Crystal Geyser, Utah: Active Travertine Deposits of a Cold-water Carbon Dioxide-driven Geyser and Related Ancient Deposits of the Little Grand Wash Fault

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A Thesis

Presented to

the Faculty of the Department of Earth and Atmospheric Sciences

University of Houston

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In Partial Fulfillment

of the Requirements for the Degree

Master of Science

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By

Jennifer A. Barth

Summer 2012

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## Crystal Geyser, Utah: Active Travertine

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## ABSTRACT

An active travertine sloping terraced deposit has been precipitated from the cool waters erupting from Crystal Geyser, located on the eastern bank of the Green River, near the town of Green River, Utah, since 1936. The conduit of water to the surface is an abandoned oil well, which tapped into an aquifer at depth. Below the modern ochre travertine is an older deposit, which has a gray color and is a naturally occurring precursor to the modern one. Eruptions are fueled by pressure generated by the build-up of CO<sub>2</sub>. Genetically related ancient travertine deposits are found in the immediate proximity of the modern deposit, derived from fluid flow channeled through the Little Grand Wash Fault.

A combination of abiotic and biotic activity contributes to the development of the modern deposit. The travertine is composed of various concentrations of calcite and aragonite, but calcite generally dominates. The iron-oxide lending the travertine its ochre color is due, in part, to filamentous iron-oxidizing bacteria, possibly *Leptothrix*. Textures created by iron-oxide-precipitating bacteria strongly resemble those of the ancient micro-fossil *Frutexites*. Abiotic constituents include pisoids and intraclasts. Intraclasts serve as the nuclei for larger pisoids. The pisoids develop their coatings tumbling inside the well vent and are expelled during eruptions. Pisoid nuclei may contain spherulites, formed both abiotically and biotically as a result of bacteria induced carbonate precipitation. Plant material, diatoms, and siliciclastics are cemented into the deposit.

Carbonate textures include sparry mosaics composed of anhedral to

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subhedral crystals, sparse occurrences of poikilotopic cement, disrupted "lacy laminations" formed by cyanobacteria, columnar crusts, spherulites, radiating isopachous cements, and feathery crystal splays. The deposit displays laminations that range from less than 1 mm to 2 cm, often undulating due to the turbulent nature of the environment and as a result of the formation of rimstone pool and micro-terrace morphologies.

The ancient aragonite deposits consists of needle-like to bladed crystals. Laminations of aragonite are truncated by iron-oxide laminae that also display textures similar to *Frutexites*. Iron-oxides are more pronounced in samples collected from the deposit in the nearby ridge and they may display a convoluted pattern consistent with the deforming activities of the fault.

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#### Chapter 1: INTRODUCTION

Travertines, freshwater carbonates, have been studied extensively in the last few decades as they provide an enormous amount of information regarding conditions at the time of their deposition. Travertines can provide sensitive records indicating the state of water chemistry, tectonic activity, biotic activity, and even climate. But, while all deposits are unique in their own way, their method of formation is fairly common.

The travertines forming from the waters of Crystal Geyser develop in a very unusual way. They precipitate from the cold waters erupting from the carbon-dioxide-driven geyser. Most travertines precipitated from geysers are of the hot-water variety. Crystal Geyser is not a completely naturally occurring geyser, since it relies on an abandoned oil well bore as its conduit to the surface, but its eruptions and travertine precipitation are completely natural.

This location has garnished much attention since the geyser first began erupting in 1936, not just for thrill of the eruptions, but for the sight of the beautiful ochre-colored terraced mound of travertine. In addition, research has been conducted on the geyser and on the adjacent Little Grand Wash Fault to better understand carbon dioxide sequestration. This area serves as a small-scale model of what may happen should escape pathways be generated in abandoned hydrocarbon reservoirs used to store CO<sub>2</sub>. While some analysis has been conducted on the travertine to enhance these studies, very little interest was given to the rock itself. The modern Crystal Geyser deposit and the ancient

travertine deposits of the Little Grand Wash Fault were the object of this study to provide the first detailed characterization of this unusually occurring rock.

#### 1.1 Regional Geologic Setting and Location of Field Site

Crystal Geyser is located 14.5 kilometers southeast of the town of Green River, Utah, and is situated on the eastern bank of the Green River, adjacent to the Little Grand Wash Fault (Figure 1). These features are located within the northern section of the Paradox Basin of the Colorado Plateau, which has producing natural gas and oil fields, as well as carbon dioxide fields. This region is characterized by northwest-trending faults and folds (Vrolijk et al., 2005).

In this area, carbon dioxide has accumulated in Mesozoic to Paleozoic strata, dominantly in the Jurassic Navajo Sandstone (Allis et al., 2005). The Jurassic Navajo Sandstone is likely the source of the carbon dioxide that is fueling the eruptions of Crystal Geyser. "The Colorado Plateau and Four Corners region of the western United States contains at least nine producing or abandoned CO<sub>2</sub> fields with up to 28 trillion cubic feet of CO<sub>2</sub> gas" (Shipton et al., 2004, p.43). Heath (2004) determined that clay-carbonate diagenetic reactions within impure carbonate rocks are the dominant source for the vast quantities of carbon dioxide gas in the region.

One of the more important structural features in this location is the Little Grand Wash Fault, a normal fault that is traceable for almost 30 km, displaying a general east-west trend and splitting into two fault strands west of the field site (Figure 1B; Dockrill and Shipton, 2010). The Crystal Geyser and the Little Grand Wash Fault reside on the north section of the Cane Creek plunging anticline with the San Rafael Swell approximately 21 km to the west and the



**Figure 1:** (A) Location of field site in east-central Utah (outlined in black). Indicated on the Google Earth image are major identifiable features in close proximity to the field site. Red box highlights a close-up image of the field area. (B) Locations of Crystal Geyser (red dot), the town of Green River (white) and a partial trace of the Little Grand Wash Fault which cuts under the river. Modified from GoogleEarth.com Book Cliffs 13 km to the north (Figure 1A; Campbell and Baer, 1978; Baer and Rigby, 1978). McKnight (1940) reports the vertical separation along the Little Grand Wash Fault to be around 320 m, but Shipton et al. (2004) put it at between 180 to 210 m. The Little Grand Wash Fault cuts through the Jurassic Summerville Formation and the Cretaceous Mancos Shale rocks with travertine precipitation being concentrated in the footwall. The age of the Little Grand Wash fault is unknown, but cross-cutting relationships show that it was active until at least the Middle Cretaceous (Shipton et al., 2004; Vrolijk et al., 2005).

### **1.2 History of Crystal Geyser**

Travertine deposits at the Crystal Geyser site were identified as early as 1869 by the John Wesley Powell Expedition during his exploration of the Colorado River and related canyons (Powell, 1987). His very brief journal description states that he and his crew stopped "to examine some interesting rocks, deposited by mineral springs that at one time must have existed here, but which are no longer flowing" (Powell, 1987, p. 199). It is unclear if he was referring to the ancient deposits of aragonite, derived from fault-channeled spring flow, or to a more recent deposit, which may have been a naturally occurring precursor to that developing today. This may have occurred if there was natural upward seepage of groundwater, which likely would have had sporadic flow, explaining why it was not witnessed by Powell and his crew. Powell was a remarkable artist who filled his journal with incredible drawings of things he saw on his journey, but, unfortunately, this site was not one of them.

The present geyser was created in 1935 when a petroleum geologist, Glen Ruby, had an exploratory well drilled after having been attracted to the location by oil and gas seeps (Waltham, 2001). The well, which was drilled to a depth of 800 m to the bottom of the Triassic section, tapped into a carbondioxide-charged aquifer at around 215 m. According to McKnight (1940), shows of oil and gas were reported by drillers down to a depth of 863 m.

The temperature of the water escaping from the well (roughly 18 degrees Celsius) suggests that it originates from the shallow Navajo-Wingate aquifer

(Shipton et al., 2004). According to drilling records, the well was spudded into 21.5 m of travertine, indicating that a natural travertine-depositing spring system was already in place before the well was drilled (Baer and Rigby, 1978). This record is in accordance with the statements written by John Wesley Powell in 1869. It is further supported by the presence of a small naturally occurring spring a few meters north of the well, which actively bubbles with muddy water whenever there is geyser activity and may be the remnants of the original water source. Shortly after drilling, the well was abandoned.

Official records obtained from the State of Utah website (www.Utah.gov) indicate that the well was plugged and abandoned, but, judging by the geyser activity, it was clearly just abandoned or inadequately plugged when oil was not discovered. No other records were found pertaining to the drilling history of the well. Part of the well pipe is visible and stands about 2 m above ground level (Figures 2 and 3). The pipe is heavily corroded at the base and contains several gunshot holes through which water can be expelled instead of erupting from the top.



**Figure 2**: Photograph of the modern travertine deposit. White arrow points to the well pipe, which stands approximately 2 m above ground level and provides the conduit for that is saturated with respect to calcite water to escape from the subsurface.



**Figure 3**: Well pipe of the abandoned Glen Ruby #1-X well stands approximately 2 m above ground level. Water is bubbling up from the base due to corrosion of the pipe.

Descriptions and photographic evidence of the geyser indicate that past eruptions were dramatically more pronounced than today (Figure 4; Evans et al., 2005). Decreases in the magnitude of eruptions may be attributed to lower pressures resulting from the depletion of carbon dioxide over time or the reduction of water in the aquifer feeding the geyser. Further reduction in the magnitude of the eruptions can be due to the holes now in the pipe, which allow for decreases in pressure, as well as to debris, thrown into the well by tourists, blocking the pipe. There is also the strong and likely possibility that mineral precipitation within the well is causing blockage. Various anecdotal evidence from unverifiable sources online even describes unsuccessful attempts to plug the well by throwing dynamite as well as railroad scraps down the pipe.



**Figure 4**: (A) Photograph of an eruption taken in May, 2010. (B) Photograph of an eruption taken circa 1950 (from Evans et al., 2005).

Environmental concerns were raised in 1978 regarding the amount of salts that was flowing into the Green River as a result of the geyser eruptions. Baer and Rigby (1978) estimated that approximately 2730 metric tons of salts were annually being fed to the Colorado River as a result of water contributed by the Green River. Several proposals were made to stop the water from reaching the river, including sealing the well with a grout curtain or drilling a relief well to divert the flow (Baer and Rigby, 1978). Attempts to seal the well were unsuccessful and further proposals were considered too expensive or ineffectual, since the gas and water would likely find another pathway to escape elsewhere. Since the time the well was abandoned, Crystal Geyser has erupted fairly periodically, expelling large quantities of carbon dioxide and travertine-depositing water.

Crystal Geyser is not entirely natural because it relies on a man-made well for its conduit to the surface. But, its eruptions and consequent travertine precipitation are primarily due to large amounts of carbon dioxide in the subsurface which degasses very rapidly with eruptions. It is believed, with some debate, that the carbon dioxide is derived from acidic groundwater reacting with carbonate constituents of the Navajo Sandstone, which saturates the water and generates pressure (Waltham, 2001). The water migrates upward to charge a shallow aquifer. The pressure generated by the gas eventually exceeds the pressure generated by the hydrostatic head and the geyser erupts. The water that erupts is rich in dissolved minerals, which readily precipitate, forming a travertine mound.

## **1.3 Description of Field Site**

Geyser eruptions are typically preceded by upwelling of water at the base of the pipe, which fills the pool around it, along with an increase in gas expulsion (Figure 5). This is recognized by the pungent odor of hydrogen sulfide gas and a misty haze billowing from the top of the pipe. Water may retreat back into the well and rise again repeatedly. This behavior is shortly followed by a long period of water upwelling from the pipe, which expels large volumes of fluid that flow down the travertine mound and into the river. A subsequent eruption of varying magnitude and time follows. When an eruption ends, any water in the pool drains back down the well through corroded holes at the base of the pipe. Following more spectacular and voluminous eruptions, the pool will completely dry up and remain that way for several hours.



**Figure 5**: Water spewing from the top of the pipe and flowing from the base during the early phase of an eruption. Pipe stands 2 m above ground level.

A few meters north of the well is a small muddy spring, which actively bubbles through several small conduits whenever there is geyser activity (Figure 6). It has roughly a ten-minute lag time between when the geyser begins to display its precursor activity to an eruption and its own activity. Generally, it continues to bubble for a short time after eruptions cease. Its activity is directly correlated with that of the geyser, but, interestingly, the water bubbling in the pool is substantially cooler. Furthermore, during one field excursion, the geyser was witnessed by the author and a field assistant to have erupted continuously for almost 12 hours. The muddy pool also displayed large amounts of activity at this time, continuing for several hours after the eruption of the geyser stopped. The water of the pool drained shortly after the geyser's water drained, but it continued to rapidly eject gas from one of the open conduits, producing a loud squealing noise and causing the mud to sputter. This may have been the path of water to the surface before the well was drilled and the origin of the 21 m of travertine that drillers documented. Shipton et al. (2004, p. 46) stated that, "The close correlation of the timing of the geyser and activity of these springs suggest that the latter either reflects some escape of the  $CO_2$ -charged waters from the well bore at shallow levels, or that these pools could be the original, pre-well flow paths for the CO<sub>2</sub>-charged waters to the surface." It is possible that there may have been several naturally occurring springs at this site, but that they were starved following the redirection of water and gas through the well and their remnants were covered by the travertine precipitating from the geyser.



**Figure 6**: Photograph is of a naturally occurring muddy spring just north of the well. Water and gas are expelled through small, open conduits, causing bubbling. Approximately 3 m across longest axis.

The maximum lateral extent of the active travertine deposit is approximately 85 m. The nature of the active travertine varies at any given location. Near the well, the travertine is relatively flat lying and is heavily ironoxide-stained. It is extremely brittle, shatters easily, and is prone to splitting along near horizontal planes. Pisoids of varying sizes cover the ground surrounding the well and are interpreted to have formed inside the well vent and were ejected during eruptions (see section on SEM analysis). Many of the pisoids become cemented into the travertine. Small, white bulbish features, interpreted to be evaporites, have precipitated on the edges of sites that frequently are submerged and then exposed. Down slope, the travertine is more porous and spongy, sometimes incorporating vegetation. It forms a bright orange, red, and yellow sloping terraced mound, which is ornamented with a myriad of micro-terraces. These deposits combine to form large lobes, which fan towards the river in the direction of the flowing water (Figures 7, 8, and 9). Micro-terraces form small rimstone pools in which water accumulates. Micro-terraces and rimstone pools are very pronounced in areas where water actively flows due to the continual precipitation of carbonate (Figures 10 and 11). Long strands of cyanobacteria and algae coat these areas during warmer seasons giving a dark green hue to the deposit and providing a sticky substrate for carbonate accumulation (Figure 11). The northernmost section of the deposit is heavily weathered and bleached, indicating that the water from the well rarely, if at all, flows in that direction (Figure 8). Remnants of micro-terraces and rimstone pools can be observed in that area.



**Figure 7**: View of the bright orange-colored deposit of the modern travertine facing north along the Green River. Well pipe can be seen at the back of the deposit for scale (white arrow).



**Figure 8**: View of the modern deposit facing south along the Green River. This side receives very little if any water from the well and has become weathered and bleached. A field assistant stands atop the deposit towards the right side of the photograph for scale (black arrow).



**Figure 9**: View of the actively precipitating terraced mound travertine facing east. Note the well-developed micro-terraces. Rock hammer for scale is approximately 35 cm long.



**Figure 10**: Close-up photograph of micro-terraces along the vertical face of a terraced mound. Note the plant root encrusted in the travertine just below the marker used for scale. Marker is approximately 13 cm long.



**Figure 11**: Photograph of strands of dark green cyanobacteria and algae coating the surface of the travertine deposit. Well pipe at the back of the deposit (white arrow) is for scale.

The active travertine deposits lie atop or immediately adjacent to an older travertine deposit that is believed to be the result of fault-derived fluid flow, most likely through the Little Grand Wash Fault as a conduit (Doelling, 1994; Shipton et al., 2004). Baer and Rigby (1978) identified a third and more ancient spring deposit, which sits at an elevation of 37 m higher than the modern deposit. Burnside (2010) identified six deposits in the area, five of them ancient (Figure 12). These deposits form resistive caps to small buttes atop the ridge to the east (Figure 13A). Figure 12 displays the locations of all six deposits, including the modern Crystal Geyser travertine, in relation to one another, according to Burnside (2010).



**Figure 12**: Cross-section running parallel to the trace of the Little Grand Wash Fault indicating the location of active and ancient travertine deposits. Modified from Burnside (2010).

These older deposits are crudely laminated and have undergone severe weathering, this being more apparent on the deposits located on the ridge. They display large veins of dominantly aragonitic composition, which form beautiful fan-shaped splays of white acicular to bladed crystals that resemble the hot water travertine crusts described by Guo and Riding (1992). The veins are extremely dense and the crystals splinter easily. Veins on the ridge display reddish brown bands of the sandstone host rock and thin laminations of ironoxides that appear to be poorly formed shrubs. Very large carbonate veins were observed cropping out on a cliff face to the west in conjunction with the trace of the Little Grand Wash Fault (Figure 13B).



**Figure 13**: (A) Photograph of one of the older ridge-capping travertine deposits facing east. Camera case used for scale is approximately 10 cm long. (B) Photograph of the largest aragonite vein (white arrow) accumulations within the cliff to the west of Crystal Geyser.

The deposit underlying and adjacent to the Crystal Geyser travertine (Figures 14, 15, and 16) commonly develops ellipsoidal to spherical domes formed by the botryoidal splays of crystals from a central point (Figure 17). This deposit is overlain by a breccia, which contains large carbonate clasts that appear very similar to the carbonate veins and are interpreted to be chunks of the other ancient travertine deposits washed down from the ridge (Figure 18).



**Figure 14:** Site of active travertine deposition at the farthest southwest edge of the terraced mound deposit, immediately adjacent to an older deposit (white arrow). Both deposits terminate at the river bank to the right. Note the variation in colors in the younger deposit and the blocky calcite veins in the older deposit.



**Figure 15:** Image of the ancient travertine immediately adjacent to and partially overlain by the modern deposit (lower left). Rock hammer to the lower left for scale is approximately 35 cm long.



**Figure 16**: Close-up of fanshaped aragonite veins. Marker used for scale is approximately 13 cm long.



**Figure 17**: Ellipsoidal to spherical aragonite dome formed by the botryoidal splay of aragonite crystals. Rock hammer used for scale is approximately 35 cm long.

**Figure 18**: Breccia overlying the ancient travertine deposit contains carbonate clasts derived from the deposits on top of the ridge. Rock hammer used for scale is approximately 35 cm long.

Baer and Rigby (1978, p. 128) estimated that the age of the oldest deposit was within "several hundred thousand years", but Shipton et al. (2004) narrowed that figure down to 200,000 years based on the uplift rate of the Colorado Plateau. Burnside (2010) conducted a U-Th analysis on the deposits and determined that they ranged in age from a minimum to a maximum of 5,029 and 113,912 years old, respectively.

## **1.4 Previous Work**

Due to the unusual mode of precipitation occurring at Crystal Geyser, studies have been conducted at this site to investigate the concept of carbon dioxide sequestration (Allis, 2001; Heath, 2004; Allis, 2005; Dockrill, 2005; Williams, 2005; Fessenden et al., 2008). Crystal Geyser is used as a small-scale analogue of what could occur should a focused release point be generated in a location where carbon dioxide has been sequestered.

Dockrill (2005) provided a field description and, thus far, the most detailed petrographic analysis of the travertine deposits along with geochemical data. He also provided isotopic data of the travertine in order to describe how the fluid continued to degas. This provided insight as to how the modern degassing compares to the ancient degassing that occurred along faults in the area and to other nearby springs. In addition, Dockrill and Shipton (2010) provided a detailed analysis of the structural controls of CO<sub>2</sub> leakage in the area. Burnside (2010) conducted U-Th dating analysis on the ancient deposits to constrain the history of fluid migration and, therefore, rates and volumes of carbon dioxide leakage to the surface in that area. These studies were solely related to furthering carbon dioxide sequestration research and had little interest in the rock itself.

Heath's (2004) research determined that the waters erupting from the geyser are meteoric based on  $\delta^{18}$ O values, which matched isotopic data for local meteoric water values, and they are supersaturated with respect to calcite, aragonite, dolomite, and hematite. "The waters are saline and slightly acid, with

13,848 to 21,228 mg total dissolved solids (TDS) per liter and pH values from 6.07 to 6.55" (Evans et al., 2005, p. 5).

## Chapter 2: COMMON TRENDS OF TRAVERTINE DEPOSITS

#### 2.1 Introduction

Petrologic studies of travertine deposits have only occurred in the last few decades, providing valuable information pertaining to genesis, morphology, crystal fabrics, geochemistry, and biological influence of travertine. Fouke et al. (2000, p. 565) explain that the minerals composing travertine "are a sensitive environmental record of water chemistry, hydrologic transport, climate, and microbial populations." Investigations of travertine have recognized that there are certain common trends that are likely to occur in most deposits. This pertains to their origin relative to their depositional environment, geochemistry, resulting small-scale constituents, large scale depositional morphologies, and diagenesis. But, while there may be certain trends common to most travertine deposits, there may also be much variability occurring from one system to the next. This chapter seeks to describe some of the more common findings related to travertine accumulation and diagenesis as well as possible variations within an active system.

## 2.2 Definition and History

Travertine is defined as:

Biotically and/or abiotically precipitated calcium carbonate (predominantly calcite and aragonite) from spring-fed, heated and/or ambient-temperature waters (Chafetz and Folk, 1984).

Most travertine deposits studied today are Quaternary in age, many are actively precipitating, and are "characterized by diverse arrays of crystal morphologies and macroscopic textures" (Rainy and Jones, 2007, p. 890). A sub-type of travertine, referred to as "tufa", is a cold-water variety characterized by a porous nature due to its precipitation around flora (Julia, 1983). Travertine deposits can develop anywhere from the Arctic to the tropics and some may be very extensive, spanning tens of square kilometers (Pedley et al., 2009). Recognizing older deposits in the rock record is difficult because many accumulations are poorly preserved as fragmentary erosional features.

The word "travertine" itself originates from the Italian word "*travertino*", derived from the Latin phrase "*lapis tiburtinus*," which means "The Stone of Tibur" (Chafetz and Folk, 1984). It is most noted for its exploitation as a building material, specifically in ancient Rome, and for its modern exportation from Italy to be used in construction around the globe. Little research was conducted on travertine in ancient times, though precipitating hot springs themselves garnished much attention and Rome's aqueducts and plumbing systems likely were encrusted with bothersome travertine deposits (Pentecost, 2005). The Romans often used travertine to construct their public monuments, such as statues and buildings, as well as using it for decorative features in their homes (Pedley, 2009). Construction of the Roman Colosseum alone is believed to have required over 200,000 tons of travertine blocks (Ford and Pedley, 1996).

#### 2.3 Depositional Environment

Travertine may precipitate under a wide variety of conditions. Where there may be common trends from one deposit to another regarding formation, fabrics, and diagenesis, the variability within any one system makes each travertine deposit unique. Travertine may precipitate in cold or boiling water, in water partially saturated or supersaturated with respect to calcite, in chemically toxic water or non-toxic water, and may be either completely abiotically precipitated or biotically precipitated. It is a sensitive recorder of its environment and is, therefore, an important component in deducing geologic history.

Travertine can precipitate under a wide range of geochemical conditions due to variability of CO<sub>2</sub> saturation with respect to calcite, pH, and temperature. But, this is not to say that travertine precipitation can occur anywhere. Specific environmental parameters must exist within a depositional setting that can produce adequate geochemical conditions. The parameters of the depositional setting relate, in part, to the type of rock already present, source of groundwater, and amount of rainfall.

Most travertine deposits are the result of spring-fed waters depositing calcium carbonate derived from the dissolution of limestone bedrock. Travertine precipitation most commonly occurs in regions of active tectonism where the temperature of groundwater is frequently high and the dissolution of country rock is enhanced (Piper et al., 2007). As meteoric water passes into the subsurface and reaches a limestone formation, the rock dissolves and releases Ca and CO<sub>3</sub>
into solution. Travertine precipitation occurs when the waters return to the surface. Therefore, there must be a route for the ion-enriched water to flow back to the surface, i.e., a spring. By definition, travertine is derived from spring-fed waters. The conduit that allows passage for the water is commonly generated by tectonic or volcanic activity creating fractures. Once the water reaches the surface, precipitation may occur. Whereas these deposits can be quite complex and vary significantly from one another, the circumstances under which they are deposited are fairly common. In contrast, the travertine deposits of Crystal Geyser are the result of atypical circumstances. The geyser is unusual because it was not naturally created, it erupts only cold water (approximately 18 degrees Celsius), and its eruptions are driven by the degassing of large volumes of carbon dioxide.

#### 2.4 Geochemistry

"The species of calcium carbonate deposited is a function of the solution from which it is derived" (Utech, 1988, p. 27). Travertine may be composed of either calcite or aragonite and its precipitation is greatly influenced by the saturation state of the water.

For precipitation to occur, the bicarbonate ion, HCO<sub>3</sub>, has to be broken down to release the carbonate ion, CO<sub>3</sub>. This occurs through the following chemical reaction:

$$Ca^{2++} + 2(HCO_3)^{--} = CaCO_3 + CO_2 + H_2O_3$$

This reaction occurs abiotically and commonly when groundwater surfaces, resulting in the degassing of carbon dioxide, the constituent most likely to change in quantity. Carbon dioxide degassing may occur through a variety of methods, "including turbulence, temperature increase, reduction in partial pressure of CO<sub>2</sub>, evaporation, and/or photosynthesis" (Utech, 1988, p. 26). As CO<sub>2</sub> degasses from a system, pH of the water increases proportionally with the degassing and increases the saturation levels with respect to calcite. Surface temperature increases play a larger role in CO<sub>2</sub> degassing within cool or ambient water systems, but are negligible regarding hot water deposits. Carbon dioxide is less soluble in warmer water than it is at cooler temperatures and more degassing occurs (Chafetz et al., 1991). This may increase the production of more aragonitic precipitates than calcite. Seasonal variations may also have an effect on the mineralogy within ambient-temperature deposits. Studies have

shown that in the summer and fall months there are higher concentrations of dissolved ions in spring waters than those found in the winter and spring, which is likely due to temperature fluctuations or photosynthetic activity (Utech, 1988). Evaporation of the water could also lead to a higher concentration of calcium ions in solution.

According to Fouke et al. (2000, p. 568) "Degassing and precipitation take place simultaneously, with the rate of precipitation accelerating with the cumulative extent of degassing." Oftentimes, this is not the case as several variables are involved that can affect the rate of precipitation. For example, the process may be hindered by excessive rainfall. During periods of rainfall, karstic activity increases leading to escalated limestone dissolution, which increases the concentration of ions in solution (Love, 1985). But, high volumes of water can dilute the solution and decrease the saturation levels necessary for precipitation to occur or cause erosion of the travertine. In addition, Chafetz et al. (1991, p. 111) noted that "the ability of carbonate to precipitate and bring the system back into equilibrium lagged behind the continued loss of CO<sub>2</sub> and the result was increased levels of supersaturation". Hence, rates of precipitation do not depend solely on CO<sub>2</sub> degassing.

Most travertine is composed of low-Mg calcite, although aragonite is not uncommon, and in rare circumstances it is composed of high-Mg calcite. The precipitation of low-Mg calcite, high-Mg calcite, or aragonite depends heavily on the Mg to Ca ratio, the rate of precipitation, temperature, and the presence of

other reactors that can either catalyze or inhibit the reaction. Generally, low magnesian calcite forms when the Mg/Ca ratio is less than 2, high magnesian calcite forms when the ratio is between 2 and 12, and aragonite forms when it is greater than 12 (Utech, 1988). Also, rapid precipitation and high temperatures favor aragonite precipitation.

#### 2.5 Biotic vs. Abiotic Precipitation

Previous studies recognized that photosynthetic algae and bacteria played a role in carbonate precipitation, but to what extent was not recognized (Chafetz and Folk, 1984). There are two end-members of thought: one that believes that biogenic processes are actively responsible for carbonate precipitation and one that supports the idea that organisms are passive. Biotically induced precipitation refers to an organism's ability to alter its surrounding microenvironment to induce extracellular and/or intracellular carbonate precipitation. Organisms which may induce such precipitation include bacteria, cyanobacteria, mosses, and higher taxonomic levels of plants. Riding (2000, p. 180) stated that "biota are extensively involved in the production, accumulation, and diagenesis of sediment." Doelling (1994) and Dockrill (2005) mentioned that algae may be affecting some of the precipitation of the Crystal Geyser travertine. Dockrill (2005) also identified what he believed were bacterially induced calcite shrubs in samples from Crystal Geyser.

An argument against the concept of biotic precipitation is that biotic activity does not affect the overall chemistry of a stream and, therefore, does not affect precipitation. But, biota can influence the waters in their immediate surroundings and alter their microenvironment to induce precipitation (Chafetz et al., 1991). The most recognized method through which cyanobacteria, mosses, and higher plant taxa may biotically induce precipitation is through photosynthesis. During photosynthesis, plants remove carbon dioxide from the surrounding system and

incorporate it into their bodies as their primary source of carbon. This leaves the adjacent waters more saturated with respect to calcite and precipitation may occur. Abiotic precipitation may also occur if these organisms are a passive influence. Such would be the case if the organism was either dead, thereby, not inducing photosynthetic precipitation or if it merely acts as a substrate where water may collect. If the organism is a substrate then the water may simply be evaporating on it. This leaves any remaining water with a higher saturation state with respect to calcite and precipitation may occur, encrusting the organism.

"It has been amply demonstrated since the early 1900's that bacteria do induce the precipitation of calcium carbonate under laboratory conditions and more recently, there has also been substantial evidence to indicate that they are doing so under natural conditions in the recent, and have done so in the geologic past as well" (Buczynski, 1990, p.100). While it is generally accepted that bacteria can induce precipitation of carbonates, to what extent is still controversial. In the past, many researchers, particularly those who worked with stream water chemistry, believed that precipitation was primarily abiotic and any biotic influence was relatively minor (Utech, 1988). Resistance to the idea of bacterially induced precipitation was perpetuated by the fact that bacteria are too small to be seen under a standard microscope, that if they are present they may not have had anything to do with precipitation, and that if they were identified they could be some form of modern contamination (Folk, 1993). Even though it was known that bacterial influence could result in carbonate precipitation, some

still believed that it was not very extensive. Yet, bacteria are widespread and abundant across the Earth's surface, in all lakes and oceans, and can be found at great depths beneath the surface (Riding, 2000).

Buczynski (1990) demonstrated that bacterial carbonate precipitation replicating that of a natural environment could be produced in the laboratory. He identified three main categories of crystal aggregate forms that bacteria produced as rods, spheres, and brushes along with a sub-category of dumbbells. The experiments showed that in all cases where samples were sterilized, no precipitate developed. But, in all cases where non-sterile samples were used, there was a resulting precipitate. Therefore, the cell bodies were not just being entombed by carbonates, but their metabolic activity was essential for inducing precipitation (Buczynski and Chafetz, 1991). Bacterial cell walls have a negative charge that attracts the positively charged calcium ion, which can bind with carbonate from the surrounding waters. Therefore, bacteria can effectively alter their microenvironment to induce precipitation.

Bacterial bodies can also be identified using SEM analysis. Folk (1993) identified bacterial cells whose internal structure collapsed after HCI etching to form "bagel-like" objects on the crystal surfaces of specimens. It was also observed that if travertine were crushed and placed in weak acid, clumps of bacteria could be seen under a petrographic microscope floating out from the calcite and dissolving into the acid. While bacterial bodies can be identified in samples if the correct methods and equipment are used, Kirkland et al. (1999)

stressed caution when identifying bacterial bodies as acid etching on large euhedral crystals could produce nannometer scale objects resembling nannobacteria.

"The presence or absence of bacteria is directly controlled by hot springs physical and chemical environmental conditions, which include parameters such as water temperature, flow rate, pH, light, and nutrient availability" (Fouke et al., 2003, p.1544). Bacteria then manipulate their surrounding environment, which influences carbonate precipitation. But, the environments immediately adjacent to travertine producing hot-springs provide an inhospitable environment for bacteria and other organisms to grow. Chafetz and Folk (1984) surmised that CO<sub>2</sub> degassing in locations immediately surrounding hot-springs was primarily responsible for travertine precipitation. Bacteria and cyanobacteria have a much greater influence downstream as water temperatures cool and acidity levels decrease, followed by higher taxa of vegetation farther downstream. Unlike bacteria, cyanobacteria have a much narrower environmental range. This phenomenon was noted in Yellowstone National Park where waters were cool, but high sulfur content prevented the growth of cyanobacteria (Chafetz and Folk, 1984). However, bacteria could apparently survive in that environment and could be observed with coatings of calcite. "Carbonate minerals have a great affinity for organic compounds, and Ca<sup>++</sup> is strongly attached to bacterial cell walls, so there is attractive linkage between the inorganic and organic moieties" (Folk, 1993, p. 990). Yet, a potential problem in relating bacteria to travertine

precipitation arises because specific interactions between bacteria and carbonate precipitation are complicated and difficult to isolate. Investigations have identified proteins in cyanobacteria that may lower the pH of the outer membrane and prevent extracellular precipitation despite active photosynthesis (Riding, 2003). Similar problems may eventually come to light with bacteria and demonstrate situations where they may hinder precipitation, despite their obvious involvement in inducing precipitation.

Other evidence supporting the concept of carbonate-inducing bacteria was the identification of calcite "shrubs" by Chafetz and Folk (1984). Shrubs, unlike dendrites, lack an extensive crystallographic pattern, which suggests they are biotically induced. These small-scale features are described in the section detailing travertine fabrics.

The difference in amounts of abiotic precipitates versus biotic precipitates is directly impacted by the harshness of the environment. With higher temperatures and toxicity, abiotic precipitation dominates, while with lower or more ambient temperatures and more neutral hydrogeochemical conditions, biotic precipitation may flourish. This leads to the conclusion that biotic precipitation could indeed be quite extensive under favorable conditions, but be nonexistent in more toxic environments. Also, change between dominantly abiotic precipitation to dominantly biotic precipitation may also occur within one deposit (Chafetz and Folk, 1984). So, determining which mechanism of

precipitation is more dominant must be done on a case by case basis and conclusions cannot be applied to all travertine deposits in a general sense.

#### 2.6 Large-scale Features – Morphologies

Over the years, many investigators have tried to develop a classification scheme to categorize travertine. Several techniques have been applied such as classification by physical properties, vegetation associated with a deposit, the geomorphological position of the formation, and whether the deposit was in-place or not (Utech, 1988). There are many problems associated with all of these classifying criteria. Classification by physical properties is inadequate as diagenesis can strongly impact those properties. For example, vegetation recognized as a physical property in a deposit will decompose over time and original porosity can be lost to diagenesis. Also, focusing on organic material may result in neglecting important features of abiotic precipitates (Love, 1985). Love (1985, p. 23) pointed out that classifying travertine by distinguishing between "inplace and clastic deposits" is impractical because these deposits may be "intimately related" to each other and drawing a definite distinction could be difficult. Classifying deposits according to their geomorphological position is problematic because recognition of such a feature would be difficult to pinpoint in the rock record (Utech, 1988; Love, 1985). Another method of classification, recognizing deposits by their overall morphology, has been considered. This method was developed by Chafetz and Folk (1984), who recognized five different morphological types of travertine deposits: 1) lake-fill deposits; 2) sloping mounds, fans, and cones; 3) terraced mounds; 4) fissure ridges; and 5) waterfall deposits (Chafetz and Folk, 1984). However, there is high variability between

morphologies and their constituents and, oftentimes, different morphologies are closely related to each other (Chafetz and Folk, 1984; Utech, 1985). Hence, this method cannot make a clear distinction between all deposits. But, this method avoids the problems associated with earlier classification schemes and provides a broad means of categorization.

The cascade morphologies typically form at previous sites of rapids and waterfalls, sites of increased agitation, where cyanobacteria and mosses can easily attach (Chafetz and Folk, 1984). Cascades are believed to grow very quickly by the calcite encrustation of plants and are commonly associated with travertine dams. Material that falls into the stream can rapidly become coated in carbonate and incorporated into the deposit. This implies that the constituents of the deposit can be highly variable. The overall structure of the deposit is massive, nonbedded, porous, and is irregular in texture and structure (Chafetz and Folk, 1984)

Lake-fill deposits can form very large accumulations. There are two categories of lake-fill travertines, which include the cold or ambient water variety and the hot water variety. The cold water deposits are generally composed of micrite and lack the extensive bedding that often appears within hot water travertines. The hot water travertines are quarried extensively in locations such as Italy and Idaho. The accumulations are laterally extensive and while some irregularities may occur, the travertine generally occurs in horizontal layers as a result of deposition within a shallow lake (Love, 1985). Hot water lake-fill

deposits can be important in recognizing extensive biotic precipitation. This is because the slow passage of water through lakes means that CO<sub>2</sub> evasion is reduced and other means of precipitation become more important (Pentecost, 2005). Precipitation may be enhanced through photosynthesis by cyanobacteria and evaporation but, more notably, bacterial precipitation can be extensive (Chafetz and Folk, 1984). This may be identified by small-scale constituents described as "shrubs" which will be discussed later in this manuscript.

The sloping mound, fan, and cone morphologies are similar to one another and can produce large-scale, sloping deposits with irregularly layered strata (Chafetz and Folk, 1984). These morphologies develop where water is rapidly flowing downslope in volumes sufficient to sustain filamentous cyanobacteria (Herlinger, 1981). Stratification of these deposits parallel depositional slope.

The fourth morphology, terraced mounds, strongly resembles stair steps. They are the result of pools being spring-fed or receiving water from above. This results in raised walls precipitating around the pool as the water flows over the top and down the other side. This causes shallow travertine pools at the top of the step with nearly vertical travertine walls developing at the front of the step as the water flows out of the pool and descends to the next step. Bacterial shrubs may be present in large quantities in the pools while the rims are composed of dense crystalline calcite (Chafetz and Folk, 1984).

In locations prone to tectonic activity, hydrothermal waters can rise along

linear fault features. Fissure ridges, travertine accumulation around spring orifices or fractures, form micro-terrace deposits, but likely did not form any largescale deposits that would be preserved in the rock record (Chafetz and Folk, 1984; Pentecost, 2005). Fissure ridges are composed of elongate deposits with a fracture running along the crest. Upwelling water comes through the fracture and flows down both sides. Bedding in this type of morphology is composed of steeply dipping, parallel laminae. Fissure ridges provide important records of geothermal and earthquake activity. Geothermal reservoirs are reactivated by earthquake activity, but have a tendency to be blocked by precipitating carbonate deposits between events (Piper et al., 2007).

The difference in morphologies of travertine deposits and the geochemistry of spring waters affects the organisms present, which directly influence the carbonate precipitation. "These settings, and variations within them, strongly influence both the physico-chemical factors affecting inorganic precipitation of carbonate (agitation, amount of solar heating, etc.) and the type, abundance, and growth rate of organisms, thereby affecting the organic precipitation of carbonate" (Chafetz and Folk, 1984, p. 293). On the other hand, the resulting morphology could then create another sub-environment that can either hinder or support further biotic precipitation. For example, the organisms present and the geochemistry of a lake could result in a travertine deposit much different from that associated with a fast-moving stream. The newly developing morphologies can create sub-environments that can either support or hinder

biotic precipitation. Sub-environments may be more physically stable locations for organisms to thrive or be locations that sustain toxicity and allow for dominantly abiotic precipitation. For example, at the initial site of water upwelling at a hot spring, the environmental conditions would likely be too toxic for any biotic activity to occur. The high agitation state of the water would enhance active degassing of carbon dioxide and, assuming geochemical conditions were appropriate, result in an abiotic precipitate. As this abiotic deposit continues to grow, it may generate a barrier against the upwelling water and result in, on the opposite side, a location that has much less agitation and allows for any water that trickles into it to cool. In such a case, perhaps this newly created and less toxic sub-environment would allow for more biotic activity and possibly biotic precipitates could occur. So, one side of the dam could develop an environment more hospitable to biota while the side that contains the water source continues to be toxic. The biota in the less chemically harsh sub-environment could be altering their microenvironment to induce further precipitation and generating new morphologies. This activity could continue so long as there continued to be an adequate water source and more biotically dominant precipitating morphologies could develop. But, biota can only do this as long as they have the nutrients to sustain them. So, in effect, its possible that the morphology that develops as a direct result of biotic precipitation could create a complete dam against any water intrusion, thereby, starving the sub-environment. It is a negative feedback loop. Sub-environments created within larger morphologies can create much, and

perhaps even unexpected, variability. "Morphology controls the existence and relative abundance of subenvironments, such as pools or steeply sloping surfaces, which then favor either organic or inorganic types of deposition" (Chafetz and Folk, 1984, p. 293).

# 2.7 Travertine Fabrics

Some of the more interesting fabrics identified in travertine deposits are shrubs, crystal shrubs, and ray-crystal shrubs, which are calcite or aragonite fabrics. "Shrubs", a term used to describe irregularly shaped, bush-like features are believed to be bacterially precipitated and restricted to hot-water travertine deposits. Colonies of rod-shaped bacteria clump together to form irregular bushlike features, superficially resembling dendrites, that grow upward and branch outward to obtain nutrients (Meredith, 1980). They are very distinct features that can be wide-spread across an outcrop, making them good environmental indicators (Guidry and Chafetz, 2003). Crystal shrubs are similar to bacterial shrubs, but display a more regular morphology suggesting that abiotic influence is dominant. They, however, contain bacterial fossils indicating that some biotic precipitation occurs (Chafetz and Guidry, 1999). Ray-crystal shrubs are mostly the product of abiotic precipitation, having a lesser biotic influence than crystal shrubs, and form, "subparallel to fan-shaped arrays of coarse to extremely coarsely crystalline calcite spar, commonly an order of magnitude larger than the bacterial shrubs and crystal shrub" (Chafetz and Guidry, 1999, p.59).

# 2.8 Diagenesis

Diagenesis refers to any alteration of a rock after deposition. This may be broken into four possible stages: pre-burial, early-burial, late-burial, and uplift. In the case of travertines, which are typically geologically young deposits, meteoric diagenesis is a key component within the first two stages of alteration. This takes place near the surface at low pressures and temperatures, contrary to deeper burial diagenesis which occurs at higher pressures and temperatures. "The process does not result in significant compaction or dolomitization, but cementation, sparmicritization, neomorphism and dissolution have been widely documented" (Pentecost, 2005, p. 42). As discussed earlier in this thesis, meteoric water can either promote the generation of travertine or cause dissolution and erosion. As water percolates into a deposit, it may continue to add minerals to it and continue to generate travertine. This would alter the primary fabric as a secondary fabric develops, or it may dissolve the primary fabric and leave pore space. Post-depositional infestation by microbes may also play a role (Guo and Riding, 1994).

Sparmicritization is a process where biota etch sparry carbonate rocks and leave voids that fill with micrite. The micrite often remains as a stable residue after the original crystals are gone (Bathurst, 1975).

Dissolution occurs when the water surrounding a travertine deposit is undersaturated with respect to calcite and dissolves the carbonate. This process occurs frequently from exposure to direct rainfall. Dissolution can create ragged

surfaces of initial spar crystals and destroy crystal outlines (Guo and Riding, 1994).

Neomorphism is a process where unstable carbonate crystals go into solution and precipitate in more stable forms. Aragonite, which is an unstable mineral at normal surface pressures and temperature, will go into solution and the reactants can precipitate as calcite.

#### Chapter 3: METHODOLOGY

#### 3.1 Field Investigation

The field area was visited in January of 2010 to conduct initial evaluation and sampling of the travertine at Crystal Geyser. Poor weather conditions, including nine inches of snow on the ground, did not allow for sufficient sampling and assessment at that time. A return trip was conducted in May of 2010 for further sampling and analysis. Both trips showed that sampling the modern travertine deposit with standard field tools, a rock hammer and chisel, yielded insufficient results as the rock at any given spot is either too brittle and is destroyed on impact or it is too spongy to generate a fracture. Therefore, samples were collected from the surface by removing them from the outcrop with a 9-inch angle grinder powered by a portable generator. Each sample was wrapped in plastic wrap to hold it together and these samples were placed in boxes for transport. Sampling locations were documented photographically (Figures 19 and 20).

In addition, during the summer field trip, 20 cores with a diameter of 5 cm were taken with a maximum depth of 40 cm. These were extracted using a coring drill mounted on a platform powered by a portable generator. Samples falling apart during the coring process was a frequent problem and seemed to happen most often when there was an abundance of organic material present in the sample, likely derived from decaying cyanobacteria. Cores were wrapped in pipe insulation and taped closed. Sampling of the older deposits was done using

the angle grinder and standard field tools.

Attempts were made to collect as many samples as possible with a wide distribution, while trying not to cause visible damage to the beauty of the site. Sampling at the edge of the travertine mound, near the river, was slightly hindered by the ability to get the heavy equipment to that location safely.

It was observed in the summer that any damage that was done during the winter trip had already been covered by rapid carbonate precipitation. Locations where cores were taken were filled in with carbonate muds found at the edge of the travertine mound and covered with loose fragments of travertine to act as substrates for precipitation to aid in the recovery process. It is expected that any evidence of samples having been removed during the summer is no longer visible.



Figure 19: Location of sampling sites on upper platform of travertine.



Figure 20: Location of sampling sites on terraces.

# 3.2 Laboratory Investigation

Detailed petographic, mineralogical (XRD), and scanning electron microscopic (SEM) analyses were conducted in the lab.

Petrographic analysis was conducted on 50 thin sections taken from both the modern and ancient deposits to describe the fabric and composition of each sample. An additional 10 thin sections were made of the various-sized pisoids found surrounding the well. All samples were impregnated with blue epoxy due to their fragile nature.

X-ray diffraction (XRD) was used to determine the mineralogies of the modern and ancient deposits. Specifically, XRD was used to establish the ratio of aragonite to calcite in each individual deposit and to compare deposits. A total of 88 samples were X-rayed based on distinguishing characteristics such as color, density, fabric, etc. A hand-held drill with diamond-tipped bits was used to powder the samples. Attempts were made to correlate unidentified peaks to possible iron minerals, which may be producing the orange and red colors of the modern deposit and in the bands of the ancient deposits. This was unsuccessful. The section detailing the XRD results provides possible explanations.

A Scanning Electron Microscope (SEM) was used to look for evidence of biotic precipitation and to characterize abiotic precipitates. Samples were analyzed from the ancient deposits, the modern deposits, and the various sizes of pisoids taken from around the well. Samples were coated in a carbon coater. Due to the porous nature of the travertine, it proved to be extremely difficult to produce SEM images that did not display charging. The ancient deposits are composed of very densely packed aragonite crystals, so charging was not an issue, but samples from the modern deposits and of the pisoids proved to be problematic more often than not. Samples, which failed to produce the desired results, were repeatedly coated in carbon. Attempts were then made to coat many of the samples in gold. This method worked for some of the pisoids, but not for the extremely porous modern travertine. Hence, all images of the modern travertine were taken from zones which produced minimal charging effects. All samples were kept in a vacuum oven at all times.

#### Chapter 4: DATA AND RESULTS

## 4.1 Modern Crystal Geyser Deposit

### 4.1.1 Introduction

Samples collected near the geyser vent are extremely brittle and fall apart easily when handled. The surface of the travertine near the well is relatively flatlying and pisoids litter the ground surrounding the well in copious quantities in a variety of sizes and shapes. With distance from the well, the travertines become more porous and spongy, commonly displaying well-developed laminae that may be interrupted by the development of rimstone pool morphologies. Travertine terraces develop closer to the bank of the Green River and become increasingly steep with proximity to the bank. The overall thickness of the deposit is unclear, but it is estimated to be no more than a few meters thick based on the vertical thickness of the ancient travertine deposit underlying it.

There is great variation in composition and structure within the modern travertine deposit both across the deposit as a whole and within single samples. Rimstone pools and micro-terraces cover the entire surface of the deposit. Samples are laminated and commonly alternate in color between red and yellow, with the yellow laminations typically being thinner than the red, more iron-oxiderich ones. Iron-oxide-rich laminations commonly display shrubs, demonstrating bushy structures typically attributed to bacterially induced carbonates. These iron-oxide shrubs are light to blood red in color, strongly resembling the ancient micro-fossil *Frutexites*. These shrubs are interpreted to be the product of iron-

oxidizing bacteria.

Allochems identified within the deposit include intraclasts, pisoids, diatom fossils and plant material. Intraclasts are likely derived from run-off from the nearby ridges and are frequently found mingled with pisoids around the well vent, coated in both carbonate and iron-oxides. Carbonate minerals appear as sparry mosaics, poikilotopic cements, disrupted laminations that resemble lace, clotted textures, dense columnar crusts that resemble micro-stromatolites, feathery crystal splays, feather crystal spherulites and non-feather crystal spherulites. Single carbonate crystals may be anhedral to subhedral and difficult to distinguish individually, acicular to tabular, bladed, platy, or pseudo-hexagonal with euhedral to sub-rounded faces.

# 4.1.2 Hand Sample and Core Description

Much of the travertine in the modern deposit displays well-developed laminations, which range in thickness from 1 mm to 2 cm (Figure 21). Thickness variations may be a result of several factors including seasonal growth through biotic activity (either by organism's directly inducing precipitation or by acting as a loci for accumulation during warmer months), seasonal hindrance of growth during winter months when the water freezes on the surface, or by the water switching flow paths. It is unclear how frequently the water may change flow paths, but it was documented to flow in the same general direction during both trips to the field. During the summertime, the presence of dark green filamentous strands of cyanobacteria was documented covering the surface where the majority of water was flowing, indicating that flow direction is fairly consistent to support biota and that cyanobacteria may be influencing precipitation. These cyanobacterial mats produce textures that resemble lace (see section titled Cyanobacterial Textures).



**Figure 21:** Cut slab displaying well-developed laminae (white arrows) alternating between lighter and darker shades of orange and red. Penny used for scale has a diameter of 19 mm.

Laminations are often undulatory as a result of conforming to the underlying surface and the build-up of micro-terrace and rimstone pool structures (Figure 22). Laminations alternate in color from lighter shades of yellow or red to darker, more iron-oxide-rich bands. Thin laminations sometimes appear as somewhat platy while thicker ones appear as more spongy crusts, commonly displaying carbonate shells that formed around gas bubbles (Figure 23A). For the most part, crusts precipitate vertically except for the ones precipitating on some slope faces, which display elongate branching crystals growing horizontally that resemble feathers (Figure 23B).



**Figure 22**: (A) close-up of rimstone pools (white arrows point to the edges of the pools) that cause the undulating laminations displayed in B. (B) Cut-slab through the sample shown in A, displaying undulating laminations (white arrow) alternating in color between orange and dark red.



**Figure 23:** Hand samples (A and B) displaying: (A) spongy texture formed as a result of carbonate coatings on gas bubbles. (B) Elongate crystals, which splay from a central apex resembling feathers (highlighted in white box) that grew horizontally on a slope face (white arrow points to the apex). Penny used for scale has a diameter of 19 mm.

Samples taken from around the well are very platy and brittle, displaying poorly formed laminae that formed around siliciclastic and intraclastic debris (Figure 24A). Some of the debris was coated in carbonate and appears to have been ripped up, likely by tourists walking or driving over this part of the deposit, and re-cemented. These samples are light yellow to dark red and shatter easily. Small white bulbish features, thought to be evaporites, appear on the surface as a result of repeated flooding and drying that occurs in the pool around the well vent (Figure 24A). With depth, samples display well-formed, flat-lying laminae interrupted by layers of angular to sub-rounded siliciclastics that have been cemented into the deposit (Figure 24B).



**Figure 24:** Cut slabs (A and B) displaying: (A) Platy, brittle, poorly formed laminations (white arrow) that formed around siliciclastic and intraclasts debris (red arrows) with evaporite crusts on the surface (black arrow). (B) Well-formed laminae (white arrow) with a layer of intraclasts and siliciclastics cemented into the travertine above it (black arrow). Penny used for scale has a diameter of 19 mm.

The surfaces of many of the samples display small, delicate crystal structures that grow upward in a funnel shape that increases in size upwards, clustering in a botryoidal fashion and resemble tiny flowers (Figure 25). Similar structures were reported by Parenteau and Cady (2010) and were interpreted to have a bacterial origin. These do not occur in the area immediately surrounding the well, but frequently appear within rimstone pools away from the well.



**Figure 25:** (A and B) Surface of samples covered in small crystal bundles, growing upward and clustering in a botryoidal fashion, found in rimstone pools. Penny used for scale has a diameter of 19 mm.

In hand samples, laminations that contain iron-oxide shrubs have a tendency to be thicker than ones that do not and are darker red layers (Figure 26A). Contacts between light and dark laminations can be fairly sharp and the more iron-oxide-rich ones have a tendency to be denser. Samples may display a gentle transition from iron-oxide-rich shrubby laminations into the more carbonate-rich laminations, like those shown in Figure 26B, where dark red shrub branches fade into the carbonate layer above. The section titled "Iron-oxide Textures and Microbial Influence" describe these iron-oxide-rich shrubs in greater detail.



**Figure 26:** Cut slabs (A and B) displaying bands of dark red iron-oxide-rich shrubs (white arrows) layered with lighter colored, less iron-oxide-rich laminae that show an absence of shrubs. Shrub layers are thicker than layers that do not have shrubs. Penny used for scale has a diameter of 19 mm.

The majority of the cores taken did not recover the full 40 cm capacity of the core barrel. The downward pressure of the core barrel, in conjunction with the spinning action, caused washout of weaker planes within the travertine, commonly resulting in an upwelling of beige travertine muck. Occasionally the muck would appear gray or black, suggesting the presence of decayed organic matter that resulted in weaker cementation of the travertine. This sometimes stained the remaining travertine laminae with a greenish hue. The entrapment of gas bubbles within the rock may also contribute to the weakness. It is unclear how thick the weaker planes were at any given location, but their destruction during the coring process places pieces of travertine core in contact with rock above it that it did not contact before.

Cores that were recovered from deeper depths revealed a light gray travertine that is somewhat denser than the ochre rock, presumably from greater cementation over time. It may display an abundance of detritus, siliciclastics and intraclasts, cemented within it and is abundantly pitted with horizontally elongate holes, which likely represent gas pockets, although some may be molds that contained evaporite crystals in the past (Figure 27). The detritus can be fairly large, often pebble size. Laminations may not always be readily apparent, but may appear very fine, typically less than 1 mm.

The contact between the gray and ochre travertines can be rather sharp and does not display any gradation. The ochre travertine cored above the gray is commonly segmented into thin plate-like wafers or shorter stubs of core,



**Figure 27:** Cores taken from the modern deposit display an older gray travertine underlying it with sharp contacts (red lines). It is heavily pitted with holes, which were likely gas pockets. The travertine forms thin laminations above it which split on weaker planes before transitioning into well-formed couplets of thicker, more red laminae (white arrows) and thin beige laminae (black arrow). Rulers represent thickness.
having had more planes of weakness between laminations that brought about horizontal fracture described earlier. The ochre travertine eventually transitions into uniformly thick lamination couplets of thicker, typically around 1 cm, darker red or orange laminae and very thin, no more than 3 mm, beige to light yellow platy laminae (Figure 27). The couplets are recurring and cohesive and likely lacked the organics present at greater depths, so they do not develop horizontal fractures. In addition, the well-developed couplets also display a more crystallographic pattern in their laminae, with upward branching of crystals readily apparent versus at greater depths where the segmented travertine often appears to have higher mud content.

The large quantity of detritus present in the gray travertine is distinctly absent from the ochre travertine, suggesting that detrital run-off was more frequent during the time that the gray material was deposited. The sharp contact between the gray and ochre travertines indicates an abrupt change in the environment which was more favorable to iron-oxide precipitation and the presence of organics, likely green algae. What this change may have been is unclear.

#### 4.1.3 Mineralogy

The modern travertine deposit is composed of a mixture of calcite and aragonite. In general, calcite is the dominant mineral, but there are high concentrations of aragonite in samples taken near the well with some displaying more aragonite than calcite. Distally from the well, calcite concentrations increase. Interestingly, in comparing yellow versus red laminae, red laminations always show calcite as being the dominant carbonate mineral. Light yellow laminations either are composed of aragonite as the dominant mineral or at least have higher concentrations of aragonite than the red laminations.

The gray travertine underlying the ochre is dominantly calcite with minor amounts of aragonite. Powder samples collected from the ochre travertine at the top of cores and of the gray travertine at the base, showed that the gray travertine typically contains a much higher concentration of calcite than that which lies above it.

The iron-oxide minerals present in the deposit were not identified despite their common presence in samples. Peaks in the XRD diffraction patterns almost always corresponded with either calcite or aragonite. Unidentified peaks could not be correlated to any iron-rich mineral. It is believed that this is because the iron-rich material is amorphous and, therefore, is undetectable using this method. This was determined from examining samples displaying iron-rich laminations with SEM using EDX to differentiate between carbonate and iron-oxide minerals.

#### 4.1.4. Allochems

#### 4.1.4.1 Intraclasts

Intraclasts are commonly found on the upper platform surface of the modern deposit, near the well vent and at depth within the gray travertine. These are derived from debris runoff from the ridge to the west. Intraclasts have very irregular shapes and can be as wide as 3 cm across their longest axis and as narrow as several hundreds of microns. They are generally composed of angular to sub-rounded quartz grains cemented in calcite and some may display a matrix with higher clay or iron-oxide content (Figure 28). Some of the intraclasts appear to be derived from the ancient travertine deposit located on the ridge (described in the next chapter) as the petrographic characteristics are very similar in that they appear to be composed of blades of aragonite and display iron-oxide structures that resemble *Frutexites* (Figure 29). Distinguishing between the aragonite blades of the ancient deposit and the recent cements is difficult, though. Intraclasts are almost always coated in travertine and iron-oxide cements forming concentric cortices and serve as the nucleus for large pisoids described in the next section.



**Figure 28**: Photomicrographs (A and B) of intraclasts under cross-polarized light composed of angular to sub-rounded grains of silica in a carbonate cement.



**Figure 29:** Photomicrograph under cross-polarized light of intraclasts which may have been derived from the ancient travertine deposit on the ridge to the west, which have been re-worked and cemented into the modern deposit.

### 4.1.4.2 Pisoids

#### 4.1.4.2.1 Introduction

Varying sizes of coated grains, pisoids, litter the ground surrounding the Crystal Geyser well vent intermingled with an abundance of intraclasts (Figure 30 A). The smaller of the pisoids are well-rounded and become increasingly irregular with larger size (Figure 30B). They generally display a nucleus and concentric cortices whose crystals are radially oriented. Coated grains have been studied extensively and are well-described in literature (Baker and Frostick, 1947; Jones, F. and Wilkinson,1978; Braithwaite, 1979; Risacher and Eugster, 1979; Schrieber et al., 1981; Abreu, 1990; Jones and Renaut, 1994; Jones et al., 2001; Bonny and Jones, 2008; Jones, B., 2009).

The internal structure and composition of pisoids from the field site could vary widely, although they generally display a nucleus and radiating cortex. An example of this would be a single pisoid that displayed an entire cortical layer composed of diatom molds. While diatoms were identified in a handful of pisoids, this particular phenomenon was only seen in that one pisoid.



**Figure 30:** Photograph of (A) pisoids and intraclasts littering the ground near Crystal Geyser. Rock hammer used for scale is approximately 35 cm long. (B) Various-sized pisoids collected from around Crystal Geyser and sorted by size. The irregularity of the pisoids increase with increasing size. Penny used for scale is approximately 19 mm in diameter.

## 4.1.4.2.2 Description

Pisoids range in size from 2 mm diameter to 9 mm. In thin section, the pisoids display a uniaxial cross under polarized light (Figure 31). The smaller of the pisoids are very well-rounded, while the larger ones become more irregular with increasing size. The roundness and size of the grains appear to be the result of the composition of the nucleus. The larger pisoids are the result formed with an intraclast as a nucleus. The intraclasts are normally composed of several grains of fine sand, often quartz, becoming cemented together by carbonate to form the nucleus (Figure 32). The morphology of the nucleus determines the overall irregular shape of the larger pisoids. Radiating isopachous carbonate crystals form the exterior of the allochem.



**Figure 31**: Photomicrographs (A and B) of pisoids under cross-polarized light reveal well-rounded concentric cortex, well-developed radiating isopachous carbonate cement, and a uniaxial cross. Pisoids display coatings of iron-oxide, which are likely bacterial in origin.



**Figure 32**: SEM image of the nucleus of a larger pisoid, approximately 7 to 9 mm in diameter, composed of several grains of silica cemented together, producing an intraclast, accounting for the irregular shape of the larger pisoids.

The smaller pisoids commonly contain a single quartz grain that forms the nucleus (Figure 33) or several independent grains whose coatings merged together (Figure 34). As with the larger pisoids, radiating crystals develop on the edges of these grains forming concentric coatings. The crystals in immediate contact with the grains are poorly formed and small, approximately less than 1 micron, but form the substrate for larger, bladed crystals, which range in size from 10 to 15 microns in length. Pisoids whose growth depends on the presence of grains on which to nucleate are generally formed abiotically.



**Figure 33:** SEM image of a single quartz grain (white arrow) serving as the nucleus for a pisoid. Crystals immediately in contact with the grain are small and poorly formed, but transition into larger, bladed crystals (red arrow).

**Figure 34:** SEM image of multiple siliciclastic grains (white arrow) cemented into the nucleus of a pisoid, but are not in contact with another. Cements encrusting each grain merge together. In some cases, crystals surrounding the grains in the nucleus do not form well-oriented outward splays and appear as a chaotic cluster before transitioning into a more uniform orientation. The outward radial growth of these crystals generally transitions into beautifully well-formed pseudo-hexagonal or tabular crystals that can be up to 35 microns in length (Figures 35, 36, and 37). In addition to the radial structure (Figure 38A), pisoids also display well-developed concentric laminations that may vary in thickness. In some interesting situations, the growth of a cortical lamination whose crystals are oriented radially to the nucleus will be terminated against another cortical layer whose crystals are aligned perpendicular to the radial ones (Figure 38B).



**Figure 35:** SEM image of well-developed pseudo-hexagonal crystals (white arrow).

**Figure 36**: SEM image of well-developed euhedral pseudo-hexagonal crystals (white arrow).

**Figure 37**: SEM image of poorly-formed pseudohexagonal crystals and tabular crystals.



**Figure 38:** SEM image of (A) well-oriented radial splay of crystals growing away from a single grain serving as the nucleus (white arrow) with individual cortical layers indicated by red arrows. (B) SEM image displaying the radial splay of crystals oriented perpendicular to the nucleus (direction of white arrow) and terminated against a layer, whose crystals are aligned perpendicular to the splay (red arrow).

### 4.1.4.2.3 Bacterially-induced Spherulites

In several pisoid samples, the nucleus could not be identified. Pisoids that do not display distinctive nuclei have very porous and chaotic crystal textures in their centers (Figure 39). While several fine-sand-sized grains may be found intermixed with the crystals, they do not appear to be the initial source of growth of the pisoid, i.e., they are not the nucleus. This does not occur in the larger pisoids where multiple cemented grains clearly form the nucleus. It is within the smaller pisoids (generally those that have a diameter of 5 mm or less) that spherulitic structures within the nucleus are commonly found. Spherulites typically have a diameter of no more than 30 microns.



**Figure 39:** SEM image of the chaotic crystal structure of a pisoid nucleus displaying randomly oriented crystals.

"Spherulitic morphologies are often formed by mineral growth in systems where micro-organisms are abundant" (Meakin and Jamtveit, 2009, p. 684). Many of the spherulites appear as having a rather clotted texture, displaying small (less than 1 micron) elliptical forms or aggregates of forms in the nucleus (Figure 40). These forms are interpreted to be carbonates precipitating bacteria and are similar to the bacterial colloids described by Folk (1999), Rivadeneyra et al. (2010), and Spadafora et al. (2010).



Figure 40: Aggregates of elliptically shaped bacteria in the center of a spherulite nucleus.

Bacteria typically form globular aggregates at the centers of the spherulites. In some spherulites, the bacteria are restricted to the nucleus and bladed aragonite crystals displaying well-formed, clearly-defined crystals grow in radial splays away from the bacterial clumps (Figure 41). Other spherulites display bacteria that are not restricted to the centers and are encased within the radially splaying aragonite crystals, giving them a clotted appearance (Figures 42, 43, and 44). Similar bacterially induced spherulites were described by Folk (1994), Guo (2010), and Verrechia et al. (1995).



**Figure 41:** (A and B) SEM images of spherulites containing bacterial clumps as nuclei. Straight crystal edges with a bladed morphology are formed abiotically.



**Figure 42**: SEM images (A and B) of bacterially induced spherulites displaying aggregates of bacteria in the center as well as in the radially splaying crystals, giving the crystals a clotted appearance.



**Figure 43:** SEM images (A and B) of bacterially induced spherulites. (A) Bacteria occur in the center of the spherulite (red arrow), but do not appear to be encrusted within the radiating crystals, which display sharp edges. (B) Bacteria occur in the center of the nucleus (red arrow) and are encased within the radiating crystals, giving a clotted appearance to the crystals.



**Figure 44:** SEM images (A and B) comparing the radially splaying crystals of spherulites in which the outer parts of the crystals formed abiotically (A) and biotically (B). (A) Spherulite crystals formed abiotically (no bacteria in the outer part of the crystals) display straight and smooth crystal edges. (B) Spherulite formed biotically displays a clotted appearance due to the bacteria being encrusted within the length of the crystal.

# 4.1.4.2.4 Diatoms Within Pisoids

Diatoms occur within some of the pisoids containing the bacterial spherulites (Figure 45), typically in the central area. An exception mentioned earlier is a pisoid in which almost an entire cortical layer was composed of diatom molds (Figure 46). These strongly resemble diatoms discovered in other parts of the travertine deposit and are interpreted to be of the genus *Navicula* (see section entitled Diatoms Encased in Travertine).



Figure 45: SEM image of diatoms interpreted to be of the genus *Navicula* (white arrows)

**Figure 46:** SEM image of a cortical layer of a pisoid completely filled with diatoms and diatom molds (white arrows).

#### 4.1.4.3 Diatoms Encased in Travertine

A few hand sample specimens of the modern deposit also displayed diatom blooms which strongly resemble those identified within the pisoids. Using the University of Colorado at Boulder online catalog of western diatoms as comparisons, these diatoms appear to be members of the genus *Navicula*, a Latin term meaning "small ship" (Spaulding et al., 2010). This interpretation is based on their elongate elliptical forms that are highly symmetrical, sometimes displaying striations on exterior cell walls (Figure 47). Many are broken open demonstrating raft-like halves. The exact species of *Navicula* present here was not identified as there appear to be hundreds of different varieties and doing such would far exceed the scope of this study.

"Diatoms and filamentous microbes excrete mucus that traps crystal seeds on which abiotic calcite precipitation would occur" (Guo and Riding, 1994, p. 512; Davaud and Girardclos, 2001). It is not presumed that diatoms have any direct influence on carbonate precipitation at Crystal Geyser, but that they are being entombed by it due to the sticky biofilm they create that serves as a substrate for mineral precipitation.



**Figure 47:** SEM images of (A) a single diatom displaying an elongate, elliptical, and highly symmetrical shape (white arrow). Striations line its surface. (B) Cluster of copious amounts of diatoms, some appearing as raft-like halves that have been split open (white arrows).

## 4.1.4.4 Plant Material

Several examples of plant material being entombed within the travertine deposit have been identified. If the plant material itself is not present within the sample, than frequently the mold is visible. Woody material, plant stalks, or roots, can clearly be identified through a petrographic microscope or SEM and are derived from the shrubs and bushes that grow immediately adjacent to the modern travertine deposit (Figure 48). The density of the carbonate crystals in contact with the plant material or to the molds, as compared to the surrounding pore space, indicates that the plants either served as substrates for abiotic precipitation or microbes living on the plant stalks were inducing precipitation.





# 4.1.5 Carbonate Cements and Crystal Morphology

### 4.1.5.1 Sparry Mosaics and Poikilotopic Cements

The bulk of carbonate crystals in the modern deposit are subhedral to anhedral, commonly lacking distinctive boundaries, displaying a sparry mosaic (Figure 49). Small spherulitic structures composed of radially splaying acicular crystals, described later, may develop within the spar, but do not compose the bulk of the matrix. Spar may serve as the cement between siliciclastic grains, intraclasts, or as irregular precipitates growing into pore spaces. Poikilotopic cements occur in sparse quantities (Figure 50). They may also provide a substrate for more distinctive euhedral crystals to grow on.



**Figure 49:** Photomicrograph in cross-polarized light of calcite crystals forming sparry mosaics. Individual crystals are indistinguishable.



**Figure 50:** Photomicrographs in cross-polarized light of poikilotopic calcite cements filling in pore spaces between (A) angular detrital quartz grains and (B) anhedral carbonate crystals.

### 4.1.5.2 Bladed Crystal Cements

In several samples, elongate bladed crystals fill pore spaces (Figures 51 and 52). The crystals generally are never longer than 1 mm and display fairly uniform lengths. They may form radiating isopachous cements on grains, elongate bands sometimes displaying thin iron-oxide laminae, "starbursts", and as crystals filling in pore spaces (Figure 53). These may nucleate on clots of iron-oxide, intraclasts, or zones primarily composed of small anhedral carbonate crystals.



## Figure 51:

Photomicrograph in crosspolarized light of bladed crystals forming an elongate band on the edge of calcite cemented quartz grains and filling in pore space. Thin laminations of iron-oxides interrupt the crystal growth.

## Figure 52:

Photomicrograph in crosspolarized light of bladed crystals filling in pore space and merging together. The contact where the crystals meet displays a sutured boundary (black arrow).



**Figure 53:** SEM images of bladed crystals filling in pore space. (A) A "starburst" of bladed crystals (white arrow), some are poorly formed pseudo-hexagonal crystals. (B) Bladed crystals growing perpendicular to substrate on which they are growing and filling in the pore spaces (white arrow).

#### 4.1.5.3 Columnar Crusts

Columnar crusts, similar to those described by Brasier et al. (2011) and Freyet and Verrechia (1999), are fairly common in the modern deposit. Columnar crusts are inter-layered with more micritic and iron-oxide-rich layers that display very poorly formed structures, or none at all, and contain siliciclastic debris. The influx of debris interrupts the growth of the columnar crusts and may be the product of repetitive flooding from the geyser. Columnar crusts typically do not exceed a thickness of 1.5 mm and display multiple concave stacked horizons building the column structure (Figures 54 and 55). In some situations, these crusts can be heavily coated by iron-oxide (Figure 56). Viewed in SEM, the columns appear to be composed of plate-like, jagged-edged bladed crystals that merged into a fan-shaped array in each columnar layer (Figure 57).



**Figure 54:** Photomicrograph in cross-polarized light of layers of columnar crusts (black arrows) interlayered with micrite, iron-oxides, and siliciclastics.

**Figure 55:** Photomicrograph in cross-polarized light of a close-up of columnar crusts displaying multiple concave stacked horizons of crystals.

**Figure 56:** Photomicrograph in plane light of columnar crusts heavily coated by iron-oxide.



**Figure 57:** SEM images of columnar crusts. Multiple horizons (white arrows) of a single column (tilted to the right). Individual crystals are difficult to distinguish, but appear to be bladed with jagged edges.

# 4.1.5.4 Radially Splaying Isopachous Cements

Allochems, mostly siliciclastics and pisoids, commonly found in samples collected from the upper platform of the deposit, display radiating isopachous rims of cement. The allochems display iron-oxide rims in a distinctive pattern produced by iron-oxidizing bacteria, followed by fibro-radiating tabular to bladed isopachous calcite cement filling the pore spaces (Figure 58). Many intraclasts or pisoids display multiple coatings of carbonate and iron-oxide. Tabular and bladed crystals not only form isopachous cements around grains (Figure 59), but also can form random fan-shaped and radial splays within pore spaces.



**Figure 58:** Photomicrograph in cross-polarized light of intraclasts, a pisoid, and some plant material displaying rims of iron-oxide in the distinctive pattern produced by iron-oxidizing bacteria. Exterior to the iron-oxide rims are radiating splays of isopachous carbonate cement.



**Figure 59:** SEM image of radiating isopachous cements. (A) Isopachous carbonate cements radiating around a quartz grain (white arrow). (B) Isopachous carbonate cements radiating around empty molds of unknown origin (white arrows).

#### 4.1.5.5 Calcite Feather Crystal Splays and Feather Crystal Spherulites

One of the more striking crystal structures identified in the deposit is large feathery splays of calcite that resemble the calcite feathers described by Jones and Renaut (1995), Rainy and Jones (2009), Fouke et al. (2000), and Brogi and Capezzuoli (2009) (Figures 60, 61, and 62). These calcite crystal feathers are found growing horizontally on a slope face distal from the well, perpendicular to the direction of water flow. In other deposits, similar "feather dendrites are most abundant on sloping surfaces, rimstone dams and rollovers" (Rainy and Jones, 2009, p. 1839). Steeply sloping surfaces cause water to flow more quickly, increasing turbulence, and causing carbon dioxide to degas more quickly. This results in a higher saturation state with respect to calcite and the feather dendrites precipitate rapidly. These splays can be up to 2 cm long starting from the apex of the splay to the farthest crystal tip. Individual layers of these structures terminate into thin iron-oxide bands, which coat the edges of the crystals. These feathery crystals are associated with smaller fibro-radiating bundles, which appear to have a similar crystal form (Figure 63). The bundles appear to represent the earliest development of the feather structures. Bundles can appear elsewhere in the deposit in small quantities, without the feather structures.


## **Figure 60:** Photomicrograph

Photomicrograph under cross-polarized light of fan-shaped, feather-like calcite crystal splays. Fans terminate against thin bands of iron-oxide (white arrow)

**Figure 61:** Photomicrograph in plane light of fanshaped feather-like crystal splays.

Figure 62: Photomicrograph under cross-polarized light of fan-shaped, feather-like calcite crystal splays.



**Figure 63:** Photomicrographs of radiating bundles of feathery crystals (A) in cross-polarized light. The bundles (white arrows) seem to be a stage of early development for the feather crystal splays (red arrow). (B) In plane light, a close-up view of the radiating bundles (white arrows).

Closer inspection of the crystals forming the feather splays with SEM was difficult due to issues with charging, but they appear to be composed of poorly formed, stubby, pillar-like crystals (Figure 64). The fibro-radiating bundles also appear to be composed of several hundreds of small stubby bundles, but these are formed by the clustering of acicular crystals composed of partial "wheat sheaf" structures (Figure 65A). Wheat sheafs were also described by Rainy and Jones (2000) as part of feather structures, but theirs were composed of stacked rhombohedrons of calcite. The feather splays at Crystal Geyser are composed of poorly formed clusters and higher magnification with SEM shows them to be composed of acicular crystals (Figure 65B).



**Figure 64:** SEM image showing a close-up of the crystals forming the feather crystals, which appear to be stubby, poorly-formed, and pillar-like.



**Figure 65:** (A) SEM image of hundreds of stubby "wheat sheaf" crystal morphologies combining to form radially splaying feather crystals. (B) SEM image of "wheat sheaf" forms composed of densely packed acicular crystals.

#### 4.1.5.6 Non-feather Crystal Radiating Spherulites

In several samples, radiating spherulitic bundles were identified. These differ from the feather crystal spherulites in that the crystals in these are not composed of densely packed acicular crystal bundles. Non-feather crystal spherulites are composed of individual acicular, tabular, or pseudo-hexagonal crystals. At times, a nucleus could not be identified at the center of the bundles, but others display an irregular iron-oxide globule for a nucleus (Figure 66). The edges of these bundles appear very smooth and have a diameter of approximately 50 to 200 microns. Other radiating bundles display a much more distinctive iron-oxide glob as a nucleus and the crystals are more clearly defined and appear to be more bladed than acicular (Figure 66B). These spherulitic bundles are larger than the others described, with well-formed ones displaying a diameter up to 500 microns.



**Figure 66:** Photomicrographs in plane light of (A) radiating smooth-edged spherulitic bundles (black arrows). Individual spherulite boundaries may be indistinguishable where in contact with other spherulites. Clumps of iron-oxide form the nuclei. (B) Spherulites with distinctive globules of iron-oxide for nuclei and more distinctive individual crystals (black arrows).

Spherulites with smooth edges are composed of radial splays of pseudohexagonal crystals (Figures 67 and 68) while tabular to bladed crystals form the ones with more irregular edges. Individual pseudo-hexagonal crystals may display distinctive shape and six symmetrical sides, whereas some may be slightly rounded or display some asymmetry. Clusters of the spherulites display botryoidal forms (Figure 69).



Figure 67: SEM image of spherulitic structures (white arrows) composed of radially splaying pseudo-hexagonal crystals clustering together.

**Figure 68:** SEM image of a spherulite composed of pseudo-hexagonal crystals (white arrows).



**Figure 69:** (A and B) SEM images of the botryoidal morphology formed by the clustering of spherulitic forms.

#### 4.1.6 Biotic Textures

#### 4.1.6.1 Cyanobacterial Textures

Some samples displayed thin, lacy laminations in thin section. These laminations are relatively flat-lying, although commonly undulose, display a delicate, draping appearance and are interpreted to be the encrusted remains of cyanobacteria (Figure 70), which were observed coating the surface of the travertine deposit in May 2010. There is, generally, high porosity between layers. Micrite and siliciclastics adhere to the sticky filamentous strands. Tiny, indistinct carbonate crystals grow on the edges of the strands.

Cyanobacteria mats, in some situations, appear to be the substrate on which travertine crusts grow and they may sometimes be heavily coated in ironoxides (Figure 71). It is unclear if cyanobacteria may be playing a role in inducing the precipitation of the iron-oxides, but the frequency of which the strands appear not coated in iron-oxides suggests they may be serving as a passive substrate for mineral accumulation. The cyanobacteria may also be providing a stable substrate for iron-oxidizing bacteria (described in the next section) to adhere to, explaining why some of the cyanobacteria are, or appear to be, coated in iron-oxides. Spar cements may fill in the spaces between strands, creating an irregular, clotted-looking texture (Figure 72).



**Figure 70**: Photomicrographs in plane light (A and B) displaying disrupted "lacy" laminae that are micritic, relatively parallel to one another, and display a high porosity are interpreted to be the remnants of strands of filamentous cyanobacteria.



**Figure 71:** Photomicrographs in plane light (A and B) displaying (A) what may be a heavily iron-oxide-coated cyanobacteria mat (white arrow) providing the substrate for travertine crusts and possibly iron-oxidizing bacteria and (B) strands of cyanobacteria only partially encrusted in iron-oxides.



**Figure 72:** Photomicrograph in cross polarized light of cyanobacteria where spar has filled in the spaces between filaments and iron-oxides coat the strands. This produces a clotted appearance.

#### 4.1.6.2 Iron-Oxide Textures and Microbial Influence

#### 4.1.6.2.1 Introduction

Iron-oxidizing microbes have been well-described in literature pertaining to water chemistry as they can be a pesky and abundant nuisance to meeting safety standards, not to mention taste and appearance, of drinking water (Ridgeway et al., 1981). To a lesser extent, they have been described in terms of their ability to construct iron-rich microbial mats, frequently associated with acid mine drainage (Espana et al., 2007; Pagnanelli et al., 2007). The study of ironrich microbial mats is of great relevance in the search for extraterrestrial life on Mars and in understanding the origins of massive accumulations of iron on Earth, such as the Banded Iron Formations (Baele et al., 2008; Kolo et al., 2009; Parenteau and Cady, 2010). Unlike carbonate-precipitating bacteria, which are believed to be unwillingly entombed by minerals, it is believed the ironprecipitating bacteria, at least certain species, induce mineralization as a survival mechanism. Furthermore, many iron-oxidizing microbes are also capable of oxidizing manganese, which was observed in small amounts coinciding with the iron-oxide precipitates (Tazaki, 1997).

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#### 4.1.6.2.2 Iron-oxidizing Bacteria

The distinctive ochre color of the modern travertine deposit is an obvious indication of the presence of iron-oxides. In hand sample, the iron-oxide minerals display a very prominent upward branching growth pattern, strongly resembling the structure of shrub features commonly associated with carbonate-precipitating bacteria (Chafetz and Folk, 1984) and of the ancient iron-rich structure *Frutexites*, which is interpreted to have been microbially induced (Walter and Awramik, 1979; Bohm and Brachert, 1993). These features are also very distinctive under a petrographic microscope and strongly resemble the microbial structures described by Baele et al. (2008) and Takashima et al. (2008) (Figure 73). SEM analysis of iron-oxide-rich zones suggested that the structures always occur in the presence of abundant filamentous forms that are commonly heavily encrusted by iron-oxides (Figure 74), and sometimes appearing as "gooey" globs of iron. These structures are interpreted to be the product of iron-oxidizing bacteria.



**Figure 73**: Photomicrographs (A and B) in cross-polarized light, iron-oxide shrubs growing into pore spaces displaying irregular shrubby branching patterns. (C and D) In plane light, iron-oxide shrubs displaying clotted textures.



**Figure 74**: SEM image of filamentous forms interpreted to be iron-oxidizing bacteria. (A) Copious filaments (white arrows) drape over carbonate crystals. (B) Close-up view of A displaying filaments heavily encrusted with iron-oxides (white arrows).

One of the more common and well-studied, albeit elusive, iron-oxidizing microbes is Leptothrix Ochracea, a species whose taxonomy is solely based on morphology (Fleming et al., 2011). Other species fit the genus of *Leptothrix*, but L. Ochracea is considered the type species. L. Ochracea is an elongate filamentous form frequently identified in naturally occurring freshwater springs and iron-rich microbial mats, capable of producing copious quantities of loose flocs of iron oxyhydroxides and manganese (Emerson and Revsbech, 1994; James and Ferris, 2004; Fleming et al., 2011). L. Ochracea forms a sheath exterior to its cell wall, composed of a polysaccharide material, which it sheds and regenerates following the encrustation by iron-oxide (Schieber and Glamoclija, 2007). The sheaths are typically 1 to 2 microns wide, can be several tens of microns in length, and 90 to 95 percent of the time are devoid of the actual living cell, rendering them as straw-like hollow tubes (Emerson and Weiss, 2010; Fleming et al., 2011). The bacterial cells are typically flushed away from the sheath in flowing water, making them difficult to isolate.

Takashima et al. (2008, p. 198) described iron-rich shrubs, similar to those found at Crystal Geyser, whose formation they attributed to filamentous bacteria whose "morphotypes resembled the sheath of the iron-oxidizing bacterium *Leptothrix*". The microbes identified in the Crystal Geyser travertine fit the morphological description of this bacterium and may be either *L. Ochracea* or a similar bacterium, although this microbe may not represent all iron-oxidizing microbes in this deposit. Some of the more heavily encrusted filaments may be

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cyanobacteria, but their role in iron-oxide production is unclear.

The encrustation of the filaments can make them difficult to identify, but the fortunate discovery of filaments that were only lightly encrusted supports the conclusion that these forms are iron-oxidizing bacteria. Several SEM images of lightly encrusted filaments show them to be somewhat transparent, almost ghostlike, indicating that the walls are thin and the interior is likely hollow (Figure 75). Less encrusted forms resemble those described by Florea et al. (2011).

*Leptothrix* is a curious microbe in that it may act as a tiny architect, combining with other *Leptothrix* cells to make microscopic "buildings". *Leptothrix* cells will join together in a crisscross honeycomb-like pattern, leaving a few microns of space between each layer, generating multiple level buildings that resemble scaffolding (Schieber et al., 2006). The abandonment of their polysaccharide sheaths leaves a hollow skeleton structure saturated with water, which other microbes, including other iron-oxidizers, will readily inhabit and then fill-in the porous matrix with minerals and organic material (Fleming et al., 2011). The peculiar linear alignment of crystals and stacking pattern raises the question of whether or not the crystals are actually bacterial sheaths that were encrusted by iron and then coated in carbonate, aside from the stragglers exterior to the matrix (Figure 76). Why this microbe would create this structure when it so readily abandons it is unclear.



**Figure 75**: SEM image of ghost-like transparent bacterial sheaths (white arrows). The one in the center (red arrow) appears to have broken into segments. Note how the crystals in the background can be seen through the sheath and have a uniform linear alignment from the upper left corner to the bottom right, possibly representing a structure whose matrix is composed of aligned filamentous bacteria.



**Figure 76:** SEM images (A and B) of iron-oxide bacterial filaments (white arrows) and what may be structures composed of the stacking of the encrusted filaments in a fairly well-organized linear alignment (red arrows).

*Leptothrix* sheaths are very delicate structures, easily prone to rapid degradation or being crushed. The sheath is believed to serve one of two possible purposes or both. The first possibility is that the bacteria have evolved specifically to create a protective outer layer to prevent the entombment by ironrich minerals. The second possibility is that the bacteria are using the iron as a method to transfer energy into their inner cell body, a benefit derived from the release of protons during mineral formation, and the sheath localizes precipitation (Fortin and Langley, 2005; Chan, 2006; Chan et al., 2009). If the sheath serves both of these purposes, then the bacteria are deliberately accumulating iron to gain energy and shed the sheaths before the cell itself can be entombed. In either case, "the surface reactivity of the bacterial surface confers a net negative charge to its cell wall, thereby, leading to the adherence of soluble iron on its cell walls and finally the precipitation of iron oxides under saturation conditions" (Baskar et al., 2008, p. 242). Sheaths that have been shed will flocculate out of the water column and settle. Iron minerals attached to the sheath can then act as nucleation sites for precipitation of minerals, either with more iron or a carbonate crust in the case of Crystal Geyser (Wu et al., 2009).

The bacteria described here were identified either in mat forms or as exterior coatings of spherulitic forms. The nuclei of many spherulitic forms have dense spherical iron-oxide clusters (Figures 77 and 78) that were not recognized in SEM analyses and may be more closely related to the bacteria producing spherical structures or nodules described by Kolo et al. (2009) and Villalobos et al. (2005). Layers coating the spherulites alternate between carbonate and ironoxide layers.



**Figure 77**: Photomicrograph in plane light of irregular spherulitic structures with iron-oxide globules forming the nucleus (black arrows).



**Figure 78:** Photomicrographs in cross-polarized light of (A) spherulitic forms displaying carbonate crystals radiating away from globular iron-oxide nuclei. (B) Spherulitic forms displaying poorly defined crystals forming concentric laminae around globular iron-oxide nuclei.

Heavily mineralized filaments merge together in a gooey mat upon flocculation or cling to the exterior of spherulites (Figure 79), leading to the construction of the distinctive shrub-like pattern. The filamentous mats described here are very similar to the goethite-encrusted mats described by Hofmann and Farmer (2000), although they did not identify which microbe they believed composed the mats. Those observed in Figure 79 are very heavily encrusted, but the overall size suggests these may be cyanobacteria.



**Figure 79:** SEM images of (A) heavily iron-oxide encrusted filaments (white arrow) merging into a large globular, amorphous iron-oxide precipitate. (B) Dense mats of iron-oxide mineralized filaments (white arrows) coating the exterior of spherulitic forms.

Not all of the iron-oxide precipitates contain filaments. Some appeared as nothing more than amorphous globules, indicating that there may be some abiotic precipitation occurring or filaments were broken off and flushed away (Figure 80). No definitive biotic influence was recognized on or within the amorphous globules.



**Figure 80:** SEM images (A and B) of amorphous iron-oxide mineral precipitates that do not display bacterial filaments and may be formed abiotically (white arrows).

## 4.2. Ancient Little Grand Wash Fault

## 4.2.1 Hand Sample Description

In hand sample, the ancient travertine of the Little Grand Wash Fault found adjacent to the modern deposit is composed of beautiful fan-shaped splays of aragonite crusts up to 50 cm thick, which are composed of laminations ranging in thickness from 2 mm to 3 cm. Crystals in samples appear to be much larger, but what seem to be single large crystals are actually thousands of tiny needlelike crystals that are truncated and other crystals use them as a nucleation point, commonly growing in the same direction. Thicker and larger aragonite blades are commonly "nested" together giving the appearance of a single large crystal. Lamination growth is commonly terminated against iron-rich laminations, which may be as thin as 1 mm, but no thicker than 1 cm. Samples taken from the deposit underlying and immediately adjacent to the modern deposit are purer aragonite than those sampled from the ridge. The deposits adjacent to the modern accumulation have much lower iron content and do not contain any pieces of the host rock into which they intruded, lending them a pristine white appearance (Figure 81). Individual crystals may split off into sharp splinters.

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**Figure 81:** Hand samples collected from the ancient deposit immediately adjacent to the modern deposit. Hand samples display a clean white appearance due to a lack of iron-oxide content. Penny used for scale is approximately 19 mm in diameter.

Samples taken from the ridge are a complex blend of the layered aragonite that occurs in veins with iron-oxide-rich bands, mixed in a convoluted array with fragments of the host rock (Figures 82 and 83). Aragonite and ironoxide laminations range from 1 -10 mm in thickness. The aragonite layers may be substantially thicker than those observed on the cliff face to the west. Some of the iron-rich bands display structures similar to those described in the modern deposit composed of shrub-like features (Figure 83C).



**Figure 82:** Photograph of a hand sample of the ancient travertine collected from the ridge. Note that it appears to have more iron-oxide content than samples collected adjacent to the modern deposit. Penny used for scale is approximately 19 mm in diameter.



**Figure 83:** Photographs of hand samples displaying (A) ancient travertine collected from the ridge showing a convoluted array of aragonite veins, iron-oxide bands, and intraclasts of the host rock. (B) Relatively flat-lying laminations of aragonite and iron-oxides. (C) Lamination of iron-oxide structures resembling the bacterially induced iron-oxides of the modern deposit (white arrow) and the ancient micro-fossil *Frutexites*. Penny used for scale is approximately 19 mm in diameter.

#### 4.2.2 Mineralogy

The ancient Little Grand Wash Fault travertine is almost entirely composed of aragonite with minor amounts of calcite. As with the modern deposit, the iron-oxide minerals could not be identified, although Vrolijk et al. (2005) identified the iron-oxides of the ancient deposit as goethite.

#### 4.2.3 Carbonate Textures

The travertines of the Little Grand Wash Fault display beautiful splays of well-formed needle-like or bladed aragonite crystals (Figures 84, 85, 86, 87, 88, and 89). The aragonite appears to have formed by abiotic processes, indicating that carbon dioxide degassing through the Little Grand Wash Fault was likely the most important factor in precipitation (Jones and Renaut, 1996). Individual crystal splays generally begin with a clearly defined apex and growth is terminated against iron-oxide laminations (Figure 90). Crystals are well-organized and are uniformly oriented except when in close proximity to iron-oxide bands where they become much smaller (individual crystals are indistinguishable) and poorly formed. It is unclear if the growth of the aragonite crystals was hindered by the precipitation of iron-oxides or if there was a lull in aragonite precipitation, possibly due to a decrease in carbon dioxide degassing, which allowed time for the iron-oxide minerals to precipitate.

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# Figure 84:

Photomicrograph in plane light of alternating laminations of aragonite and dark bands of ironoxide. Aragonite crystals are bladed or needle-like.

## Figure 85:

Photomicrograph in plane light displaying well-formed bladed aragonite crystals whose growth is terminated again a thin layer of ironoxide, which coats the tips of the aragonite (black arrow).

# Figure 86:

Photomicrograph in cross-polarized light of blades of aragonite being truncated by crystals growing perpendicular to their alignment (black arrow). Crystals growing in the perpendicular orientation display pseudo-hexagonal shapes (black arrows).



## **Figure 87:** Photomicrograph in cross-polarized light of splays of needle-like aragonite crystals.

# Figure 88:

Photomicrograph in cross-polarized light of blades of aragonite transitioning into smaller, needle-like crystals (black arrow).

# Figure 89:

Photomicrograph in cross-polarized light of the apexes of several clusters of aragonite splays (black arrows)



**Figure 90:** SEM image of (A) well-formed aragonite blades (red arrow) truncated by a layer of iron-oxide (white arrow), followed by the growth of a thinner aragonite layer. (B) SEM image of needle-like (white arrow) and bladed aragonite (red arrow).

The older of the ancient deposits display higher concentrations of ironoxide, i.e., there are more iron-oxide-rich laminations, in general, and they are thicker than those seen in the deposits directly underlying the modern travertine (Figures 91, 92, and 93). These deposits also contain large quantities of the sandstone host rock which were re-worked into the travertine as large clasts. Large aragonite crystals truncated by iron-oxide-rich laminations display etched and pitted crystal boundaries at the contact between aragonite and iron-oxides. Iron-oxide-rich laminations are generally composed of aragonite crystals which are smaller than those of the well-formed aragonite laminations, with anhedral to subhedral crystals typically occurring on the order of a few microns across their widest axis and blocky, euhedral crystals tens of microns in diameter. Occasionally spherulitic "starbursts" of aragonite can be identified in iron-oxide laminations displaying ragged crystal edges (Figure 94A). Contacts between aragonite and iron-oxide minerals can be somewhat indistinct or very sharp, depending on how well-formed the aragonite crystals are (Figure 94B).



**Figure 91:** Photomicrograph in cross-polarized light of a lamination of poorly formed iron-oxide shrubs (red arrow), and the apexes of aragonite splays which are nucleating on clumps of ironoxide (black arrow).

**Figure 92:** Photomicrograph in plane light of laminations of well-formed bladed aragonite crystals (black arrow) truncated by a layer of poorly-formed iron-oxide shrubs (red arrow) followed by a lamination of poorly ordered aragonite crystals.

**Figure 93:** Photomicrograph in cross-polarized light of the veins of aragonite forming a convoluted array with the host rock.


**Figure 94:** SEM image of (A) spherulitic "starburst" of aragonite within iron-oxiderich laminae (white arrow). Nucleus is composed of amorphous iron-oxides. (B) Sharp contacts between amorphous, globular iron-oxide minerals (red arrow) and platy rhombohedral stacks of carbonate minerals (white arrows).

# 4.2.4 Iron-oxide Textures

Petrographically, while not as well formed, the iron-oxide structures in the ancient deposits strongly resemble those seen in the modern deposits (Figures 95, 96, and 97). They display a shrubby branching morphology that closely resembles the ancient microfossil *Frutexites* (Walter and Awramik,1979; Bohm and Brachert, 1993) and modern microbial analogues (Baele et.al, 2008; Takashima et. al, 2008). Iron-oxide mineral growth is inhibited by either a lack of available iron or by the rapid precipitation of aragonite suppressing iron-oxide precipitation. Iron-oxides may coat the aragonite crystals, lending them a yellow color, or serve as a nucleus for aragonite fans.



**Figure 95:** Photomicrograph in plane light of iron-oxide minerals within a layer of aragonite crystals, displaying a branching pattern characteristic of shrubs.

**Figure 96:** Photomicrograph in plane light of iron-oxide minerals in a clotted fashion, resemble some of those described in the modern deposit.



SEM analyses of the ancient deposits do not reveal the filamentous bacterial forms that were identified in the modern deposit. Instead, the ancient deposits display aggregates of globular, sub-spherical forms that range in size from 1 to 5 microns (Figures 98, 99, and 100). These forms do resemble the amorphous iron-oxide mineral aggregates that occur on the very heavily encrusted filaments of the modern deposits, but it is unclear if these have a bacterial origin.



**Figure 98:** SEM image of amorphous iron-oxide mineral coating blades of aragonite. The straightedged crystals of aragonite display a pitted texture where in contact with the iron-oxide minerals (white arrow).

**Figure 99:** SEM image of amorphous iron-oxide minerals (red arrow) inhibited the growth of euhedral aragonite crystals (white arrow).



#### Chapter 5: SUMMARY AND CONCLUSIONS

# 5.1 Modern Crystal Geyser Travertine

The modern Crystal Geyser travertine deposit, while quite small in comparison to other carbonate accumulations, is remarkably fascinating in the diversity that it displays. This diversity is derived from the structures, constituents, and color variations seen in hand samples, as well as the microscopic features.

The travertine actively precipitating from the waters of Crystal Geyser forms a gently sloping mound with a maximum lateral extent of 85m and is no more than a few meters thick. The deposit is relatively flat-lying near the well and the geyser is surrounded by an abundance of pisoids and intraclasts. The sloping mound forms a fan-shaped splay eastward towards the Green River where a pronounced down-stepping terraced morphology develops. Terraces are covered in micro-terrace structures and rimstone pools. The travertine actively forming today is bright yellow to dark red in color, while an older section of the deposit is bleached to a light yellow color.

Cores taken from the field display a light gray travertine at depth. The sharp contact between the ochre travertine and the gray one below indicates an abrupt change in the environment, which, provided the gray travertine was actively precipitating, may represent the year when the well was drilled and the geyser water was redirected from its natural flow through the well bore. It is unclear if the precipitation of the gray travertine was active when the well was

spudded, but it has little resemblance to the ancient travertine intruding the country rock, suggesting that it may be more closely related to the active system.

The gray travertine is considerably denser than the ochre one above it, presumably from greater cementation over time. The abundance of pebble size detritus cemented within layers indicates that run-off from the hills to the west was more frequent during its time of deposition. Fenestrae are common within the gray travertine, likely representing gas pockets, although some may be molds that once were occupied by organic matter or evaporite crystals. The presence of abundant detrital material supports the conclusion that it formed at the surface and may represent a naturally occurring spring deposit, a precursor to the geyser.

The ochre travertine forms thin, platy laminations at its base (above the gray travertine) and transitions upward into repetitive couplets of red or orange laminae alternating with thinner beige laminations. The thickness of laminations, approximately 1 cm for orange or red and less than 3 mm for thin beige laminations, is consistent and may represent variations in modes of precipitation due to seasonal changes. The thicker laminations may represent warmer months when biotic activity is more abundant and aids precipitation. During winter months, water freezes on the surface of the deposit, hindering precipitation and the development of biota. Travertine sampled near the well is brittle and shatters easily. With distance, the travertine is more porous and spongy. Iron-oxide shrubs are visible in many of the samples.

# 5.1.1 Mineralogy

The deposit is composed of calcite and aragonite, with relative proportions varying throughout the deposit. Generally, calcite dominates, although aragonite concentrations are high near the well and aragonite abundances exceed calcite in some samples. Calcite concentrations increase with distance from the well and iron-rich laminations have a tendency to have more calcite content than aragonite. This may be due to the rate of precipitation and the biota present. Iron-rich laminations commonly display shrubs, which are interpreted to have a bacterial origin indicating that there must be periods of time when water remains in pools long enough for bacteria to grow. The iron-oxide minerals were not identified by XRD analysis, leading to the conclusion that they lack a crystal lattice and are amorphous.

XRD analysis of the gray travertine showed that it has much higher concentrations of calcite and lower concentrations of aragonite than the ochre travertine. This may be due to diagenetic alteration of aragonite to calcite or slower rates of precipitation favoring calcite.

# 5.1.2 Allochems

Clastic detritus and pisoids are found in abundance around the well bore and are frequently cemented into the deposit. Intraclasts, derived from the nearby ridges, may display very irregular shapes and can be as large as gravel size. Most are composed of angular to sub-rounded quartz grains cemented in

calcite, while others appear to be pieces of the ancient aragonite veins.

Pisoids may have a biotic or abiotic origin. Larger pisoids are formed abiotically, having a diameter of 6 to 9 mm and typically contain intraclasts as a nucleus, giving them an irregular shape. Smaller pisoids, having a diameter of 2 to 5 mm, can have a grain or a few separate grains for a nucleus or display a chaotic crystal orientation, in which the exact nucleus is difficult to identify. When a grain forms the nucleus, the pisoid has an abiotic origin, with crystals growing directly on the grain. When a pisoid displays a chaotic nucleus, spherulites develop biotically within the nucleus with clumps of bacteria at the center. Bladed aragonite crystals form a radial splay away from the bacterial clusters. Aragonite blades can form biotically or abiotically. Biotic aragonite blades display a clotted appearance from having encased bacteria within the crystals, whereas abiotic aragonite blades display sharp crystal edges. Bacterial influence on the formation of whole pisoids may occur by two possible mechanisms: A) a pisoid began forming around a grain or grains and bacteria further induced carbonate precipitation in the form of the spherulites, or B) the bacteria are completely responsible for the initial growth of the spherulites and the clustering together of the spherulites serves as the nucleus of the pisoid, with other miscellaneous grains sometimes getting trapped within them. The pisoid cortices are almost always formed abiotically.

The pisoids are found in close proximity to the geyser. The well-rounded nature of the pisoids suggests that they form under a considerable amount of

consistent agitation. The pool around the geyser vent is filled periodically with water and its agitation is dependent upon the magnitude of the eruption. The greatest magnitude of eruptions witnessed did not create agitation strong enough to increase turbidity (the water is clear) let alone lift and roll the pisoids in a manner that could produce the roundness. It is interpreted that due to the pisoids, close proximity to the geyser and the amount of agitation that they would require to be well-rounded, they must have formed by rolling around inside the geyser plumbing and were expelled during eruptions, similar to those described from other travertine accumulations (Chafetz and Folk, 1984).

Plants may have a minor impact on carbonate precipitation by either serving as a stable substrate, removing carbon dioxide through photosynthesis, or by bacteria growing on the plants and the bacteria inducing precipitation. Their impact is indicated by a higher density of carbonate crystals attaching to the plant material than in the immediate surroundings. Diatoms have little or no influence in the development of the travertine or the pisoids, based on their lack of abundance and the fact that they display only minor encrustation.

### 5.1.3 Carbonate Cements and Crystal Morphology

The modern deposit typically displays small, anhedral to subhedral carbonate spar, bladed, pseudo-hexagonal, or acicular crystals. Spar forms columnar crusts and occludes pore spaces, such as filling-in voids in between encrusted cyanobacterial strands. Acicular to pseudo-hexagonal aragonite

crystals frequently appear as radially splaying isopachous cements around allochems or clumps of iron-oxide, indicating that the crystals formed when pores were filled with water. Intraclasts and pisoids frequently displayed multiple coatings of carbonate and iron-oxides.

Feather crystal splays, identified growing horizontally on a steep slope face, are composed of stubby, densely packed, bundles of acicular crystals. These same bundles form feather crystal spherulites, which may represent the earliest phase of growth for the feather crystals. Feather crystals are composed of calcite. Notably, this particular slope where the feather calcite crystals occur also display much lower iron-oxide precipitates than other slopes. Field work also demonstrated that the consistency of the travertine at that particular spot is different from the rest, being very spongy with loose cohesion, rendering the ability to peel the layer off the deposit, much like a wet blanket, and lay it out to dry. When dry, this layer crumbles to dust easily and has proven difficult to transport. The controls on formation of these feather crystals are poorly understood, especially when trying to interpret why they have formed where they did as opposed to what occurs at similar locations of the deposit that should have the same chemical conditions.

#### 5.1.4 Microbially Induced Iron-oxide Shrubs

Both the modern and ancient deposits display iron-oxide shrubs. The iron-oxide minerals appear as amorphous globules in both deposits, but they encase filamentous microbes in the modern deposit and not in the ancient deposit. It is difficult to determine how great an impact microbes play in the iron-oxidation of the modern deposit, let alone the ancient one. But, the recognition that iron-oxidizing microbes are present at this location suggests that they may have influenced the ancient deposit. The lack of filamentous forms in the ancient deposit is hardly a conclusive indicator of abiotic precipitation because the filaments are very delicate and are typically not preserved. Alternatively, a completely different iron-oxidizing microbe that did not display the filamentous morphology may have been the dominant life form.

At least some of the iron-oxide minerals in the deposit, which lend the distinctive ochre color to the modern travertine deposit, are microbially induced. The iron-oxide textures strongly resemble the micro-fossil *Frutexites* and modern analogs of cultured iron-oxidized bacteria. Copious quantities of filamentous microbes, believed to be *Leptothrix Ochracea* or a similar species based on morphology, were identified in these iron-rich zones and display preferential mineralization by iron-oxides. The fact that *Leptothrix* is very abundant and common in natural water sources makes it a likely candidate for the filamentous microbes, but other life forms, such as cyanobacteria, may also be present, especially when identifying heavily mineralized filaments.

SEM images of the bacteria and their mineral precipitates resemble those

of Boyd and Scott (2001), Schieber and Glamoclija (2007), Baskar et al. (2008), Parenteau and Cady (2010), and Konhauser et al. (2011). While the filaments do resemble some forms of cyanobacteria, and cyanobacteria do require iron to sustain their metabolism, the overall morphology and general characteristics more closely match that of *Leptothrix* (Pentecost, 2003; Keren et al., 2004; Pedley et al., 2009). Cyanobacteria associated with iron microbial mats have a tendency to be larger, are not documented to leave behind copious amounts of empty extracellular sheaths absent the microbe cell (a trademark of the elusive Leptothrix Ochracea), and typically display some form of microstructure to their exterior membrane in the form of ribbing or a chain-like appearance instead of the smooth walls described here. This is not to say that the more heavily encrusted filaments cannot be cyanobacteria, especially the forms displaying diameters larger than 2 microns. It is impossible to determine if the microbes contained in heavy iron-oxide mineral encrustations have very thick coatings or if the microbes themselves have wider diameters. In addition, the structure of the cell wall would be hidden by the minerals where heavily encrusted. Bacteria and cyanobacteria could both be contributing to iron-oxidation at Crystal Geyser since the two are ready bedfellows, but *Leptothrix* or a similar bacterium seems to be the likely culprit based on the observed characteristics.

*Lepthothrix Ochracea* is the most abundant and productive during warmer months, supporting the interpretation that the alternation between the dark red shrub layers and lighter color carbonate layers reflects seasonal productivity of

the bacteria. Mineralization of the sheaths by iron-oxide greatly enhances the possibility of preserving the fossil (Schieber, 2004). Iron minerals encrusting bacteria typically appear as sub-spherical colloids or amorphous precipitates (Nelson et al., 1999; Emerson and Weiss, 2010; Schieber, 2004; Parenteau and Cady, 2010).

#### 5.2 Ancient Little Grand Wash Fault Deposits

Ancient travertine deposits occur as veins intruding the sandstone host rock to the east of the geyser and a deposit immediately adjacent and underlying the modern one. The deposit adjacent to the modern one is almost entirely composed of fan-shaped splays of aragonite crystals displaying a pristine white color, only occasionally marred by a thin band of iron-oxide. Deposits on the ridge occur capping hilltops and as spectacular veins cutting the reddish sandstone host strata. These contain a higher quantity of iron-oxide bands and re-worked pieces of the host rock, frequently displaying a convoluted appearance, likely as a result of being subjected to the stresses imposed by the fault.

The veins adjacent to the modern deposit are almost completely composed of blades of aragonite. Veins on the ridge are dominantly aragonite, with minor amounts of calcite. Like the modern deposit, the mineral composing the iron-oxide laminations could not be identified, but did produce the shrub textures resembling *Frutexites*. The filamentous iron-oxidizing microbes were not

identified in the ancient deposit. If similar bacterial deposits seen in the modern deposit were present at the time that the ancient deposits were forming, it is highly unlikely that any direct evidence could be found to conclusively support their identification. This is largely because of the delicate nature of bacteria and the polymers they leave behind, which are prone to rapid decay and destruction, leaving behind only the mineral precipitates. Primary structures created by the bacteria within the minerals are easily destroyed with compaction and further alterations brought on by the effects of time (weathering, dissolution, remineralization, etc.) only decrease the ability to conclusively identify biotic precipitates. So, while, the iron-oxide minerals in the ancient deposit may be nothing more than amorphous precipitates, they do display textures that resemble the microbial ones seen in the modern deposit.

The ancient deposits are interpreted to have precipitated from waters migrating through the Little Grand Wash Fault, whereupon approaching the surface, pressure decreased and carbon dioxide rapidly degassed, precipitating the spectacular aragonite veins.

# 5.3 Final Note

By their very nature, travertine deposits are sparsely preserved in the rock record, a shame since travertine provides a record of the exact environmental conditions at the time of deposition. This study not only investigates in detail the actively precipitating travertine of the Crystal Geyser, which in itself is unusual in the method by which it forms, but also explores the genetically-related ancient deposits of the Little Grand Wash Fault in the hope that future research may benefit in identifying and understanding these valuable sources of information.

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