63] and Blyakharchuk et al. [143], the degradation occurred between 16 and 8 ka BP. Seismic movements along the KFZ at this time led to the formation of surface ruptures at ca. 8.5 ka BP [131], as well as large landslides and rockslides dated to around 8.3, 9.7, and 16 ka BP [81,131]. Our ^{230}Th -U age dates for Cheybek-Kohl 2 (9.340 ± 0.043 , 10.981 ± 0.060 , and 11.109 ± 0.168 ka BP) and Meshtuyaryk (9.545 ± 0.049 ka BP) correlate well with both the onset of Holocene warming (Figure 17A) and increased seismicity.

The ^{230}Th /U date of the Totugem travertines (ca. 123 ka BP) corresponds the MIS 5e (Eemian) (Figure 17B). At this time, the most widespread sheet glaciation in the Gorny Altai was degrading [62]. The intensification of neotectonic movements along the KFZ at this time could have been caused by an isostatic response of the Earth's crust to the removal of the glacial load. An additional isostatic effect could have been caused by the catastrophic release of water from the Kurai–Chuya limnosystem during the destruction of glacial dams at the end of the late glacial–early interglacial period [58].

The age of the oldest Baltyrgan travertines, ca. 400 ka BP, corresponds to the accumulation of the upper part of the Early Middle Pleistocene molasse in the intermontane basins. At the peak of Cenozoic orogenesis in the region, forebergs formed in the marginal parts of the Kurai Basin under submeridional compression [54]. Within the foreberg the travertine material cements the Middle Pleistocene alluvial fan gravels. Deposition of travertine among the gravels occurred during the degassing of carbonaceous groundwater along the fracture zone at that time. Obviously, the Middle Pleistocene fault movements were also accompanied by earthquakes. The high seismicity of the region at that time is indicated by numerous seismites associated with the liquefaction and fluidization of soils, which were recorded in the Lower-Middle Pleistocene sediments in the west of the Chuya Basin.

Summarizing, we posit that the ages of the large paleoearthquakes and ages of the episodes of travertine formation in the rim of the Chuya and Kurai basins during the last 8000 years exhibit a close match. The stages of travertine formation between 11 and 9 ka BP fit into the period of strong paleoseismicity in the region (16 to 8 ka BP). Travertines dated to 123 and 400 ka BP mark seismic movements, which could be induced by the isostatic rebound of the Earth's crust following the removal of the glacial load and related to the most intense phase of the Cenozoic mountain formation, respectively.

5.5. Paleoclimate and Travertine Deposition

The age of the Chibit travertine, 1.243 ± 0.266 ka BP, falls into the Medieval Climate Optimum (1.2–1.3 ka), during which time the average summer temperatures in the alpine zone of the Gorny Altai were higher than today by $0.7\text{--}0.9$ °C [144]. However, Ganyushkin et al. [145] showed that the average temperatures and annual precipitation between 1.3 and 1.0 ka ago at the Mongun-Taiga Uplift (Figure 1) were close to the present-day temperatures.

Five ^{230}U -Th ages of the Meshtuyaryk and the Kuraika travertines were dated to 3.6–5.0 ka BP, which is within the time frame of the Late Holocene Akkem glacial stage

(3.5–5.3 ka BP [145]). At the same time, in the Mongun-Taiga Uplift area, the annual precipitation exceeded the modern one by 10%, and the temperature could have been 1 °C colder relative to modern values [145]. Galakhov et al. [144], however, placed the Akkem glacial stage into a narrower time range of 4.3–4.0 ka BP. At 4.0 ka BP, the mean summer temperature was 1 °C lower than the present-day values, while for the 3.5 and 5.0 ka BP this parameter was 0.5 and 0.9 °C lower than the present-day value, respectively.

Cheybek-Kohl 1 travertines (ca. 6.3 ka BP) formed under wetter and warmer conditions. The mean annual temperatures could have exceeded modern ones by 1.5–2.5 °C, whereas annual precipitation exceeded the modern norm twice [144,145].

Similar climatic conditions were present in the south-eastern part of the Gorny Altai during the formation of the Cheybek-Kohl 1 and Meshtuyaryk travertines at 7.2 to 7.9 ka BP, Cheybek-Kohl 2 and Meshtuyaryk travertines at 9.3 and 9.5 ka BP, and Cheybek-Kohl 2 travertines at 11.0 ka BP [143,145].

The ages of the Totugem travertines (ca. 123 ka BP) and the Baltyrgan travertines (ca. 400 ka BP) are poorly characterized in climatic terms. One can only state that the formation of the former coincides with the warm interglacial MIS 5e (Eemian), while the latter corresponds to the MIS 11 interglacial (Figure 17B).

As it was shown previously [22,33,146,147] warm and humid (interglacial) periods are favourable for travertine formation. All travertine-forming events at the south-western Gorny Altai fall within warm (Figure 17) and wet climatic phases.

5.6. Travertine Formation Model

All Quaternary travertine deposits of the south-eastern Gorny Altai are spatially associated with the active faults bordering the Chuya and Kurai basins. Carbonate cements of the travertines have similar isotopic–geochemical characteristics, and their ages match the ages of the paleoearthquakes and periods of increased tectonic activity of the region in the Quaternary [41,48,49,65,66]. This suggests a similar mechanism of their formation and similar compositional sources. According to stable isotope and trace-element compositions, travertines precipitated from cold groundwaters remained in prolonged contact with Upper Neoproterozoic–Paleozoic carbonate aquifers (Figure 18). The rapid rise of these waters towards the surface was triggered by earthquakes. During seismic shifts, zones of open fracturing were formed and/or renewed along active faults, serving as pathways for groundwater migration to the Earth's surface. Near and on the surface the rapid rise of water was accompanied by rapid CO₂ degassing and CaCO₃ precipitation. One of the important arguments supporting the seismogenic characteristic of travertines is the observed existence of three periods of travertine precipitation in the Meshtuyaryk deposit, separated by long periods of no carbonate formation (Table 4). All three groups of ²³⁰Th-U dates obtained for travertines of the Meshtuyaryk deposit correspond to the ages of large paleoearthquakes whose epicentral zones were located in the immediate vicinity of this deposit [49]. According to the ²³⁰Th-U dating, travertine deposition occurred during warm (Figure 17) and humid periods (interglacials). Warming, ice rebound, and permafrost degradation may result in seismicity and fracturing, which channelled groundwaters previously sealed in carbonate aquifers. During interglacials, the overall volume and dynamics of groundwater are expected to increase.

5.7. Implications for Paleoseismology and Long-Term Fault History

The possibilities of the paleoseismological method in determining the ages of paleoearthquakes are limited, to a significant extent, by the preservation in the relief of fault scarps and other varieties of primary seismic dislocations, as well as seismogravitational deformations. These are destroyed by erosion processes, as a rule, within several thousand years, which limits their use for paleoseismological analysis. For example, in the Gorny Altai and in climatically similar regions of the northern Tien Shan, there are known fault scarps with ages up to 13–14 ka [61,148] and landslides up to 16 ka [81]. Therefore, for the reconstruction of more ancient seismic events, various secondary seismodislocations in

unconsolidated soils, united under the term “seismites”, have recently become significant. The analysis of these in the Gorny Altai has allowed us to extend its seismic record to the Middle Pleistocene [58–60,62,149,150]. The main disadvantage of the analysis of seismo-gravity structures and seismites is that in most cases they allow neither identification of the focal zones of paleoearthquakes nor specific active faults associated with seismic events.

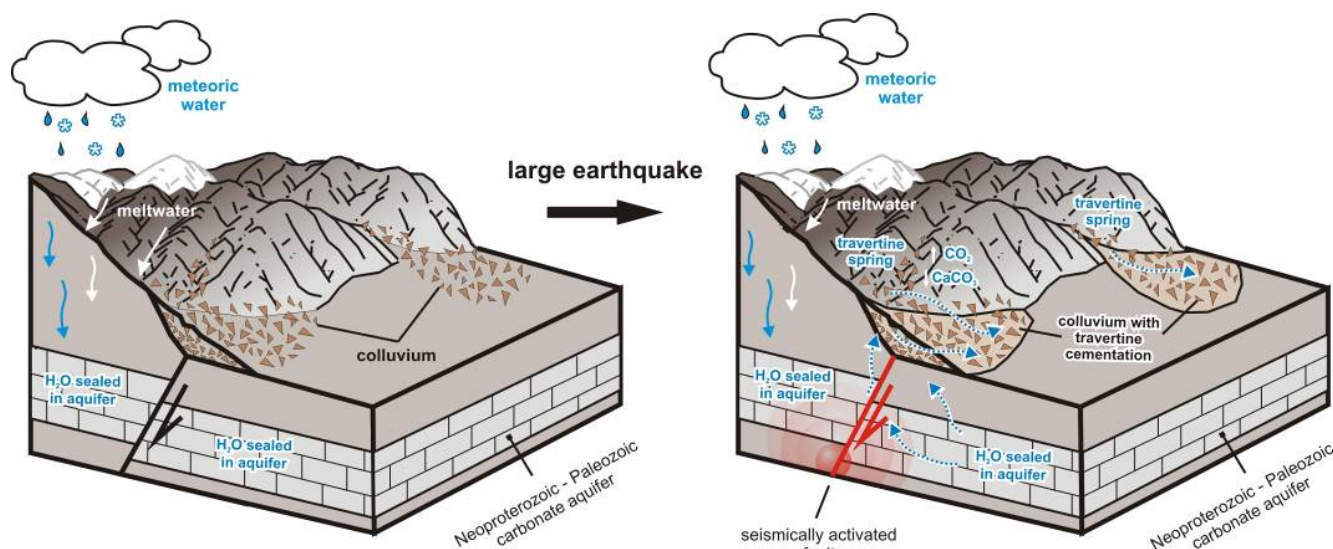


Figure 18. Generalized model of the formation of the south-eastern Gorny Altai travertines.

According to our proposed model, travertines located along active faults and possessing specific carbon isotope properties, mark the fracture zones included in the systems of surface ruptures of paleoearthquakes. The found match between the times of travertine formation in the south-eastern Gorny Altai and the ages of paleoearthquakes over the last 8 ka BP (Figure 17A) allow to consider travertines as an analogue of colluvial wedges, the age of which determines the age of paleoearthquakes. Consequently, the radiometric ages of travertine carbonates can be used as a tool to rebuild the sequence of ancient and historical earthquakes in the region. In contrast to surface earthquake ruptures and seismo-gravitational structures, travertine bodies are more resistant to weathering. This allows us, by determining their radiometric ages, to identify episodes of seismic activity on a much longer temporal scale. The results of our ^{230}Th -U dating demonstrated the possibility of detecting travertine with ages up to 400 ka BP (Figure 17B). Unlike seismites, large landslides and rockslides, the travertines we studied clearly indicate the fault on which the seismogenic displacement occurred. Furthermore, their resistance to weathering allows using coeval travertines to assess the length of the surface rupture system of a particular earthquake; in other words, the distance between such travertines can be used as an analogue of the “surface rupture length” parameter when estimating the moment magnitudes of paleoearthquakes. Consequently, seismogenic travertines become an important tool in the analysis of seismically active regions.

6. Conclusions

This study describes seven travertine deposits of the south-western Gorny Altai. The analysis of the morphology of travertine bodies, their petrography and mineralogy, mineral and rock chemistry, stable isotope geochemistry of carbonates, and ^{230}Th -U geochronology of carbonates in comparison with data on neotectonics, active tectonics, paleoseismicity and paleoclimate of the region allow the following main conclusions.

- (1) The travertine deposits have been found to be spatially associated with the active faults bordering the Chuya and Kurai basins. Travertines predominantly cement Middle

- Pleistocene-Holocene colluvial, alluvial, and alluvial fan deposits, transforming them into breccias, conglomerates, and sandstones.
- (2) Ca-carbonates of fossil travertines are primary precipitates and show no indications of diagenetic alteration. Precipitation of calcite and aragonite in fossil travertines was probably controlled by rapid CO₂ degassing and the Mg/Ca ratios of the spring water.
 - (3) The isotope and trace-element data jointly indicate a hypogean origin of the paleofluid from the fossil Gorny Altai travertine system and the Upper Neoproterozoic–Paleozoic limestone-dolostone as fluid source rocks.
 - (4) The times of travertine formation match the ages of paleoearthquakes over the last 8 ka BP (Figure 17A), and episodes of travertine deposition at 9.0–11.0 ka BP correspond to the period of elevated paleoseismicity of the region at 8.0–16.0 ka BP. The 123 ka BP travertine resulted from a slip triggered by the Middle Pleistocene deglaciation, while that of 400 ka BP represents seismic motions during the main Cenozoic orogenic phase. Episodes of travertines formation were triggered by large seismic events, which induced the rapid rise of bicarbonate groundwaters previously sealed in carbonate aquifers along seismically activated ruptures. All travertine-forming events at the south-western Gorny Altai fall within warm and wet climatic phases (interglacials), when ice rebound and permafrost degradation occurred.
 - (5) The obtained results allow using travertines with similar isotopic characteristics and structural position as indicators of fault activity both in the south-western Siberian Altai and in other seismically active regions of the world. Radiometric ages of carbonates make it possible to determine the age of ancient and historical earthquakes, detailing and significantly extending the data of instrumental and historical seismology and paleoseismology.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/min13020259/s1>, Table S1: Carbon and oxygen isotope compositions of CaCO₃ from travertines of the south-eastern Gorny Altai. Table S2: Description of travertine samples, dated by the ²³⁰Th-U method. Figure S1: Biota in the seepage zone of a modern spring at the Chibit deposit.

Author Contributions: Project idea, E.V.D., S.N.K., Y.D. and E.V.S.; conceptualization, E.V.D., S.N.K. and Y.D.; field work, E.V.D., G.G.R. and S.N.K.; paleoseismological study, E.V.D.; ²³⁰Th-U dating, Y.D. and D.S.; SEM and EPMA analyses, S.N.K. and E.V.S.; isotope analysis, Y.D. and V.N.R.; interpretation of analytical data: E.V.D., S.N.K. and Y.D.; writing—original draft preparation, E.V.D., S.N.K. and Y.D.; visualization: E.V.D. and S.N.K.; funding acquisition, E.V.D. All authors have read and agreed to the published version of the manuscript.

Funding: The work was supported by the Russian Science Foundation [Project 21-17-00058].

Data Availability Statement: Not applicable.

Acknowledgments: D. Scholz thanks the DFG (German Research Foundation) for funding (INST 247/889-1 FUGG) and M. Großkopf, M. Weber, and V. Blumrich for assistance with U-series dating at the University of Mainz. D. Scholz is also thankful to K.P. Jochum, M.O. Andreae and G.H. Haug from the Max Planck Institute for Chemistry, Mainz, for long-lasting support. We thank the anonymous reviewers for their valuable comments, which we accepted with gratitude.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Pentecost, A. *Travertine*; Springer: Berlin, Germany, 2005; p. 446.
2. Jones, B.; Renaut, R.W. Calcareous spring deposits in continental settings. In *Carbonates in Continental Settings: Facies, Environments, and Processes*; Alonso Zarza, A.M., Taner, L.H., Eds.; Elsevier: Amsterdam, The Netherlands, 2010; Volume 61, pp. 177–224.
3. Capezzuoli, E.; Gandin, A.; Pedley, M. Decoding tufa and travertine (freshwater carbonates) in the sedimentary record: The state of the art. *Sedimentology* **2014**, *61*, 1–21. [[CrossRef](#)]
4. Pedley, H.M. Classification and environmental models of cool freshwater tufas. *Sediment. Geol.* **1990**, *68*, 143–154. [[CrossRef](#)]
5. Ford, T.D.; Pedley, H.M. A review of tufa and travertine deposits of the world. *Earth Sci. Rev.* **1996**, *41*, 117–175. [[CrossRef](#)]
6. Pentecost, A. British travertines: A review. *Proc. Geol. Assoc.* **1993**, *104*, 23–39. [[CrossRef](#)]

7. Pentecost, A.; Viles, H. A review and reassessment of travertine classification. *Géographie Phys. Quat.* **1994**, *48*, 305–314. [\[CrossRef\]](#)
8. Zentmyer, R.; Myrow, P.M.; Newell, D.L. Travertine deposits from along the South Tibetan Fault System near Nyalam, Tibet. *Geol. Mag.* **2008**, *145*, 753–765. [\[CrossRef\]](#)
9. Ruszkiczay-Rüdiger, Z.; Csillag, G.; Fodor, L.; Braucher, R.; Novothny, Á.; Thamó-Bozsó, E.; Virág, A.; Pazonyi, P.; Timár, G.; Aumaitre, G.; et al. Integration of new and revised chronological data to constrain the terrace evolution of the Danube River (Gerecse Hills, Pannonian Basin). *Quat. Geochronol.* **2018**, *48*, 148–170. [\[CrossRef\]](#)
10. Barnes, I.; O’Neil, J.R. Calcium-magnesium carbonate solid solutions from Holocene conglomerate cements and travertines in the Coast Range of California. *Geochim. Cosmochim. Acta* **1971**, *35*, 699–718. [\[CrossRef\]](#)
11. Boch, R.; Spötl, C.; Reitner, J.M.; Kramers, J. A Lateglacial travertine deposit in Eastern Tyrol (Austria). *Austrian J. Earth Sci.* **2005**, *98*, 78–91.
12. Lugli, S.; Tang, Y.; Reghizzi, M.; Qiao, X.; Schreiber, B.C.; Deng, G. Seasonal pattern in the high-elevation fluvial travertine from the Jiuzhaigou national nature reserve, Sichuan, southwestern China. *J. Sediment. Res.* **2017**, *87*, 253–271. [\[CrossRef\]](#)
13. Claes, H.; Soete, J.; Van Noten, K.; El Desouky, H.; Marques Erthal, M.; Vanhaecke, F.; Özkul, M.; Swennen, R. Sedimentology, three-dimensional geobody reconstruction and carbon dioxide origin of Pleistocene travertine deposits in the Ballık area (south-west Turkey). *Sedimentology* **2015**, *62*, 1408–1445. [\[CrossRef\]](#)
14. Claes, H.; Huysmans, M.; Soete, J.; Dirix, K.; Vassilieva, E.; Marques Erthal, M.; Vandewijngaerde, W.; Hamaekers, H.; Aratman, C.; Özkul, M.; et al. Elemental geochemistry to complement stable isotope data of fossil travertine: Importance of digestion method and statistics. *Sediment. Geol.* **2019**, *386*, 118–131. [\[CrossRef\]](#)
15. Crossey, L.J.; Fischer, T.P.; Patchett, P.J.; Karlstrom, K.E.; Hilton, D.R.; Newell, D.L.; Huntoon, P.; Reynolds, A.C.; de Leeuw, G.A.M. Dissected hydrologic system at the Grand Canyon: Interaction between deeply derived fluids and plateau aquifer waters in modern springs and travertine. *Geology* **2006**, *34*, 25–28. [\[CrossRef\]](#)
16. Teboul, P.-A.; Durlet, C.; Gaucher, E.C.; Virgone, A.; Girard, J.-P.; Curie, J.; Lopez, B.; Camoin, G.F. Origins of elements building travertine and tufa: New perspectives provided by isotopic and geochemical tracers. *Sediment. Geol.* **2016**, *334*, 97–114. [\[CrossRef\]](#)
17. Pazdur, A.; Pazdur, M.F.; Starkel, L.; Szulc, J. Stable isotopes of Holocene calcareous tufa in southern Poland as palaeoclimatic indicators. *Quat. Res.* **1988**, *30*, 177–189. [\[CrossRef\]](#)
18. Frank, N.; Braum, M.; Hambach, U.; Mangini, A.; Wagner, G. Warm period growth of travertine during the last Interglaciation in southern Germany. *Quat. Res.* **2000**, *54*, 38–48. [\[CrossRef\]](#)
19. Minissale, A.; Kerrick, D.M.; Magro, G.; Murrell, M.T.; Paladini, M.; Rihs, S.; Sturchio, N.C.; Tassi, F.; Vaselli, O. Geochemistry of Quaternary travertines in the region north of Rome (Italy): Structural, hydrologic, and paleoclimatic implications. *Earth Planet. Sci. Lett.* **2002**, *203*, 709–728. [\[CrossRef\]](#)
20. Martin-Algarra, A.; Martin-Martin, M.; Andreo, B.; Julia, R.; Gonzalez-Gomez, C. Sedimentary patterns in perched spring travertines near Granada (Spain) as indicators of the paleohydrological and palaeoclimatic evolution of a karst massif. *Sediment. Geol.* **2003**, *161*, 217–228. [\[CrossRef\]](#)
21. Liu, Z.; Zhang, M.; Li, Q.; You, S. Hydrochemical and isotope characteristics of spring water and travertine in the Baishuitai area (SW China) and their meaning for paleoenvironmental reconstruction. *Environ. Geol.* **2003**, *44*, 698–704. [\[CrossRef\]](#)
22. Faccenna, C.; Soligo, M.; Billi, A.; De Filippis, L.; Funicello, R.; Rossetti, C.; Tuccimei, P. Late Pleistocene depositional cycles of the Lapis Tiburtinus travertine (Tivoli, central Italy): Possible influence of climate and fault activity. *Glob. Planet. Change* **2008**, *63*, 299–308. [\[CrossRef\]](#)
23. Altunel, E.; Hancock, P.L. Active fissuring, faulting and travertine deposition at Pamukkale, western Turkey. In *Neotectonics and Active Faulting*; Stewart, I.S., Vita-Finzi, C., Owen, L.A., Eds.; Zeitschrift für Geomorphologie: Stuttgart, Germany, 1993; Volume 94, pp. 285–302.
24. Çakır, Z. Along-strike discontinuity of active normal faults and its influence on quaternary travertine deposition; examples from western Turkey. *Turk. J. Earth Sci.* **1999**, *8*, 67–80.
25. Hancock, P.L.; Chalmers, R.M.L.; Altunel, E.; Çakır, Z. Travertines: Using travertine in active fault studies. *J. Struct. Geol.* **1999**, *21*, 903–916. [\[CrossRef\]](#)
26. Altunel, E.; Karabacak, V. Determination of horizontal extension from fissure-ridge travertines: A case study from the Denizli Basin, southwestern Turkey. *Geodin. Acta* **2005**, *18*, 333–342. [\[CrossRef\]](#)
27. Mesci, B.L.; Gürsoy, H.; Tatar, O. The evolution of travertine masses in the Sivas Area (Central Turkey) and their relationships to active tectonics. *Turk. J. Earth Sci.* **2008**, *17*, 219–240.
28. Brogi, A.; Capezzuoli, E. Travertine deposition and faulting: The fault-related travertine fissure-ridge at Terme S. Giovanni, Rapolano Terme (Italy). *Int. J. Earth Sci.* **2009**, *98*, 931–947. [\[CrossRef\]](#)
29. Brogi, A.; Capezzuoli, E.; Aqué, R.; Branca, M.; Voltaggio, M. Studying travertines for neotectonics investigations: Middle–Late Pleistocene syn-tectonic travertine deposition at Serre di Rapolano (Northern Apennines, Italy). *Int. J. Earth Sci.* **2010**, *99*, 1383–1398. [\[CrossRef\]](#)
30. Nishikawa, O.; Furuhashi, K.; Masuyama, M.; Ogata, T.; Shiraishi, T.; Shen, C. Radiocarbon dating of residual organic matter in travertine formed along the Yumoto Fault in Oga Peninsula, northeast Japan: Implications for long-term hot spring activity under the influence of earthquakes. *Sediment. Geol.* **2012**, *243–244*, 181–190. [\[CrossRef\]](#)
31. Temiz, U. Age of fault reactivation by using U/Th dating method of carbonate precipitates: An example from the active Manisa Fault (West Turkey). *Geodin. Acta* **2012**, *1–2*, 1–11. [\[CrossRef\]](#)

32. Temiz, U.; Gökten, Y.E.; Eikenberg, J. Strike-slip deformation and U/Th dating of travertine deposition: Examples from North Anatolian Fault Zone, Bolu and Yeniçağ Basins, Turkey. *Quat. Int.* **2013**, *312*, 132–140. [\[CrossRef\]](#)
33. De Filippis, L.; Faccenna, C.; Billi, A.; Anzalone, E.; Brilli, M.; Soligo, M.; Tuccimei, P. Plateau versus fissure ridge travertines from Quaternary geothermal springs of Italy and Turkey: Interactions and feedbacks between fluid discharge, paleoclimate, and tectonics. *Earth-Sci. Rev.* **2013**, *123*, 35–52. [\[CrossRef\]](#)
34. De Filippis, L.; Anzalone, E.; Billi, A.; Faccenna, C.; Poncia, P.P.; Sella, P. The origin and growth of a recently-active fissure ridge travertine over a seismic fault, Tivoli, Italy. *Geomorphology* **2013**, *195*, 13–26. [\[CrossRef\]](#)
35. Ascione, A.; Iannace, A.; Imbriale, P.; Santangelo, N.; Santo, A. Tufa and travertines of southern Italy: Deep-seated, fault-related CO₂ as the key control in precipitation. *Terra Nova* **2014**, *26*, 1–13. [\[CrossRef\]](#)
36. Mohajjel, M.; Taghipour, K. Quaternary travertine ridges in the Lake Urmia area: Active extension in NW Iran. *Turk. J. Earth Sci.* **2014**, *23*, 602–614. [\[CrossRef\]](#)
37. Erol, S.Ç.; Özkul, M.; Aksoy, E.; Kele, S.; Ghaleb, B. Travertine occurrences along major strike-slip fault zones: Structural, depositional and geochemical constraints from the Eastern Anatolian Fault System (EAFS), Turkey. *Geodin. Acta* **2015**, *27*, 155–174. [\[CrossRef\]](#)
38. Selim, H.H.; Yavuz, O.; Gürer, Ö.F.; Karakaş, A.; Taş, K.Ö. Age determination for segments of the North Anatolian Fault (NAF) northern branch by ²³⁴U/²³⁰Th dating of Soğucak (Yalova) range-front travertines, south Marmara, Turkey. *Quat. Int.* **2016**, *425*, 416–424. [\[CrossRef\]](#)
39. Sinisi, R.; Petruccio, A.V.; Agosta, F.; Paternoster, M.; Belviso, C.; Grassa, F. Fault and fluid interaction in the Bradano Trough, southern Italy. *Tectonophysics* **2016**, *690*, 206–218. [\[CrossRef\]](#)
40. Frery, E.; Gratier, J.P.; Ellouzi-Zimmerman, N.; Deschamps, P.; Blamart, D.; Hamelin, B.; Swennen, R. Geochemical transect through a travertine mound: A detailed record of CO₂-enriched fluid leakage from Late Pleistocene to present-day e Little Grand Wash fault (Utah, USA). *Quat. Int.* **2017**, *437*, 98–106. [\[CrossRef\]](#)
41. Kokh, S.N.; Sokol, E.V.; Deev, E.V.; Ryapolova, Y.M.; Rusanov, G.G.; Tomilenko, A.A.; Bul'bak, T.A. Post-Late Glacial calcareous tufas from the Kurai fault zone (Southeastern Gorny Altai, Russia). *Sediment. Geol.* **2017**, *355*, 1–19. [\[CrossRef\]](#)
42. Martínez-Díaz, J.J.; Hernández-Enrile, J.L. Using travertine deformations to characterize paleoseismic activity along an active oblique-slip fault: The Alhama de Murcia fault (Betic Cordillera, Spain). *Acta Geol. Hisp.* **2001**, *36*, 297–313.
43. Uysal, I.T.; Feng, Y.; Zhao, J.; Isik, V.; Nuriel, P.; Golding, S.D. Hydrothermal CO₂ degassing in seismically active zones during the late Quaternary. *Chem. Geol.* **2009**, *265*, 442–454. [\[CrossRef\]](#)
44. Uysal, I.T.; Feng, Y.; Zhao, J.; Altunel, E.; Weatherley, D.; Karabacak, V.; Cengiz, O.; Golding, S.D.; Lawrens, M.G.; Collerson, K.D. U-series dating and geochemical tracing of Late Quaternary travertines in co-seismic fissures. *Earth Planet. Sci. Lett.* **2007**, *257*, 450–462. [\[CrossRef\]](#)
45. Brogi, A.; Capezzuoli, E. Earthquake impact on fissure-ridge type travertine deposition. *Geol. Mag.* **2014**, *151*, 1135–1143. [\[CrossRef\]](#)
46. Gradziński, M.; Wróblewski, W.; Duliński, M.; Hercman, H. Earthquake-affected development of a travertine ridge. *Sedimentology* **2014**, *61*, 238–263. [\[CrossRef\]](#)
47. Karabacak, V.; Uysal, I.T.; Mutlu, H.; Ünal-İmer, E.; Dirik, R.K.; Feng, Y.-X.; Akiska, S.; Aydoğdu, İ.; Zhao, J.-X. Are U-Th dates correlated with historical records of earthquakes? Constraints from co-seismic carbonate veins within the North Anatolian Fault Zone. *Tectonics* **2019**, *38*, 2431–2448. [\[CrossRef\]](#)
48. Deev, E.V.; Dublyansky, Y.V.; Pozdnyakova, N.I.; Scholz, D.; Kokh, S.N.; Sokol, E.V.; Rusanov, G.G. ²³⁰Th/U dating of travertines related to paleoearthquakes in Gorny Altai: First results. *Dokl. Earth Sci.* **2021**, *500*, 820–825. [\[CrossRef\]](#)
49. Deev, E.; Dublyansky, Y.; Kokh, S.; Scholz, D.; Rusanov, G.; Sokol, E.; Khvorov, P.; Reutsky, V.; Panin, A. Large Holocene paleoseismic events and synchronized travertine formation: A case study of the Kurai Fault Zone (Gorny Altai, Russia). *Int. Geol. Rev.* **2022**. [\[CrossRef\]](#)
50. Mancini, A.; Frondini, F.; Capezzuoli, E.; Mejia, E.G.; Lezzi, G.; Matarazzi, D.; Brogi, A.; Swennen, R. Evaluating the geogenic CO₂ flux from geothermal areas by analysing quaternary travertine masses. New data from western central Italy and review of previous CO₂ flux data. *Quat. Sci. Rev.* **2019**, *215*, 132–143. [\[CrossRef\]](#)
51. Molnar, P.; Tapponnier, P. Cenozoic tectonics of Asia: Effects of a continental collision. *Science* **1975**, *189*, 419–426. [\[CrossRef\]](#) [\[PubMed\]](#)
52. Delvaux, D.; Cloetingh, S.; Beekman, F.; Sokoutis, D.; Burov, E.; Buslov, M.M.; Abdrakhmatov, K.E. Basin evolution in a folding lithosphere: Altai–Sayan and Tien Shan belts in Central Asia. *Tectonophysics* **2013**, *602*, 194–222. [\[CrossRef\]](#)
53. Deev, E.V.; Nevedrova, N.N.; Zol'nikov, I.D.; Rusanov, G.G.; Ponomarev, P.V. Geoelectrical studies of the Chuya basin sedimentary fill (Gorny Altai). *Russ. Geol. Geophys.* **2012**, *53*, 92–107. [\[CrossRef\]](#)
54. Nevedrova, N.N.; Deev, E.V.; Sanchaa, A.M. Deep structure and margins of the Kurai Basin (Gorny Altai), from controlled-source resistivity data. *Russ. Geol. Geophys.* **2014**, *55*, 98–107. [\[CrossRef\]](#)
55. Rusanov, G.G.; Deev, E.V.; Zolnikov, I.D.; Khazin, L.B.; Khazina, I.V.; Kuz'mina, O.B. Reference section of Neogene–Quaternary deposits in the Uimon Basin (Gorny Altai). *Russ. Geol. Geophys.* **2017**, *58*, 973–983. [\[CrossRef\]](#)
56. Deviatkin, E.V. *Cenozoic Deposits and Neotectonics in South-Eastern Altai*; Nauka: Moscow, Russia, 1965; p. 244.
57. Deev, E.V. Localization Zones of Ancient and Historical Earthquakes in Gorny Altai. *Izv. Phys. Solid Earth* **2019**, *55*, 451–470. [\[CrossRef\]](#)

58. Deev, E.V.; Zolnikov, I.D.; Gus'kov, S.A. Seismites in Quaternary sediments of southeastern Altai. *Russ. Geol. Geophys.* **2009**, *50*, 546–561. [\[CrossRef\]](#)
59. Deev, E.V.; Zolnikov, I.D.; Bortodovsky, A.P.; Goltsova, S.V. Neotectonics and paleoseismicity of the lower Katun' valley (Gorny Altai). *Russ. Geol. Geophys.* **2012**, *53*, 883–894. [\[CrossRef\]](#)
60. Deev, E.V.; Zolnikov, I.D.; Goltsova, S.V.; Rusanov, G.G.; Emanov, A.A. Traces of paleoearthquakes in the Quaternary deposits of intermontane basins in central Gorny Altai. *Russ. Geol. Geophys.* **2013**, *54*, 312–323. [\[CrossRef\]](#)
61. Deev, E.V.; Zolnikov, I.D.; Turova, I.V.; Rusanov, G.G.; Ryapolova, Y.M.; Nevedrova, N.N.; Kotler, S.A. Paleoseismicity in the Uimon basin (Gorny Altai). *Russ. Geol. Geophys.* **2018**, *59*, 437–452. [\[CrossRef\]](#)
62. Deev, E.; Turova, I.; Borodovskiy, A.; Zolnikov, I.; Pozdnyakova, N.; Molodkov, A. Large earthquakes in the Katun Fault zone (Gorny Altai): Paleoseismological and archaeoseismological evidence. *Quat. Sci. Rev.* **2019**, *203*, 68–89. [\[CrossRef\]](#)
63. Butvilovsky, V.V. *Paleogeography of the Latest Glaciation and Holocene of Altai: An Event–Catastrophic Model*; Tomsk University: Tomsk, Russia, 1993; p. 253. (In Russian)
64. Rusanov, G.G.; Deev, E.V.; Ryapolova, Y.M.; Zolnikov, I.D. Paleohydrothermal activity of faults in the Gorny Altai based on travertine dating. *Geol. Miner. Resour. Sib.* **2013**, *4*, 53–64.
65. Deev, E.V.; Sokol, E.V.; Ryapolova, Y.M.; Kokh, S.N.; Rusanov, G.G. Quaternary travertine of the Kurai fault zone (Gorny Altai). *Dokl. Earth Sci.* **2017**, *473*, 261–265. [\[CrossRef\]](#)
66. Kokh, S.N.; Sokol, E.V.; Deev, E.V.; Ryapolova, Y.M.; Rusanov, G.G. Modern and paleotravertines from Gorny Altai: Indicative features. *Dokl. Earth Sci.* **2018**, *483*, 1399–1404. [\[CrossRef\]](#)
67. GeoMapApp, Version 3.6.15. Available online: <http://www.geomapp.org> (accessed on 5 December 2022).
68. Turkin, Y.A.; Fedak, S.I. *Geology and Structural-and-Compositional Complexes of Gorny Altai*; STT: Tomsk, Russia, 2008; p. 460. (In Russian)
69. Nevedrova, N.N.; Epov, M.I.; Antonov, E.Y.; Dashevskii, Y.A.; Duchkov, A.D. Deep structure of the Chuya basin (Gorny Altai) as imaged by TEM soundings. *Russ. Geol. Geophys.* **2001**, *42*, 1399–1416.
70. Delvaux, D.; Theunissen, K.; Van Der Meer, R.; Berzin, N. Dynamics and paleostress of the Cenozoic Kurai-Chuya depression of Gorny Altai (South Siberia): Tectonic and climatic control. *Russ. Geol. Geophys.* **1995**, *36*, 26–45.
71. Deev, E.V.; Krzhivoblotskaya, V.E.; Borodovskiy, A.P.; Entin, A.L. Active faults and Late Holocene surface rupturing earthquakes in the Kokorya Basin (Gorny Altai, Russia). *Dokl. Earth Sci.* **2022**, *506*, 666–670. [\[CrossRef\]](#)
72. Zol'nikov, I.D.; Deev, E.V.; Lyamina, V.A. New data on Quaternary morpholithogenesis in the Chuya basin (Gorny Altai). *Russ. Geol. Geophys.* **2010**, *51*, 339–348. [\[CrossRef\]](#)
73. Shokalsky, S.P.; Turkin, Y.A.; Fedak, S.I. *State Geological Map of the Russian Federation. Scale 1: 1 000 000, 3rd. Series Altai-Sayan. Sheet M-45—Gorno-Altaiisk*, 3rd ed.; VSEGEI: St. Petersburg, Russia, 2011.
74. Deev, E.V.; Turova, I.V.; Borodovskiy, A.P.; Zolnikov, I.D.; Oleszczak, L. Unknown large ancient earthquakes along the Kurai fault zone (Gorny Altai): New results of paleoseismological and archaeoseismological studies. *Int. Geol. Rev.* **2017**, *59*, 293–310. [\[CrossRef\]](#)
75. Bachmanov, D.M.; Kozhurin, A.I.; Trifonov, V.G. The active faults of Eurasia database. *Geodyn. Tectonophys.* **2017**, *8*, 711–736. [\[CrossRef\]](#)
76. Leskova, E.V.; Emanov, A.A. Hierarchical properties of the tectonic stress field in the source region of the 2003 Chuya earthquake. *Russ. Geol. Geophys.* **2013**, *54*, 87–95. [\[CrossRef\]](#)
77. Rogozhin, E.A.; Ovsyuchenko, A.N.; Marakhanov, A.V.; Ushanova, E.A. Tectonic setting and geological manifestations of the 2003 Altai earthquake. *Geotectonics* **2007**, *41*, 87–104. [\[CrossRef\]](#)
78. Lunina, O.V.; Gladkov, A.S.; Novikov, I.S.; Agatova, A.R.; Vysotskii, E.M.; Emanov, A.A. Geometry of the fault zone of the 2003 Ms=7.5 Chuya earthquake and associated stress fields, Gorny Altai. *Tectonophysics* **2008**, *453*, 276–294. [\[CrossRef\]](#)
79. Turova, I.; Deev, E.; Pozdnyakova, N.; Entin, A.; Nevedrova, N.; Shaparenko, I.; Bricheva, S.; Korzhenkov, A.; Kurbanov, R.; Panin, A. Surface-rupturing paleoearthquakes in the Kurai Fault Zone (Gorny Altai, Russia): Trenching and geophysical evidence. *J. Asian Earth Sci.* **2020**, *197*, 104399. [\[CrossRef\]](#)
80. Korzhenkov, A.M.; Deev, E.V.; Pozdnyakova, N.I. Young landforms created by earthquakes in the foothills of the Kurai Range (Gorny Altai). *Seism. Instrum.* **2022**, *58*, 424–441. [\[CrossRef\]](#)
81. Deev, E.V.; Zolnikov, I.D.; Kurbanov, R.N.; Panin, A.V.; Murray, A.; Korzhenkov, A.M.; Turova, I.V.; Pozdnyakova, N.I.; Vasiliev, A.V. OSL dating of the Sukor earthquake-induced rockslide in Gorny Altai: Paleoseismological and paleogeographic implications. *Russ. Geol. Geophys.* **2022**, *63*, 743–754. [\[CrossRef\]](#)
82. Ershov, E.D. (Ed.) *Geocryology of the USSR. Vol. V. Mountain Regions of the Southern USSR*; Nedra: Moscow, Russia, 1989; p. 359. (In Russian)
83. Olenchenko, V.V.; Kozhevnikov, N.O.; Antonov, E.Y.; Pospeeva, E.V.; Potapov, V.V.; Shein, A.N.; Stefanenko, S.M. Distribution of permafrost in Chuiskaya Basin (Gorny Altai) according to transient electromagnetic soundings data. *Earth's Cryosphere* **2011**, *15*, 15–22.
84. Fedak, S.I.; Turkin, Y.A.; Gusev, A.I.; Shokalsky, S.P.; Rusanov, G.G.; Borisov, B.A.; Belyaev, G.M.; Leontyeva, E.M. *State Geological Map of the Russian Federation. Scale 1: 1 000 000. Third Generation. Series: Altai-Sayan. Sheet M-45—Gorno-Altaiisk. Explanatory Note*; VSEGEI: St. Petersburg, Russia, 2011; p. 567. (In Russian)

85. Lavrent'ev, Y.G.; Korolyuk, V.N.; Usova, L.V.; Nigmatulina, E.N. Electron probe microanalysis of rock-forming minerals with a JXA-8100 electron probe microanalyzer. *Russ. Geol. Geophys.* **2015**, *56*, 1428–1436. [\[CrossRef\]](#)
86. Feng, D.; Chen, D.; Peckmann, J. Rare earth elements in seep carbonate as tracers of variable redox conditions at ancient hydrocarbon seeps. *Terra Nova* **2009**, *21*, 49–56. [\[CrossRef\]](#)
87. Spötl, C. Long-term performance of the Gasbench isotope ratio mass spectrometry system for the stable isotope analysis of carbonate microsamples. *Rapid Commun. Mass Spectrom.* **2011**, *25*, 1683–1685. [\[CrossRef\]](#)
88. Parkhurst, D.L.; Appelo, C.A.J. User's Guide to PHREEQC (Version 2) a Computer Program for Speciation, Batch-Reaction, One-Dimensional Transport, and Inverse Geochemical Calculations: U.S Geological Survey Water-Resources Investigations Report 99-4259. 1999. Available online: <https://pubs.er.usgs.gov/publication/wri994259> (accessed on 1 December 2022).
89. Yang, Q.; Scholz, D.; Jochum, K.P.; Hoffmann, D.L.; Stoll, B.; Weis, U.; Schwager, B.; Andreae, M.O. Lead isotope variability in speleothems—A promising new proxy for hydrological change? First results from a stalagmite from western Germany. *Chem. Geol.* **2015**, *396*, 143–151. [\[CrossRef\]](#)
90. Obert, J.C.; Scholz, D.; Felis, T.; Brocas, W.M.; Jochum, K.P.; Andreae, M.O. $^{230}\text{Th}/\text{U}$ dating of Last Interglacial brain corals from Bonaire (southern Caribbean) using bulk and theca wall material. *Geochim. Cosmochim. Acta* **2016**, *178*, 20–40. [\[CrossRef\]](#)
91. Gibert, L.; Scott, G.R.; Scholz, D.; Budsky, A.; Ferrandez, C.; Martin, R.A.; Ribot, F.; Leria, M. Chronology for the Cueva Victoria fossil site (SE Spain): Evidence for Early Pleistocene Afro-Iberian dispersals. *J. Hum. Evol.* **2016**, *90*, 183–197. [\[CrossRef\]](#)
92. Cheng, H.; Edwards, R.L.; Shen, C.C.; Polyak, V.J.; Asmerom, Y.; Woodhead, J.; Hellstrom, J.; Wang, Y.; Kong, X.; Spötl, C.; et al. Improvements in ^{230}Th dating, ^{230}Th and ^{234}U half-life values, and U–Th isotopic measurements by multi-collector inductively coupled plasma mass spectrometry. *Earth Planet. Sci. Lett.* **2013**, *371*, 82–91. [\[CrossRef\]](#)
93. Bantsev, D.V.; Ganyushkin, D.A.; Chistyakov, K.V.; Ekaykin, A.A.; Tokarev, I.V.; Volkov, I.V. Formation of glacier runoff on the northern slope of Tavan Bogd mountain massif based on stable isotopes data. *Ice Snow* **2018**, *58*, 333–342. [\[CrossRef\]](#)
94. Bantsev, D.; Ganyushkin, D.; Terekhov, A.; Ekaykin, A.; Tokarev, I.; Chistyakov, K. Isotopic composition of glacier ice and meltwater in the arid parts of the Altai Mountains (Central Asia). *Water* **2022**, *14*, 252. [\[CrossRef\]](#)
95. Bantsev, D.V. Isotopic composition of glacio-nival systems components as an indicator of their runoff-forming features in South-Eastern Altai. Ph.D. Thesis, Saint-Petersburg State University, Saint-Petersburg, Russia, 2020.
96. Craig, H. Isotopic variations in meteoric waters. *Science* **1961**, *133*, 1702–1703. [\[CrossRef\]](#)
97. Taylor, S.R.; McLennan, S.M. *The Continental Crust: Its Evolution and Composition*; Blackwell Scientific Publications: Oxford, UK, 1985; p. 312.
98. Jaffey, A.H.; Flynn, K.F.; Glendenin, L.E.; Bentley, W.C.; Essling, A.M. Precision measurement of the half-lives and specific activities of ^{235}U and ^{238}U . *Phys. Rev. C* **1971**, *4*, 1889–1906. [\[CrossRef\]](#)
99. Janssens, N.; Capezzuoli, E.; Claes, H.; Muchez, P.; Yu, T.-L.; Shen, C.-C.; Ellam, R.M.; Swennen, R. Fossil travertine system and its palaeofluid provenance, migration and evolution through time: Example from the geothermal area of Acquasanta Terme (Central Italy). *Sediment. Geol.* **2020**, *398*, 105580. [\[CrossRef\]](#)
100. Folk, R.L. Interaction between bacteria, nannobacteria, and mineral precipitation in hot springs of central Italy. *Géographie Phys. Et Quat.* **1994**, *48*, 233–246. [\[CrossRef\]](#)
101. Loste, E.; Wilson, R.M.; Seshadri, R.; Meldrum, F.C. The role of magnesium in stabilizing amorphous calcium carbonate and controlling calcite morphologies. *J. Cryst. Growth* **2003**, *354*, 206–218. [\[CrossRef\]](#)
102. Jones, B. Review of calcium carbonate polymorph precipitation in spring systems. *Sediment. Geol.* **2017**, *353*, 64–75. [\[CrossRef\]](#)
103. Boch, R. Carbonates in natural and geotechnical settings—chemical sediments as environmental archives. *Jahrb. Der Geol. Bundesanst.* **2019**, *159*, 67–130.
104. Luo, L.; Capezzuoli, E.; Rogerson, M.; Vaselli, O.; Wen, H.; Lu, Z. Precipitation of carbonate minerals in travertine-depositing hot springs: Driving forces, microenvironments, and mechanisms. *Sediment. Geol.* **2022**, *438*, 106207. [\[CrossRef\]](#)
105. Friedman, I. Some investigations of the deposition of travertine from Hot Springs—I. The isotopic chemistry of a travertine-depositing spring. *Geochim. Et Cosmochim. Acta* **1970**, *34*, 1303–1315. [\[CrossRef\]](#)
106. Fouke, B.W.; Farmer, J.D.; Des Marais, D.J.; Pratt, L.; Sturchio, N.C.; Burns, P.C.; Discipulo, M.K. Depositional facies and aqueous-solid geochemistry of travertine depositing hot springs (Angel Terrace, Mammoth hot springs, Yellowstone national park, USA). *J. Sediment. Res.* **2000**, *70*, 565–585. [\[CrossRef\]](#) [\[PubMed\]](#)
107. Okumura, T.; Takashima, C.; Shiraishi, F.; Akmaluddin; Kano, A. Textural transition in an aragonite travertine formed under various flow conditions at Pancuran Pitu, Central Java, Indonesia. *Sediment. Geol.* **2012**, *265–266*, 195–209. [\[CrossRef\]](#)
108. Kanellopoulos, C. Distribution, lithotypes and mineralogical study of newly formed thermogenic travertines in Northern Euboea and Eastern Central Greece. *Cent. Eur. J. Geosci.* **2012**, *4*, 545–560. [\[CrossRef\]](#)
109. Gonzalez, L.A.; Lohmann, K.C. Controls on mineralogy and composition of spelean carbonates: Carlsbad Caverns, New Mexico. In *Paleokarst*; James, N.P., Choquette, P.W., Eds.; Springer: Berlin, Germany, 1987; pp. 81–101.
110. Hill, C.A.; Forti, P. *Cave Minerals of the World*; National Speleological Society Inc.: Huntsville, AL, USA, 1997; p. 463.
111. Frisia, S.; Borsato, A.; Fairchild, I.J.; McDermott, F.; Selmo, E.M. Aragonite-calcite relationships in speleothems (Grotto de Clamouse, France): Environment, fabrics and carbonate geochemistry. *J. Sediment. Res.* **2002**, *72*, 687–699. [\[CrossRef\]](#)
112. Rowling, J. Studies on aragonite and its occurrence in caves, including New South Wales caves. *J. Proc. R. Soc. N. S. W.* **2004**, *137*, 123–149.

113. Okumura, T.; Takashima, C.; Kano, A. Textures and processes of laminated travertines formed by unicellular cyanobacteria in Myokwn hot spring, southwestern Japan. *Isl. Arc* **2013**, *22*, 410–426. [\[CrossRef\]](#)
114. Dupraz, C.; Reid, P.R.; Braissant, O.; Decho, A.W.; Norman, R.S.; Visscher, P.T. Processes of carbonate precipitation in modern microbial mats. *Earth-Sci. Rev.* **2009**, *96*, 141–162. [\[CrossRef\]](#)
115. Rainey, D.K.; Jones, B. Abiotic versus biotic controls on the development of the Fairmont Hot Springs carbonate deposit, British Columbia, Canada. *Sedimentology* **2009**, *56*, 1832–1857. [\[CrossRef\]](#)
116. Peng, X.; Jones, B. Patterns of biomediated CaCO₃ crystal bushes in hot spring deposits. *Sediment. Geol.* **2013**, *294*, 105–117. [\[CrossRef\]](#)
117. Fernández-Díaz, L.; Putnis, A.; Prieto, M.; Putnis, C.V. The role of magnesium in the crystallization of calcite and aragonite in porous medium. *J. Sediment. Res.* **1996**, *66*, 482–491. [\[CrossRef\]](#)
118. Davis, K.J. The role of Mg²⁺ as an impurity in calcite growth. *Science* **2000**, *290*, 1134–1137. [\[CrossRef\]](#) [\[PubMed\]](#)
119. De Choudens-Sánchez, V.; González, L.A. Calcite and aragonite precipitation under controlled instantaneous supersaturation: Elucidating the role of CaCO₃ saturation state and Mg/Ca ratio on calcium carbonate polymorphism. *J. Sediment. Res.* **2009**, *79*, 363–376. [\[CrossRef\]](#)
120. Rossi, C.; Lozano, R.P. Hydrochemical controls on aragonite versus calcite precipitation in cave dripwaters. *Geochim. Et Cosmochim. Acta* **2016**, *192*, 70–96. [\[CrossRef\]](#)
121. Fermani, S.; Njegić Džakula, B.; Reggi, M.; Falini, G.; Kral, D. Effects of magnesium and temperature control on aragonite crystal aggregation and morphology. *Crystengcomm* **2017**, *19*, 2451–2455. [\[CrossRef\]](#)
122. Oomori, T.; Kaneshima, H.; Maezato, Y.; Kitano, Y. Distribution coefficient of Mg²⁺ ions between calcite and solution at 10–50 °C. *Mar. Chem.* **1987**, *20*, 327–336. [\[CrossRef\]](#)
123. Chafetz, H.S.; Folk, R.L. Travertines: Depositional morphology and the bacterially constructed constituents. *J. Sediment. Res.* **1984**, *54*, 289–316. [\[CrossRef\]](#)
124. Gibbs, R.J. Mechanisms controlling world water chemistry. *Science* **1970**, *170*, 1088–1090. [\[CrossRef\]](#)
125. Moral, F.; Cruz-Sanjulián, J.J.; Olías, M. Geochemical evolution of groundwater in the carbonate aquifers of Sierra de Segura (Betic Cordillera, southern Spain). *J. Hydrol.* **2008**, *360*, 281–296. [\[CrossRef\]](#)
126. Fairchild, I.J.; Borsato, A.; Tooth, A.F.; Frisia, S.; Hawkesworth, C.J.; Huang, Y.; McDermott, F.; Spiro, B. Controls on trace element (Sr–Mg) compositions of carbonate cave waters: Implications for speleothem climatic records. *Chem. Geol.* **2000**, *166*, 255–269. [\[CrossRef\]](#)
127. Spence, J.; Telmer, K. The role of sulfur in chemical weathering and atmospheric CO₂ fluxes: Evidence from major ions, δ¹³C_{DIC}, and δ³⁴S_{SO₄} in rivers of the Canadian Cordillera. *Geochim. Et Cosmochim. Acta* **2005**, *69*, 5441–5458. [\[CrossRef\]](#)
128. Calmels, D.; Gaillardet, J.; Brenot, A.; France-Lanord, C. Sustained sulfide oxidation by physical erosion processes in the Mackenzie River basin: Climatic perspectives. *Geology* **2007**, *35*, 1003–1006. [\[CrossRef\]](#)
129. Hammer, Ø.; Jamtveit, B.; Benning, L.G.; Dysthe, D.K. Evolution of fluid chemistry during travertine formation in the Troll thermal springs, Svalbard, Norway. *Geofluids* **2005**, *5*, 140–150. [\[CrossRef\]](#)
130. Arenas, C.; Vázquez-Urbez, M.; Auqué, L.; Sancho, C.; Osacár, C.; Pardo, G. Intrinsic and extrinsic controls of spatial and temporal variations in modern fluvial tufa sedimentation: A thirteen-year record from a semi-arid environment. *Sedimentology* **2014**, *61*, 90–132. [\[CrossRef\]](#)
131. Rogozhin, E.A.; Ovsyuchenko, A.N.; Marakhanov, A.V. Major earthquakes of the southern Gornyi Altai in the Holocene. *Izv. Phys. Solid Earth* **2008**, *44*, 469–486. [\[CrossRef\]](#)
132. Rasmussen, S.O.; Andersen, K.K.; Svensson, A.M.; Steffensen, J.P.; Vinther, B.M.; Clausen, H.B.; Siggaard-Andersen, M.-L.; Johnsen, S.J.; Larsen, L.B.; Dahl-Jensen, D.; et al. A new Greenland ice core chronology for the last glacial termination. *J. Geophys. Res.* **2006**, *111*, D06102. [\[CrossRef\]](#)
133. Vinther, B.M.; Clausen, H.B.; Johnsen, S.J.; Rasmussen, S.O.; Andersen, K.K.; Buchardt, S.L.; Dahl-Jensen, D.; Seierstad, I.K.; Siggaard-Andersen, M.-L.; Steffensen, J.P.; et al. A synchronized dating of three Greenland ice cores throughout the Holocene. *Journ. Geophys. Res.* **2006**, *111*, D13102. [\[CrossRef\]](#)
134. Lisiecki, L.E.; Raymo, M.E. A Pliocene-Pleistocene stack of 57 globally distributed benthic δ¹⁸O records. *Paleoceanography* **2005**, *20*, PA1003. [\[CrossRef\]](#)
135. Wells, D.L.; Coppersmith, K.J. New empirical relationship among magnitude, rupture length, rupture width, rupture area and surface displacement. *Bull. Seismol. Soc. Am.* **1994**, *84*, 974–1002. [\[CrossRef\]](#)
136. Hampel, A.; Hetzel, R.; Maniatis, G. Response of faults to climate-driven changes in ice and water volumes on Earth's surface. *Philos. Trans. R. Soc. A* **2010**, *368*, 2501–2517. [\[CrossRef\]](#) [\[PubMed\]](#)
137. Hampel, A.; Karow, T.; Maniatis, G.; Hetzel, R. Slip rate variations on faults during glacial loading and post-glacial unloading: Implications for the viscosity structure of the lithosphere. *J. Geol. Soc. Lond.* **2010**, *167*, 385–399. [\[CrossRef\]](#)
138. Muir Wood, R. Extraordinary deglaciation reverse faulting in northern Fennoscandia. In *Earthquakes at North-Atlantic Passive Margins: Neotectonics and Postglacial Rebound*; Gregersen, S., Basham, P.W., Eds.; Kluwer Academic Publishers: Dordrecht, The Netherlands, 1989; pp. 141–173.
139. Arvidsson, R. Fennoscandian earthquakes: Whole crustal rupturing related to postglacial rebound. *Science* **1996**, *274*, 744–746. [\[CrossRef\]](#)
140. Gregersen, S. Earthquakes and change of stress since the ice age in Scandinavia. *Bull. Geol. Soc. Den.* **2002**, *49*, 73–78.

141. Olesen, O.; Blikra, L.H.; Braathen, A.; Dehls, J.F.; Olsen, L.; Rise, L.; Roberts, D.; Riis, F.; Faleide, J.I.; Anda, E. Neotectonic deformation in Norway and its implications: A review. *Nor. J. Geol.* **2004**, *84*, 3–34.
142. Kukkonen, I.T.; Olesen, O.; Ask, M.V.S. The PFDP Working Group Postglacial faults in Fennoscandia: Targets for scientific drilling. *GFF* **2010**, *132*, 71–81. [[CrossRef](#)]
143. Blyakharchuk, T.A.; Wright, H.E.; Borodavko, P.S.; van der Knaap, W.O.; Ammann, B. Late-glacial and Holocene vegetational changes on the Ulagan high-mountain plateau, Altai Mountains, southern Siberia. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **2004**, *209*, 259–279. [[CrossRef](#)]
144. Galakhov, V.P.; Chernykh, D.V.; Mardasova, E.V. Mid-Late Holocene mean temperature fluctuations of a warm period in high mountains of the central Russian Altai. *Eurasian J. Math. Comput. Appl.* **2017**, *5*, 14–26. [[CrossRef](#)]
145. Ganyushkin, D.; Chistyakov, K.; Volkov, I.; Bantsev, D.; Kunaeva, E.; Brandová, D.; Raab, G.; Christl, M.; Egli, M. Palaeoclimate, glacier and treeline reconstruction based on geomorphic evidences in the Mongun-Taiga massif (south-eastern Russian Altai) during the Late Pleistocene and Holocene. *Quat. Int.* **2018**, *470*, 26–37. [[CrossRef](#)]
146. Croci, A.; Della Porta, G.; Capezzuoli, E. Depositional architecture of a mixed travertine-terrigenous system in a fault-controlled continental extensional basin (Messinian, Southern Tuscany, Central Italy). *Sediment. Geol.* **2016**, *332*, 13–39. [[CrossRef](#)]
147. Priewisch, A.; Crossey, L.J.; Karlstrom, K.E.; Polyak, V.J.; Asmerom, Y.; Nereson, A.; Ricketts, J.W. U-series geochronology of large-volume Quaternary travertine deposits of the southeastern Colorado Plateau: Evaluating episodicity and tectonic and paleohydrologic controls. *Geosphere* **2014**, *10*, 401–423. [[CrossRef](#)]
148. Landgraf, A.; Dzhumabaeva, A.; Abdrakhmatov, K.E.; Strecker, M.R.; Macaulay, E.A.; Arrowsmith, J.R.; Sudhaus, H.; Preusser, F.; Rugel, G.; Merchel, S. Repeated large-magnitude earthquakes in a tectonically active, low-strain continental interior: The northern Tien Shan, Kyrgyzstan. *J. Geophys. Res. Solid Earth* **2016**, *121*, 3888–3910. [[CrossRef](#)]
149. Deev, E.; Korzhenkov, A.; Turova, I.; Pavlis, T.L.; Luzhanskii, D.; Mažeika, J.; Abdieva, S.; Yudakhin, A. Large ancient earthquakes in the western Issyk-Kul basin (Kyrgyzstan, northern Tien Shan). *J. Asian Earth Sci.* **2018**, *166*, 48–65. [[CrossRef](#)]
150. Deev, E.V.; Zolnikov, I.D.; Lobova, E.Y. Late Pleistocene–Holocene coseismic deformations in the Malyy Yaloman River valley (Gorny Altai). *Russ. Geol. Geophys.* **2015**, *56*, 1256–1272. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.