



## Characteristic of Travertine Deposits: A Systematic Literature Review

Isman Saleh

Universitas Halu Oleo, Indonesia

Author correspondence: [ismansaleh96@uho.ac.id](mailto:ismansaleh96@uho.ac.id)\*

**Abstract.** Travertine is a non-marine carbonate rock precipitated from calcium- and bicarbonate-rich waters, commonly associated with hot springs, streams, and lakes in tectonically active regions. This study presents a systematic literature review of travertine deposit characteristics, encompassing mineralogical composition, geochemical signatures, petrographic textures, morphological types, isotopic properties, biotic–abiotic controls on formation, early diagenesis, and petrophysical implications. The synthesis indicates that travertine is predominantly composed of calcite, with aragonite forming under conditions of elevated temperature, high Mg/Ca ratios, and rapid CO<sub>2</sub> degassing. Travertines display exceptional textural diversity, ranging from abiotic crystalline crusts to microbially mediated fabrics such as shrub, peloidal, and stromatolitic structures. Major morphologies include fissure ridges, mounds, terraces, cascades, and slopes, strongly governed by tectonic setting, topography, hydrology, and substrate geology. Stable isotopes ( $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$ ), strontium isotopes, trace elements, and REE patterns effectively constrain fluid provenance and distinguish thermogene from meteogene travertines. Microbial activity plays a crucial role in biomineralization, influencing precipitation rates, crystal morphology, and lamination patterns. Early diagenetic processes occurring during active deposition may significantly modify primary fabrics and geochemical signals. Travertine petrophysical properties exhibit distinctive porosity–velocity relationships, making them valuable analogues for subsurface carbonate reservoirs. This review highlights that travertines record complex interactions among physical, chemical, biological, and geological processes and hold significant value for paleoenvironmental reconstruction and carbonate reservoir studies.

**Keywords:** Diagenesis; Isotope geochemistry; Mineralogy; Petrography; Travertine.

### 1. INTRODUCTION

Travertine is a terrestrial carbonate rock precipitated from calcium- and bicarbonate-rich waters, typically associated with hot springs, streams, and lakes (Rodríguez-Berriguete, Alonso-Zarza, Cabrera, & Rodríguez-González, 2012; Roshanak, Moore, Zarasvandi, Keshavarzi, & Gratzner, 2018). These deposits have attracted significant scientific attention due to their value as archives of paleoenvironmental, paleoclimatic, and tectonic information (Capezzuoli, Gandin, & Pedley, 2013; Prado-Pérez, Delgado-Huertas, Crespo, Sánchez, & Villar, 2013). Travertine deposits are globally distributed, occurring predominantly in tectonically active regions where faults provide conduits for CO<sub>2</sub>-rich fluids to reach the surface (Canora, Cuevas, Martínez Díaz, & Garralón, 2023; Croci, Porta, & Capezzuoli, 2016). The study of travertine characteristics—including mineralogy, geochemistry, petrography, morphology, and isotopic composition—is essential for understanding their formation processes and for their application as analogues for subsurface carbonate reservoirs (Claes et al., 2017, 2015; Soete et al., 2015).

Despite extensive research, the terminology and classification of travertine remain debated. The distinction between travertine and tufa, for instance, has been variably based on water temperature, CO<sub>2</sub> origin, fabric, and hardness (Capezzuoli et al., 2013; Rodríguez-

Berriguete et al., 2012; Salminen, Brasier, Karhu, & Melezhik, 2014). Travertine is generally used for hard, crystalline deposits formed from hydrothermal waters, while tufa refers to softer, porous deposits from ambient-temperature waters (Camuera, Alonso-Zarza, Rodríguez-Berriguete, & Rodríguez-González, 2014; Capezzuoli et al., 2013; Rodríguez-Berriguete et al., 2012). Based on CO<sub>2</sub> origin, travertines are classified as thermogene (deep-sourced CO<sub>2</sub>) or meteogene (soil/atmosphere-derived CO<sub>2</sub>) (Rodríguez-Berriguete et al., 2012; Roshanak et al., 2018; Tchouatcha et al., 2023; Török et al., 2017).

This systematic literature review aims to synthesize current knowledge on the characteristics of travertine deposits, encompassing their mineralogical composition, geochemical signatures, petrographic features, morphological types, isotopic properties, and the biotic and abiotic factors controlling their formation.

## **2. THEORETICAL STUDY**

### **Definition and Classification**

The classification of travertine deposits has evolved considerably. Traditionally, the term "travertine" referred to compact freshwater carbonates suitable for building construction, while "tufa" denoted softer, more friable deposits (Camuera et al., 2014). More recent scientific definitions distinguish these deposits based on water temperature and CO<sub>2</sub> source (Capezzuoli et al., 2013; Rodríguez-Berriguete et al., 2012). Thermogene travertines form from warm to hot waters where CO<sub>2</sub> originates from deep-seated thermal processes, including decarbonation of marine carbonates and magmatic sources (Roshanak et al., 2018; Tchouatcha et al., 2023; Török et al., 2017). Meteogene travertines (or tufas) precipitate from cooler waters where CO<sub>2</sub> derives from soil respiration and groundwater dissolution (Camuera et al., 2014; Rodríguez-Berriguete et al., 2012). The  $\delta^{13}\text{C}$  values serve as a key discriminator: thermogene travertines typically exhibit positive  $\delta^{13}\text{C}$  values ranging from  $-4\text{‰}$  to  $+8\text{‰}$ , while meteogene deposits show negative values from  $-12\text{‰}$  to  $-2\text{‰}$  (Camuera et al., 2014; Tchouatcha et al., 2023).

Morphologically, travertine deposits are classified into several types including fissure ridges, mounds, terraced mounds, cascades, and self-built channels (Brilli, Giustini, Barone, Fayek, & Scardozzi, 2017; Capezzuoli et al., 2013; Kalender, Okan, İnceöz, ÇETİNDAG, & Yıldırım, 2015). Fissure ridges are elongated mounds with a central fissure along their long axis, formed by hydrothermal waters rising along fractures (Brilli et al., 2017; You, Wen, Luo, Lu, & Li, 2023). Mound travertines develop around spring orifices and can reach considerable dimensions (Mohammadi et al., 2019; Roshanak et al., 2018). These morphological types are

intimately linked to the tectonic setting, substrate geology, and hydrological conditions (Canora et al., 2023; Mohammadi et al., 2019).

### **Mineralogical Composition**

Travertine deposits are mineralogically dominated by calcium carbonate, primarily as calcite and/or aragonite (Rodrigo-Naharro, Herrero, Delgado-Huertas, Granados, & Villar, 2019; Rodríguez-Berriguete et al., 2012; Soete et al., 2015). The mineralogical variety is relatively limited compared to the enormous diversity of textures and fabrics observed (Rodríguez-Berriguete et al., 2012). Calcite is the most common and stable polymorph, while aragonite occurs under specific conditions (Okumura, Takashima, & Kano, 2013; Rodrigo-Naharro et al., 2019; Rodríguez-Berriguete et al., 2012). The factors controlling calcite versus aragonite precipitation include: (1) water temperature, with aragonite favored above 40–45°C; (2) Mg/Ca ratio of the parent water; (3) CO<sub>2</sub> degassing rate; and (4) kinetic effects (Asta et al., 2017; Rodrigo-Naharro et al., 2019). In some deposits, both minerals coexist, as documented at Mammoth Hot Springs where aragonite dominates in proximal vent areas and calcite in more distal settings (Boever et al., 2021; Fouke, 2011).

Minor mineral phases in travertines include dolomite (rare and mostly restricted to Precambrian examples), quartz, clay minerals, iron oxides/hydroxides, gypsum, and opaline silica (Porrás-Toribio, Pi-Puig, Villanueva-Estrada, Rubio-Ramos, & Solé, 2022; Salminen et al., 2014; Soete et al., 2015). The Huanglong travertines in China, for example, consist of >95% calcite with CaCO<sub>3</sub> purity generally exceeding 96% (Gao, Liu, Sun, et al., 2024; Gao, Liu, Zhang, et al., 2024). Similarly, Pleistocene travertines from Turkey consist of over 94% calcite (Soete et al., 2015). The Carpinis travertine deposit in Romania contains more than 95% calcite and aragonite, with subordinate dolomite (<3%), limonite, clay minerals (<3%), and quartz (<2%) (Marinescu, Udubasa, & Tiess, 2017).

Some travertine systems exhibit unusual mineralogical assemblages. The Tamiahua travertines in Mexico contain aragonite, gypsum, anhydrite, and elemental sulfur as essential minerals, with calcite, celestine, barite, jarosite, opal, and fluorite as accessories (Porrás-Toribio et al., 2022). Iron-rich travertines, such as those at Ilia hot spring in Greece, contain ferrihydrite alternating with calcium carbonate layers (Kanellopoulos, Thomas, Xirokostas, & Arizteguí, 2019).

### **Geochemical Characteristics**

The geochemical composition of travertines reflects the chemistry of their parent waters and the geological substrate through which fluids circulate (Capezzuoli et al., 2013; Viaroli et al., 2024). Major and trace element concentrations provide information about fluid

sources, water-rock interactions, and precipitation conditions (Janssens et al., 2020; Kalender et al., 2015). Strontium isotope ratios ( $^{87}\text{Sr}/^{86}\text{Sr}$ ) are particularly useful for identifying fluid source rocks and subsurface interactions (Canora et al., 2023; Claes et al., 2017; Zentmyer, Myrow, & Newell, 2008). For instance, travertines near Nyalam, Tibet, exhibit high  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios (mean 0.7168), indicating fluid interaction with radiogenic crystalline rocks of the Greater Himalaya (Zentmyer et al., 2008).

Rare earth element (REE) patterns in travertines can indicate fluid provenance and temperature conditions. Positive Eu anomalies suggest contributions from deep-seated crustal fluids in contact with volcanic rocks (Bissé, Ekoko, Gerber, Ekomane, & Franchi, 2021; Tchouatcha et al., 2023). The Cameroon Volcanic Line travertines display strong positive Eu anomalies ( $>4$ ), indicating deep crustal fluid contributions (Bissé et al., 2021).

Trace element concentrations vary significantly between travertine types. Aragonite-bearing samples tend to show higher concentrations of Sr, Ba, and U, while calcitic samples are enriched in Mg (Asta et al., 2017). Some travertines contain remarkably high concentrations of potentially toxic elements; for example, travertines near Ghorveh, Iran, contain up to 10 g/kg of arsenic (Mohammadi et al., 2021).

### **Stable Isotope Geochemistry**

Stable oxygen and carbon isotopes are fundamental tools for characterizing travertine deposits (Prado-Pérez et al., 2013; Roshanak et al., 2018; You et al., 2023). The  $\delta^{13}\text{C}$  values reflect the  $\text{CO}_2$  source: thermogene travertines with deep-sourced  $\text{CO}_2$  typically show positive values, while meteogene deposits exhibit negative values (Camuera et al., 2014; Canora et al., 2023; Tchouatcha et al., 2023). The Qorveh-Takab travertines in Iran display  $\delta^{13}\text{C}$  values of +6.08‰ to +9.84‰ and  $\delta^{18}\text{O}$  values of -0.6‰ to -11.9‰ (VPDB), consistent with a thermogene origin with crustal magmatic  $\text{CO}_2$  affinity (Roshanak et al., 2018).

The  $\delta^{18}\text{O}$  values are used to estimate paleotemperatures of precipitating waters (Asta et al., 2017; Prado-Pérez et al., 2013; You et al., 2023). The Xiagei banded travertines in China yield calculated paleotemperatures of 44.3 to 86.8°C (You et al., 2023). However, isotopic disequilibrium during rapid  $\text{CO}_2$  degassing can complicate temperature estimates (Asta et al., 2017; Rodrigo-Naharro et al., 2019).

### **Petrographic Features and Textures**

Travertine deposits exhibit an extraordinary diversity of textures and fabrics at both macro- and microscopic scales (Gandin & Capezzuoli, 2013; Rodríguez-Berriguete et al., 2012; Tchouatcha et al., 2023). The main textural categories include crystalline crusts, microbially mediated crusts (microbialites), and granular deposits (Gandin & Capezzuoli,

2013). Crystalline crusts encompass dendritic, feather-like, palisade, and fibrous textures formed by rapid abiotic precipitation from supersaturated waters (Bissé et al., 2021; Tchouatcha et al., 2023; You et al., 2023). Microbially mediated textures include shrub-like, laminated, clotted peloidal, and stromatolitic fabrics (Gandin & Capezzuoli, 2013; Guido & Campbell, 2017; Tchouatcha et al., 2023).

At the lithotype scale, common types include reed travertine, shrub travertine, paper-thin raft, crystalline crust, and coated grain travertine (Canora et al., 2023; Claes et al., 2017). The Ballık travertines in Turkey are dominated by peloidal, phyto, and dendritic lithotypes with honeycomb and bacteriform shapes suggesting microbial influence (Claes et al., 2017). The Gazda quarry travertines in Hungary display phytohermal, wavy laminated, massive, and flat laminated lithofacies representing reed mound, slope, lacustrine, and palustrine environments (Török et al., 2017).

Vertical structural diversity is also notable. The Huanglong travertines exhibit porous travertine, dense travertine, and detritus travertine in their vertical profiles (Gao, Liu, Sun, et al., 2024; Gao, Liu, Zhang, et al., 2024). Porosity types in travertines include mouldic, interlaminar, interpeloidal, framework, and vug porosity, each with distinct implications for acoustic and petrophysical properties (Soete et al., 2015).

### **Biotic and Abiotic Controls on Formation**

Travertine formation results from the interplay of physical, chemical, and biological processes (Fouke, 2011; Gao, Liu, Sun, et al., 2024; Okumura et al., 2013). The primary abiotic mechanism is CO<sub>2</sub> degassing from supersaturated waters upon reaching the surface, which elevates pH and drives CaCO<sub>3</sub> precipitation (Fouke, 2011; Okumura et al., 2013; Rodrigo-Naharro et al., 2019). Temperature, flow velocity, water chemistry, and topography are key physical-chemical controls (Fouke, 2011; Veysey et al., 2008).

Biological influences on travertine formation are increasingly recognized (Bissé et al., 2021; Fouke, 2011; Kanellopoulos et al., 2019; Okumura et al., 2013). Cyanobacteria, algae, and other microorganisms contribute through several biomineralization processes: (1) trapping and binding of carbonate crystals by filamentous organisms and extracellular polymeric substances (EPS); (2) EPS acting as templates for crystal nucleation; (3) formation of calcified sheaths; and (4) alteration of existing crystals by endolithic organisms (Kanellopoulos et al., 2022). At Myoken Hot Spring, Japan, diurnal cycles of unicellular cyanobacteria control sub-millimeter lamination, with daytime aragonite layers and nighttime calcite layers (Okumura et al., 2013). At Mammoth Hot Springs, Yellowstone, Sulfurihydrogenibium-dominated

microbial mats become entombed in travertine accumulating at rates exceeding 5 mm per day (Dong et al., 2019).

The relative importance of biotic versus abiotic processes varies with environmental conditions. In fast-flowing, high-temperature settings, abiotic precipitation dominates, producing crystalline crusts (Bissé et al., 2021; Mohammadi et al., 2019). In lower-energy, lower-temperature environments, microbial mediation becomes more significant, producing micritic and peloidal fabrics (Bissé et al., 2021; Fouke, 2011).

### **Diagenesis**

Early diagenetic processes can profoundly alter primary travertine fabrics and geochemical signatures (Boever, Brasier, Foubert, & Kele, 2017; Boever et al., 2021). These processes include neomorphism (inversion of aragonite to calcite and recrystallization), cementation, and dissolution (Boever et al., 2017, 2021; Mohammadi et al., 2019). At Mammoth Hot Springs, diagenesis begins during spring activity as warm waters circulate through porous fabrics below the active surface, resulting in coarsening and homogenization of primary textures (Boever et al., 2021). Aragonite is completely transformed to calcite below depths of 5–10 m, corresponding to approximately 4,000 years (Boever et al., 2021).

The susceptibility to diagenesis depends on the reactivity of initial precipitates, with metastable phases like aragonite being particularly prone to alteration (Boever et al., 2017). Organic compounds commonly play a crucial role in hosting early transformations (Boever et al., 2017). The mound travertines of western Iran show more extensive diagenetic overprinting (dissolution, cementation, Mn/Fe-oxide formation) compared to adjacent fissure ridge travertines, reflecting the control of porosity on diagenetic processes (Mohammadi et al., 2019).

### **Tectonic and Volcanic Associations**

Travertine deposits are intimately associated with active tectonics and volcanism (Canora et al., 2023; Capezzuoli et al., 2013; Croci et al., 2016; Karabaçak, Mutlu, & Deniz, 2020). They commonly occur along basin-bounding normal faults in extensional settings (Croci et al., 2016; Soete et al., 2015), and less frequently along strike-slip faults (Canora et al., 2023). Faults provide pathways for CO<sub>2</sub>-rich fluids to ascend from depth (Canora et al., 2023; Rizzo et al., 2019; Zentmyer et al., 2008). The relationship between travertine deposition and seismogenic activity has been documented through U-Th dating, which reveals clustering of precipitation ages around periods of volcanic and tectonic activity (Karabaçak et al., 2020; Rizzo et al., 2019).

The substrate geology exerts a major control on travertine characteristics. Adjacent travertine bodies in western Iran show markedly different morphology, lithofacies, diagenesis, and geochemistry due to differences in their underlying substrates—carbonate versus volcanic (Mohammadi et al., 2019). Fissure ridges formed on hard limestone substrates display sparitic fabrics, while mounds on volcanic substrates show micritic fabrics with higher non-carbonate content (Mohammadi et al., 2019, 2021).

### **3. RESEARCH METHODS**

This systematic literature review was conducted following established protocols for synthesizing scientific literature. A comprehensive search was performed across major scientific databases including Scopus, Web of Science, and Google Scholar using keywords such as "travertine," "travertine characteristics," "travertine mineralogy," "travertine geochemistry," "travertine petrography," "travertine morphology," "travertine isotopes," and "travertine formation." The search encompassed publications from peer-reviewed journals, including *Sedimentology*, *Sedimentary Geology*, *The Depositional Record*, *Quaternary International*, *Journal of Sedimentary Research*, and other relevant earth science journals.

Inclusion criteria required that studies: (1) focused on natural travertine deposits; (2) provided data on one or more characteristics of travertine (mineralogy, geochemistry, petrography, morphology, isotopic composition); (3) were published in English in peer-reviewed outlets; and (4) contributed to understanding travertine formation processes or classification. Studies focusing exclusively on tufa without travertine comparison, or on non-carbonate spring deposits without relevance to travertine characterization, were excluded.

Selected references were analyzed for their contributions to understanding travertine composition, texture, morphology, geochemistry, isotopic signatures, diagenesis, and controlling factors. Data were synthesized thematically rather than chronologically to provide a coherent overview of travertine characteristics.

### **4. RESULTS AND DISCUSSION**

#### **Mineralogical Characteristics**

The reviewed literature consistently demonstrates that travertine deposits are mineralogically simple yet texturally complex. Calcite is the dominant mineral in most travertine deposits worldwide (Gao, Liu, Sun, et al., 2024; Gao, Liu, Zhang, et al., 2024; Marinescu et al., 2017; Prado-Pérez et al., 2013; Soete et al., 2015). The Pleistocene travertines of the Ballık area in Turkey consist of over 94% calcite (Soete et al., 2015), while the

Huanglong travertines in China achieve  $\text{CaCO}_3$  purities of 96–99% (Gao, Liu, Sun, et al., 2024; Gao, Liu, Zhang, et al., 2024). The Carpinis deposit in Romania similarly contains >95% calcite and aragonite (Marinescu et al., 2017).

Aragonite occurrence is controlled by specific physicochemical conditions. The Azuaje travertine in Gran Canaria demonstrates that volcanic settings can produce predominantly aragonitic deposits (Rodríguez-Berriguete et al., 2012). At El Saladillo and El Reventón in Spain, aragonite precipitation is consistent with mesothermal waters (>40–45°C), rapid  $\text{CO}_2$  degassing, high Sr/Mg ratios, and Mg/Ca ratios >1 (Rodrigo-Naharro et al., 2019). The coexistence of calcite and aragonite within single deposits, as observed at Crystal Geysir, Utah (Cosmidis et al., 2021), and at Iliia, Greece (Kanellopoulos et al., 2019), reflects fluctuating environmental conditions including temperature, fluid chemistry, and microbial activity.

The role of microbial activity in controlling  $\text{CaCO}_3$  polymorphism is an emerging area of research. At Myoken Hot Spring, Japan, aragonite precipitates during daytime when cyanobacterial biofilms are active, while calcite forms at night in the absence of microbial effects, despite stable physicochemical conditions (Okumura et al., 2013). At Crystal Geysir, carbonate polymorphism in pisoids appears controlled by local fluctuations in iron redox state caused by episodic blooms of iron-oxidizing bacteria (Cosmidis et al., 2021).

### **Textural and Petrographic Diversity**

The textural diversity of travertines is one of their most striking characteristics. The reviewed studies document a wide spectrum of fabrics ranging from finely laminated to massive, and from micritic to coarsely crystalline (Claes et al., 2015; Gandin & Capezzuoli, 2013; Rodríguez-Berriguete et al., 2012; Tchouatcha et al., 2023). Gandin and Capezzuoli (2013) proposed a systematic textural classification subdividing travertine lithofacies into abiotic crystalline crusts, microbially mediated crusts, and granular deposits. This classification recognizes that the association of crystalline crusts and laminar curled microbialites has no counterpart in the marine realm (Gandin & Capezzuoli, 2013).

Crystalline crust textures include dendritic, feather-like, fan, and palisade fabrics (Boever et al., 2021; Tchouatcha et al., 2023; You et al., 2023). These form under fast-flowing conditions from highly supersaturated waters (Bissé et al., 2021; Mohammadi et al., 2019). The Xiagei banded travertines display thick-laminated palisade crystalline crust and thin-laminated composite crystalline crust, with the former associated with higher precipitation temperatures (66.6–86.8°C) and the latter with lower temperatures (56.6–77.7°C) (You et al., 2023).

Microbially influenced textures include shrub-like, peloidal, clotted, and stromatolitic fabrics (Claes et al., 2015; Guido & Campbell, 2017; Török et al., 2017). Shrub travertine fabrics have been variably interpreted as abiogenic or bacterial in origin (Guido & Campbell, 2017). Detailed textural studies suggest that microbes act as catalysts for mineralization of shrubby fabrics, with a continuum from strongly arborescent shrubs (bacterial influence dominates) to geometric crystal shrubs (crystalline habit governed by physicochemical processes) (Guido & Campbell, 2017).

The substrate geology significantly influences textural development. Fissure ridge travertines on carbonate substrates display homogeneous sparitic fabrics with dendritic structures, while mound travertines on volcanic substrates show heterogeneous micritic fabrics with clastic components (Mohammadi et al., 2019). This demonstrates that subsurface geology exerts a major control on precipitation processes and resulting textures (Mohammadi et al., 2019).

### **Morphological Types and Depositional Environments**

Travertine deposits exhibit diverse morphologies controlled by tectonic setting, topography, hydrology, and fluid chemistry (Capezzuoli et al., 2013; Kalender et al., 2015; Varejão, Alonso, Athayde, Bahniuk Rumbelsperger, & Cury, 2024). The main morphological types include: a.) Fissure ridges: Elongated mounds with central fissures, containing both bedded (porous, flanking) and banded (massive, vein-filling) travertine (Brilli et al., 2017; Scardozzi, 2019; You et al., 2023). These form along fractures where hydrothermal fluids ascend, b.) Mounds: Dome-shaped accumulations around spring orifices (Guido & Campbell, 2017; Mohammadi et al., 2019; Roshanak et al., 2018). Active and inactive mounds can display different textural characteristics depending on substrate and fluid properties (Mohammadi et al., 2019, 2021), c.) Terraces and cascades: Stepped morphologies formed by water flowing over slopes (Fouke, 2011; Varejão et al., 2024; Zentmyer et al., 2008). The Mammoth Hot Springs system exemplifies terrace development with systematic downstream correlations between facies, microbial communities, and water chemistry (Fouke, 2011), d.) Slope deposits: Including smooth slopes and steep slopes with varying facies associations (Claes et al., 2017, 2015; Varejão et al., 2024).

The Vega Botijuela travertine system in Argentina demonstrates geomorphological compartmentalization into proximal, intermediate, and distal zones, with spring waters in the proximal zone and mixed carbonate-siliciclastic sedimentation toward the distal zone (Varejão et al., 2024). Vertical facies stacking is typically coarsening-upward, with carbonate mudstone interbedded with grainstone, rudstone, and boundstone (Varejão et al., 2024). This represents

one of the first attempts to establish vertical stacking patterns for travertine facies associations (Varejão et al., 2024).

The evolution from subaqueous to subaerial deposition is documented in several systems. The Ballık travertines evolved from dominantly subaqueous (sub-horizontal and biostromal reed facies) to dominantly subaerial precipitation in thin water films (cascade, waterfall, and biohermal reed facies), with general progradation indicated by stacked waterfall travertines creating sigmoidal clinofolds (Claes et al., 2015).

### **Isotopic Signatures and Fluid Provenance**

Stable isotope data provide critical constraints on travertine classification and fluid provenance. The compilation of data from reviewed studies reveals distinct isotopic fields for thermogene and meteogene travertines. Thermogene travertines typically display positive  $\delta^{13}\text{C}$  values reflecting deep  $\text{CO}_2$  sources (Canora et al., 2023; Roshanak et al., 2018; Tchouatcha et al., 2023; You et al., 2023), while meteogene deposits show negative  $\delta^{13}\text{C}$  values (Camuera et al., 2014; Karabaçak et al., 2020).

The Qorveh-Takab travertines exhibit  $\delta^{13}\text{C}$  values of +6.08‰ to +9.84‰, indicating crustal magmatic  $\text{CO}_2$  affinity, with heavy carbon isotope content potentially enhanced by algal photosynthetic activity (Roshanak et al., 2018). The Carraclaca travertines in Spain show isotopic signals indicating hydrothermal origin, with  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios suggesting fluid interaction with Miocene sediments and Alpujarride basement (Canora et al., 2023). The Ballık travertines display mixed isotopic signatures pointing to palaeofluids combining deeply originated heavy carbon  $\text{CO}_2$  with lighter carbon  $\text{CO}_2$  of shallow origin, classifying them as endogenic travertines (Claes et al., 2015).

Parent  $\text{CO}_2$  evaluation for the Xiagei banded travertines indicates that  $\text{CO}_2$  mainly derived from decarbonation of marine carbonates, with contributions from magmatic  $\text{CO}_2$  and dissolution of marine carbonates (You et al., 2023). This magmatic  $\text{CO}_2$  component may indicate lithospheric delamination and asthenosphere upwelling in the eastern Tibetan Plateau (You et al., 2023).

Fluid inclusion studies provide direct information about the origin, temperature, and subsurface interaction of travertine-precipitating fluids (Capezzuoli et al., 2013; Janssens et al., 2020; Rizzo et al., 2019). At Pamukkale and Reşadiye, Turkey, fluid inclusions are mainly primary with low salinity and homogenization temperatures around 136–140°C, with noble gas compositions indicating atmosphere-derived fluids mixed with mantle and crustal components (Rizzo et al., 2019).

## **Diagenetic Overprinting**

Early diagenesis represents a significant challenge for interpreting primary travertine characteristics (Boever et al., 2017, 2021; Mohammadi et al., 2019). The review by De Boever et al. (2017) demonstrates that diagenesis may affect whole rocks but typically starts in nano- and micro-environments, with the potential for alteration depending on the reactivity of initial precipitates. Processes including neomorphism, cementation, and replacement generally result in overall coarsening and homogenization of primary microtextures (Boever et al., 2017).

The Y-10 core from Mammoth Hot Springs illustrates the progressive nature of diagenesis (Boever et al., 2021). Diagenesis begins during spring activity as warm waters circulate through porous fabrics, resulting in neomorphism of aragonite and calcite cementation that creates new intracrystalline microporosity (Boever et al., 2021). Subsequent circulation of meteoric fluids leads to dissolution and cementation near the core top (Boever et al., 2021). These findings have important implications for the interpretation of geochemical proxies in ancient travertine deposits.

The differential diagenetic susceptibility of different travertine morphotypes is well illustrated by the adjacent fissure ridge and mound travertines in western Iran (Mohammadi et al., 2019). The more porous mound carbonates are affected by dissolution, cementation, and formation of Mn/Fe-oxide/hydroxides, while the fissure ridge carbonates show limited diagenetic overprint (Mohammadi et al., 2019). This demonstrates the strong control of primary porosity on early diagenetic processes.

## **Petrophysical Properties**

Travertine petrophysical properties are of increasing interest due to their relevance as analogues for subsurface carbonate reservoirs (Claes et al., 2017, 2015; Soete et al., 2015). Sonic velocity measurements on Pleistocene travertines reveal that porosity, pore types, and cementation control compressional-wave and shear-wave velocities (Soete et al., 2015). At 40 MPa confining pressure,  $V_p$  ranges between 3695 and 6097 m/s and  $V_s$  between 2037 and 3140 m/s (Soete et al., 2015). Importantly, travertines define a specific velocity-porosity relationship that differs from marine carbonates, with higher acoustic velocities attributed to their rigid framestone architecture with large primary pores (Soete et al., 2015).

Porosity and permeability vary significantly among facies. The Budakalász travertines show terrace, smooth slope, and marsh-pool facies with porosities of 5–15%, while reed facies may reach up to 27% (Claes et al., 2017). Permeability is strongly anisotropic, mainly controlled by better connectivity along layer-parallel primary pores (Claes et al., 2017).

## **Biotic Contributions**

The role of microorganisms in travertine formation has been increasingly documented across diverse settings (Bissé et al., 2021; Dong et al., 2019; Fouke, 2011; Kanellopoulos, Lamprinou, Politi, Voudouris, & Economou-Amilli, 2022; Okumura et al., 2013). At the hot springs of North-West Euboea Island, Greece, 81 taxa of Cyanobacteria belonging to six orders were identified, with temperature, salinity, and sunlight access as the main factors controlling biodiversity (Kanellopoulos et al., 2022). Four biomineralization processes were identified: trapping of crystals by filaments and EPS, EPS-templated nucleation, calcified sheath formation, and endolithic alteration (Kanellopoulos et al., 2022).

The Cameroon Volcanic Line travertines demonstrate the coexistence of biotic and abiotic precipitation within the same system (Bissé et al., 2021). Long feather-like calcite crystals form in fast-flowing water where enhanced CO<sub>2</sub> degassing favors abiotic CaCO<sub>3</sub> precipitation, while laminated micrite and microsparite form in ponds where microbial activity fosters precipitation (Bissé et al., 2021).

In the Terma Los Hornos travertine system, Argentina, both abiogenic and biogenic carbonate structures coexist (Mors, Gómez, Astini, Celestian, & Corsetti, 2021). Laminated pisoids with laterally constant laminae suggest predominantly abiogenic origin, while dendritic pisoids exhibit intimate relationships with diatoms and filamentous bacteria suggesting stronger biotic influence (Mors et al., 2021).

## **5. CONCLUSIONS AND RECOMMENDATIONS**

This systematic literature review reveals that travertine deposits are characterized by a distinctive combination of features that reflect the complex interplay of physical, chemical, biological, and geological factors during their formation. The key findings can be summarized as follows: a.) Travertines are predominantly composed of calcite, with aragonite occurring under specific conditions of elevated temperature, high Mg/Ca ratios, and rapid CO<sub>2</sub> degassing, b.) An extraordinary diversity of textures exists, ranging from abiotic crystalline crusts to microbially mediated fabrics. The textural classification into crystalline crusts, microbialites, and granular deposits provides a systematic framework. Substrate geology exerts a major control on textural development, c.) Travertine morphologies include fissure ridges, mounds, terraces, cascades, and slopes, controlled by tectonic setting, topography, and hydrology. Facies stacking patterns are typically coarsening-upward with progradational to aggradational architecture, d.) Stable isotope signatures effectively discriminate thermogene from meteogene travertines. Strontium isotopes and REE patterns constrain fluid provenance

and water-rock interactions. Trace element concentrations reflect parent water chemistry and mineralogical controls,e.) Both biotic and abiotic processes contribute to travertine formation, with their relative importance varying with environmental conditions. Microbial communities influence precipitation rates, crystal morphology, mineralogy, and lamination patterns,f.) Early diagenetic processes begin during active spring deposition and can significantly alter primary fabrics and geochemical signatures. Understanding diagenetic overprinting is essential for accurate paleoenvironmental interpretation.

Future research should focus on developing comprehensive facies models applicable to the geological record, better constraining the role of microbial communities in controlling travertine mineralogy and texture, and improving understanding of diagenetic pathways and their effects on geochemical proxies. The growing interest in travertines as analogues for pre-salt carbonate reservoirs ensures continued advancement in characterizing these fascinating deposits.

## REFERENCES

- Asta, M. P., Auqué, L. F., Pérez Sanz, F. J., Gimeno Serrano, M. J., Acero, P., Blasco, M., ... A. Collado, J. M. (2017). Travertines Associated With the Alhama-Jaraba Thermal Waters (NE, Spain): Genesis and Geochemistry. *Sedimentary Geology*. <https://doi.org/10.1016/j.sedgeo.2016.11.010>
- Bissé, S. B., Ekoko, B. E., Gerber, J., Ekomane, E., & Franchi, F. (2021). Influence of Biotic vs Abiotic Processes on the Genesis of Non-marine Carbonates Along the Cameroon Volcanic Line (Cameroon) and Palaeofluid Provenance. *The Depositional Record*. <https://doi.org/10.1002/dep2.154>
- Boever, E. D., Brasier, M., Foubert, A., & Kele, S. (2017). What Do We Really Know About Early Diagenesis of Non-Marine Carbonates? *Sedimentary Geology*. <https://doi.org/10.1016/j.sedgeo.2017.09.011>
- Boever, E. D., Jaramillo-Vogel, D., Bouvier, A., Frank, N., Schröder-Ritzrau, A., Baumgartner, L., ... Foubert, A. (2021). The Fate of a Travertine Record: Impact of Early Diagenesis on the Y-10 Core (Mammoth Hot Springs, Yellowstone National Park, USA). *The Depositional Record*. <https://doi.org/10.1002/dep2.143>
- Brilli, M., Giustini, F., Barone, P. M., Fayek, A., & Scardozzi, G. (2017). Characterizing the *Alabastro Listato* or *fiorito* of *Hierapolis* in *Phrygia*: A Simple Method to Identify Its Provenance Using Carbon Stable Isotopes. *Archaeometry*. <https://doi.org/10.1111/arc.12315>
- Camuera, J., Alonso-Zarza, A. M., Rodríguez-Berriguete, Á., & Rodríguez-González, A. (2014). Origin and Palaeo-Environmental Significance of the Berrazales Carbonate Spring Deposit, North of Gran Canaria Island, Spain. *Sedimentary Geology*. <https://doi.org/10.1016/j.sedgeo.2014.04.005>

- Canora, C., Cuevas, J., Martínez Díaz, J. J., & Garralón, A. (2023). Analysis of a Travertine System Controlled by the Transpressional Activity of the Alhama De Murcia Fault: The Carralaca Site, Eastern Betic Cordillera, Spain. *Frontiers in Earth Science*. <https://doi.org/10.3389/feart.2023.1060363>
- Capezzuoli, E., Gandin, A., & Pedley, M. (2013). Decoding Tufa and Travertine (Fresh Water Carbonates) in the Sedimentary Record: The State of the Art. *Sedimentology*. <https://doi.org/10.1111/sed.12075>
- Claes, H., Degros, M., Soete, J., Claes, S., Kele, S., Mindszenty, A., ... Swennen, R. (2017). Geobody Architecture, Genesis and Petrophysical Characteristics of the Budakalász Travertines, Buda Hills (Hungary). *Quaternary International*. <https://doi.org/10.1016/j.quaint.2016.09.007>
- Claes, H., Soete, J., Noten, K. V., Desouky, H. E., Erthal, M. M., Vanhaecke, F., ... Swennen, R. (2015). Sedimentology, Three-dimensional Geobody Reconstruction and Carbon Dioxide Origin of Pleistocene Travertine Deposits in the Ballık Area (South-west Turkey). *Sedimentology*. <https://doi.org/10.1111/sed.12188>
- Cosmidis, J., O'Reilly, S. S., Ellison, E. T., Crispin, K. L., Diercks, D. R., & Templeton, A. S. (2021). *Carbonate Polymorphism Controlled by Microbial Iron Redox Dynamics at a Natural CO2 Leakage Site (Crystal Geyser, Utah)*. <https://doi.org/10.31223/x5pw43>
- Croci, A., Porta, G. D., & Capezzuoli, E. (2016). Depositional Architecture of a Mixed Travertine-Terrigenous System in a Fault-Controlled Continental Extensional Basin (Messinian, Southern Tuscany, Central Italy). *Sedimentary Geology*. <https://doi.org/10.1016/j.sedgeo.2015.11.007>
- Dong, Y., Sanford, R. A., Inskeep, W. P., Srivastava, V., Bulone, V., Fields, C. J., ... Fouke, B. W. (2019). Physiology, Metabolism, and Fossilization of Hot-Spring Filamentous Microbial Mats. *Astrobiology*. <https://doi.org/10.1089/ast.2018.1965>
- Fouke, B. W. (2011). Hot-spring Systems Geobiology: Abiotic and Biotic Influences on Travertine Formation at Mammoth Hot Springs, Yellowstone National Park, USA. *Sedimentology*. <https://doi.org/10.1111/j.1365-3091.2010.01209.x>
- Gandin, A., & Capezzuoli, E. (2013). Travertine: Distinctive Depositional Fabrics of Carbonates From Thermal Spring Systems. *Sedimentology*. <https://doi.org/10.1111/sed.12087>
- Gao, W., Liu, X., Sun, D., Xu, R., Zhao, S., Zhang, Z., ... Tang, J. (2024). *Travertine Mineralogical Characteristics and Development Level in Huanglong, a World Natural Heritage, China : derived From Late Pleistocene to Early Holocene Glacial U-Shaped Valley Carbonate Deposits*. <https://doi.org/10.21203/rs.3.rs-4710379/v1>
- Gao, W., Liu, X., Zhang, W., Sun, D., Chen, Z., Zhang, Q., ... Zheng, J. (2024). Travertine Mineralogical Characteristics and Spatial Distribution in Huanglong, China, a World Natural Heritage: Derived From Late Pleistocene to Early Holocene Glacial U-Shaped Valley Carbonate Deposits. *Acs Omega*. <https://doi.org/10.1021/acsomega.4c08897>
- Guido, D. M., & Campbell, K. A. (2017). Upper Jurassic Travertine at El Macanudo, Argentine Patagonia: A Fossil Geothermal Field Modified by Hydrothermal Silicification and Acid Overprinting. *Geological Magazine*. <https://doi.org/10.1017/s0016756817000498>

- Janssens, N., Capezzuoli, E., Claes, H., Muchez, P., Yu, T., Shen, C., ... Swennen, R. (2020). Fossil Travertine System and Its Palaeofluid Provenance, Migration and Evolution Through Time: Example From the Geothermal Area of Acquasanta Terme (Central Italy). *Sedimentary Geology*. <https://doi.org/10.1016/j.sedgeo.2019.105580>
- Kalender, L., Okan, Ö. Ö., İnceöz, M., ÇETİNDAG, B., & Yıldırım, V. (2015). Geochemistry of Travertine Deposits in the Eastern Anatolia District: An Example of the Karakoçan-Yoğunağaç (Elazığ) and Mazgirt-Dedebağ (Tunceli) Travertines, Turkey. *Turkish Journal of Earth Sciences*. <https://doi.org/10.3906/yer-1504-27>
- Kanellopoulos, C., Lamprinou, V., Politi, A., Voudouris, P., & Economou-Amilli, A. (2022). Insights on the Biomineralisation Processes and Related Diversity of Cyanobacterial Microflora in Thermogenic Travertine Deposits in Greek Hot Springs (North-West Euboea Island). *The Depositional Record*. <https://doi.org/10.1002/dep2.197>
- Kanellopoulos, C., Thomas, C., Xirokostas, N., & Arizteguí, D. (2019). Banded Iron Travertines at the Ilia Hot Spring (Greece): An Interplay of Biotic and Abiotic Factors Leading to a Modern Banded Iron Formation Analogue? *The Depositional Record*. <https://doi.org/10.1002/dep2.55>
- Karabaçak, V., Mutlu, H., & Deniz, K. (2020). Manifestations of Quaternary Syn-eruptive Fluid Circulations on Carbonate Veins, Central Anatolian Volcanic Province. *Journal of Quaternary Science*. <https://doi.org/10.1002/jqs.3260>
- Marinescu, M., Udubasa, S. S., & Tiess, G. (2017). Research, Assessment and Management of the Travertine Resources From the Banpotoc-Carpinis Deposit (South Apuseni Mts., Romania). *Gospodarka Surowcami Mineralnymi*. <https://doi.org/10.1515/gospo-2017-0020>
- Mohammadi, Z., Capezzuoli, E., Claes, H., Alipoor, R., Muchez, P., & Swennen, R. (2019). Substrate Geology Controlling Different Morphology, Sedimentology, Diagenesis and Geochemistry of Adjacent Travertine Bodies: A Case Study From the Sanandaj-Sirjan Zone (Western Iran). *Sedimentary Geology*. <https://doi.org/10.1016/j.sedgeo.2019.06.005>
- Mohammadi, Z., Claes, H., Cappuyns, V., Nematollahi, M. J., Helser, J., Amjadian, K., & Swennen, R. (2021). High Geogenic Arsenic Concentrations in Travertines and Their Spring Waters: Assessment of the Leachability and Estimation of Ecological and Health Risks. *Journal of Hazardous Materials*. <https://doi.org/10.1016/j.jhazmat.2020.124429>
- Mors, R. A., Gómez, F. J., Astini, R. A., Celestian, A. J., & Corsetti, F. A. (2021). Assessing the Origin of Pisoids Within a Travertine System in the Border of Puna Plateau, Argentina. *Sedimentology*. <https://doi.org/10.1111/sed.12946>
- Okumura, T., Takashima, C., & Kano, A. (2013). Textures and Processes of Laminated Travertines Formed by Unicellular Cyanobacteria in Moken Hot Spring, Southwestern Japan. *Island Arc*. <https://doi.org/10.1111/iar.12034>
- Porras-Toribio, I., Pi-Puig, T., Villanueva-Estrada, R. E., Rubio-Ramos, M. A., & Solé, J. (2022). Mineralogy, Geochemistry, and Stable Isotopes (C, O, S) of Hot Spring Waters and Associated Travertines Near Tamiahua Lagoon, Veracruz, Gulf of Mexico (Mexico). *Minerals*. <https://doi.org/10.3390/min12070822>

- Prado-Pérez, A. J., Delgado-Huertas, A., Crespo, M. T., Sánchez, A. M., & Villar, L. (2013). Late Pleistocene and Holocene Mid-Latitude Palaeoclimatic and Palaeoenvironmental Reconstruction: An Approach Based on the Isotopic Record from a Travertine Formation in the Guadix-Baza Basin, Spain. *Geological Magazine*. <https://doi.org/10.1017/s0016756812000726>
- Rizzo, A. L., Uysal, İ. T., Mutlu, H., Ünal-İmer, E., Dirik, K., Yüce, G., ... Deniz, K. (2019). Geochemistry of Fluid Inclusions in Travertines From Western and Northern Turkey: Inferences on the Role of Active Faults in Fluids Circulation. *Geochemistry Geophysics Geosystems*. <https://doi.org/10.1029/2019gc008453>
- Rodrigo-Naharro, J., Herrero, M. J., Delgado-Huertas, A., Granados, A., & Villar, L. (2019). Current Travertines Precipitation Related to Artificial CO<sub>2</sub> Leakages From a Natural Reservoir (Gañuelas-Mazarrón Tertiary Basin, SE Spain). *Journal of Hydrology*. <https://doi.org/10.1016/j.jhydrol.2019.123997>
- Rodríguez-Berriguete, Á., Alonso-Zarza, A. M., Cabrera, M. C., & Rodríguez-González, A. (2012). The Azuaje Travertine: An Example of Aragonite Deposition in a Recent Volcanic Setting, N Gran Canaria Island, Spain. *Sedimentary Geology*. <https://doi.org/10.1016/j.sedgeo.2012.07.010>
- Roshanak, R., Moore, F., Zarasvandi, A., Keshavarzi, B., & Gratzer, R. (2018). Stable Isotope Geochemistry and Petrography of the Qorveh–Takab Travertines in Northwest Iran. *Austrian Journal of Earth Sciences*. <https://doi.org/10.17738/ajes.2018.0005>
- Salminen, P. E., Brasier, M., Karhu, J. A., & Melezhik, V. A. (2014). Travertine Precipitation in the Paleoproterozoic Kuetsjärvi Sedimentary Formation, Pechenga Greenstone Belt, NE Fennoscandian Shield. *Precambrian Research*. <https://doi.org/10.1016/j.precamres.2014.09.023>
- Scardozi, G. (2019). The Provenance of Marbles and Alabasters Used in the Monuments of Hierapolis in Phrygia (Turkey): New Information From a Systematic Review and Integration of Archaeological and Archaeometric Data. *Heritage*. <https://doi.org/10.3390/heritage2010035>
- Soete, J., Kleipool, L. M., Claes, H., Claes, S., Hamaekers, H., Kele, S., ... Swennen, R. (2015). Acoustic Properties in Travertines and Their Relation to Porosity and Pore Types. *Marine and Petroleum Geology*. <https://doi.org/10.1016/j.marpetgeo.2014.09.004>
- Tchouatcha, M. S., Kouske, A. P., Tamfuh, P. A., Prétat, A., Toyama, R., Feumba, R., ... Tchameni, R. (2023). First Evidence of Sinter and Travertine in Cameroon: Fault Reactivation and Geothermal Implications. *Comptes Rendus Géoscience*. <https://doi.org/10.5802/crgeos.230>
- Török, Á., Mindszenty, A., Claes, H., Kele, S., Fodor, L., & Swennen, R. (2017). Geobody Architecture of Continental Carbonates: “Gazda” Travertine Quarry (Süttő, Gerecse Hills, Hungary). *Quaternary International*. <https://doi.org/10.1016/j.quaint.2016.09.030>
- Varejão, F. G., Alonso, G., Athayde, G. B., Bahniuk Rumbelsperger, A. M., & Cury, L. F. (2024). Facies Stacking and Lateral Variability of Travertines From the Quaternary Vega Botijuela, Salar De Antofalla Basin, Argentina. *Sedimentology*. <https://doi.org/10.1111/sed.13240>

- Veysey, J., Fouke, B. W., Kandianis, M. T., Schickel, T. J., Johnson, R. W., & Goldenfeld, N. (2008). Reconstruction of Water Temperature, pH, and Flux of Ancient Hot Springs From Travertine Depositional Facies. *Journal of Sedimentary Research*. <https://doi.org/10.2110/jsr.2008.013>
- Viaroli, S., Latini, T., Cuoco, E., Mormone, A., Piochi, M., & Maggi, M. (2024). Geochemical Evolution in Historical Time of Thermal Mineral Springs at Campetti Southwest (Veii, Central Italy) Through Geoarcheological Investigation. *Water*. <https://doi.org/10.3390/w16081113>
- You, Y., Wen, H., Luo, L., Lu, Z., & Li, L. (2023). Stable Carbon and Oxygen Isotopic Features of Banded Travertines From the Xiagei Fissure Ridge System (Shangri-La, China). *Minerals*. <https://doi.org/10.3390/min13010076>
- Zentmyer, R. A., Myrow, P. M., & Newell, D. L. (2008). Travertine Deposits From Along the South Tibetan Fault System Near Nyalam, Tibet. *Geological Magazine*. <https://doi.org/10.1017/s0016756808005323>