Interpreting the origin and evolution of ‘karst’ features from a siliceous hydrothermal terrane: A case study from the Upper Geyser Basin in Yellowstone National Park, USA

Kevin W. Blackwood¹, Lainee A. Sanders¹, and Stacy I. Gantt-Blackwood²

¹Department of Environmental Health Science, East Central University, 1100 E. 14th Street, PMB J-4, Ada, OK 74820, USA

²Arbuckle Karst Geoscience LLC., 1100 E. 14th Street, Horace Mann: Office 127 D, Ada, OK 74820, USA

Abstract: The Upper Geyser Basin in Yellowstone National Park occurs over a siliceous hydrothermal terrane containing numerous hot springs and geysers. The pool and vent-conduit geometries of these hydrothermal features share a resemblance to conventional karst features known from other rock types, suggesting karst processes could be responsible for their origin and/or evolution. Hypogene speleogenesis is a cave-forming process in which the formation of caves is decoupled from and occurs independently of surface recharge. The geologic setting for hypogene speleogenesis typically occurs at the distal end of regional groundwater systems wherein the hydrogeology is manifested by ascending fluids and/or by geochemical interactions, and whereby the source of aggressiveness occurs at or below the water table. Applying the notion of hypogene speleogenesis, we compare with it the aspects of the hydrogeology, geochemistry, geomorphology, and geological setting of the Upper Geyser Basin to determine if this process might serve as an effective mechanism for the origin and/or evolution of these hydrothermal features. Applying karst concepts to these hydrothermal features may be significant as it could provide new insights into understanding their origin, function, and evolution.

Keywords: hypogene, speleogenesis, Yellowstone, geysers, caves

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INTRODUCTION

The Upper Geyser Basin in Yellowstone National Park (Figs 1 and 2) contains numerous hot springs and geysers with pool and vent-conduit geometries that resemble karst features such as rise pools and vertical cave entrance shafts. The development of karst features is traditionally associated with the dissolution of carbonate rocks such as limestone, dolomite, and marble, whereas the hydrothermal features in the Upper Geyser Basin occur within an amorphous opaline silica known as ‘geyserite’ (Jennings, 1971; Braunstein & Lowe, 2001). Silicate karst is documented from Africa, Australia, South America, and Europe, while caves formed within geyserite deposits are known from the Bakony Mountains in Hungary and their origin is attributed to the concurrent development of geyserite deposition and dissolution by alkaline solutions (Gunn, 2004; Eszterhas & Szentes, 2013). Amorphous silica (such

as geyserite) becomes increasingly soluble at high temperature and pH (Palmer, 2007), conditions which are common in the Upper Geyser Basin. As such, the boiling temperatures and alkaline-chloride waters of the Upper Geyser Basin is appropriate for the dissolution of geyserite and the development of caves.

The floors of many of the hot spring pools in the Upper Geyser Basin are visible and their depths can be measured, but the extent of the vent conduits remains unknown. However, exploration of the Old Faithful geyser-vent conduit using a video camera by Hutchinson et al. (1997) revealed the presence of chambers at depths of about 14 m. More recently, geophysical investigations of hydrothermal tremors at Old Faithful and Lone Star geysers have revealed the presence of large subsurface cavities laterally offset from the main geyser vents (Vandemeulebrouck et al., 2013, 2014). How these cavities and chambers formed is of interest because of the role they play in geyser function, as well as how they may evolve over-time.

Fig. 1. The Upper Geyser Basin shown within Yellowstone National Park.

Fig. 2. A satellite photograph of the Upper Geyser Basin and its associated geyser groups.

PURPOSE AND SCOPE

In this paper we investigate the formation of these hot spring pools, vent conduits, and subsurface cavities ‘through the lens’ of karst hydrogeology. This paper includes discussions of (1) the geologic setting of Yellowstone and the Upper Geyser Basin; (2) the hydrogeology of the Upper Geyser Basin and Old Faithful geyser; (3) the geochemistry of the hydrothermal fluids and sinter deposits; and (4) the geomorphology of the Upper Geyser Basin hydrothermal features. From this discussion, we compare these various characteristics of the Upper Geyser Basin thermal features with a model of cave formation known as ‘hypogene speleogenesis’. Through this approach, we present possible mechanisms by which these features form and what effect this might have on geyser function and evolution.

METHOD OF EXAMINATION

In this study we rely heavily on a review of existing literature, observations in the field through permitted off-boardwalk travel, and speculation. All off-boardwalk travel was permitted under ‘Yellowstone Research Permit YELL-2017-SCI-7094’ and was conducted primarily in the Geyser Hill Group of the Upper Geyser Basin.

We speculated in a previous review (Blackwood et al., 2016) that hypogene speleogenesis may be responsible for the development of these hydrothermal features because of the favorable hydrogeology and geochemistry. Since many hypogenic caves are diagnosed by their morphological features, only after the kinetics that formed them have ceased, most of our field surveys are focused on identifying morphological features within geysers and hot springs. This was aided with the use of distance measurement devices, underwater cameras, and FLIR infrared thermal imagery cameras. Several of the pools and vents were also mapped or sketched. The morphological features of interest in our surveys include wall and ceiling features that are indicative of formation by rising fluids. We are interested in these morphologies to see how they might compare to the literature on the hydrogeology and geochemistry within the model of hypogene speleogenesis.

Chemical measurements were also collected using multi-parameter meters with the main interest being temperature, pH, total dissolved solids, and specific conductance. These were mainly used to confirm that the pools being surveyed were (1) thermal and; (2) of the alkaline type.

We speculated that some of the deep hot spring pools might have formerly been subsurface cavities, such as the steam chambers of geysers, but became unroofed through hydrothermal explosion or collapse. Therefore, we looked for seemingly extinct geyser cones within close proximity to hot spring pools.

In this paper we will sometimes refer to vent conduits and subterranean cavities or chambers as ‘caves’. We mean this in the sense that is concerned with karst hydrogeology; such that fluids are moving through pores in a soluble solid material in which the porosity and permeability has been enhanced through dissolution to allow for turbulent flow and the mobilization of dissolved and eroded material (Ford & Williams, 2007; Palmer, 2007; Alexander, pers. comm.). Speleology involves the direct observation of caves, which would be possible if the thermal fluids were cooled to ambient temperature. However, direct observation is not currently possible within the deeper vent conduits of these boiling thermal features. Our observations during these surveys were limited by these extreme fluid conditions as well as our commitment to have as little impact as possible on these unique geological system.

HYPOGENE SPELEOGENESIS

In this study, we compare various geological characteristics of the Upper Geyser Basin thermal

features with a model of cave formation known as 'hypogene speleogenesis' to determine if and how closely these features fit within that model. Hypogene speleogenesis is a cave-forming process in which the formation of caves is decoupled from and occurs independently of surface recharge. The geologic setting for hypogene speleogenesis occurs at the distal end of regional groundwater systems wherein the hydrogeology is manifested by ascending fluids and/or by geochemical interactions, and whereby the source of aggressiveness occurs at or below the water table (Palmer, 2007; Klimchouk, 2011). The ascension of fluids is driven primarily by hydrostatic pressure from below, confined by intervening beds of low-permeability rock, or other sources of energy such as tectonics or geothermal convection. Fluid aggressiveness may occur by chemical, physical, and/or microbial processes. The resulting geomorphic expressions of hypogene speleogenesis appear as vertical fluid ascension caves and shafts, cupolas and domes, irregular rooms, and isolated chambers, typically at the distal end of regional groundwater flow systems (Klimchouk, 2011).

STUDY AREA

Yellowstone National Park encompasses an area of nearly 9,000 km² in northwestern Wyoming, with minor extensions into southern Montana and eastern Idaho (Fig. 1). The park currently sits over a mantle plume which is estimated to extend to a depth of 600 km, but may extend much deeper with depths exceeding 1,000 km (Yuan & Decker, 2005; Obrebski et al., 2011, Tian & Zhao, 2012). The underlying mantle plume has produced numerous episodes of rhyolitic-basaltic volcanic activity, throughout the Snake River Valley and Yellowstone region, as the North American plate has migrated in a southwesterly direction for approximately the last 17 million years. This hot-spot migration has resulted in three caldera-forming events within the park boundaries during the last 2.2 million years (Christiansen, 2001; Yuan & Decker, 2005; Obrebski et al., 2011). Nearly 50 post-caldera volcanic events also have been documented for the Yellowstone Caldera and are associated with two major resurgent domes known as the Mallard Lake and the Sour Creek Domes (Christiansen, 2001).

These post-caldera volcanic events, collectively known as the Plateau Rhyolite, formed the Yellowstone Plateau which produced a significant effect on the regional topography and climate (Christiansen, 2001; Pierce, 2004). The annual precipitation rate, due to orographic effects of the Plateau, is about 180 - 200 cm of precipitation per year. Previously, the Yellowstone Plateau was the site of the largest alpine glacial icecap in the western United States during the time of the Pleistocene (Yousif, 2002; Pierce, 2004). The massive glacial icecap likely had a significant effect on crustal deformation, as well as volcanic and tectonic activity of the region. Yellowstone is also one of the most seismically active areas in the Western United States with more than 44,000 earthquakes recorded and occurring at a rate of about 1,500 to

2,000 earthquakes per year since 1973 (Farrell et al., 2009).

This combination of geothermal convection, high annual precipitation rates, crustal deformation, and active seismicity has resulted in the park being the most active hydrothermal region in the world with more than 10,000 hydrothermal features (Rinehart, 1980; Fournier, 1989). Meteoric fluids percolate deep into the crust where they are heated by the underlying magma plume, become buoyed by thermal expansion, and carry dissolved solids to the surface whereupon they deposit large mounds of siliceous sinter and travertine around hot springs and geysers (Rinehart, 1980; Knauss & Wolery, 1988; Fournier, 1989; Hurwitz & Lowenstern, 2014). Travertine deposition is not associated with the alkaline-chloride waters of the principal geyser basins, but these do occur outside the Yellowstone Caldera with the greatest deposits around Mammoth Hot Springs where caves are also known to occur (Barger, 1977; Pisarowicz, 2003; Pentecost, 2005). Thermal alkaline-chloride waters, with pH values ranging from 6.7 to 9.6, are associated with all of the principal geyser basins as well as the deposition of siliceous sinter within Yellowstone National Park (White et al., 1975; Hurwitz & Lowenstern, 2014).

The Upper Geyser Basin, which is the focus of this study, encompasses an area of about seven km² within the Firehole River Basin and is underlain by fractured rhyolites of the Biscuit Basin lava flow (Bindeman & Valley, 2000). The Upper Geyser Basin contains the greatest concentration of geysers in the world, with nearly 300 of its springs known to erupt as geysers (Bryan, 2008). The lithology of the Upper Geyser Basin consists of top layer of siliceous sinter (6 m thick), glacially emplaced and consolidated gravels of rhyolite and obsidian (70 m thick) and underlain by fractured rhyolite (White et al., 1975; Rinehart, 1980). The altitude of the geyser basin is approximately 2,200 m above mean sea level, and at this altitude the boiling point of water is 94°C, and is near-neutral on the pH scale at about 6.2 (Braunstein & Lowe, 2001; Guidry & Chafetz, 2002). The main sites that are the focus of this study include Old Faithful and the Geyser Hill Group.

HYDROGEOLOGY

The hydrogeology of the Yellowstone Plateau occurs as a mostly meteoric groundwater system in which water is recharged locally from rain or snowmelt; a regional magmatic groundwater component is also present (Fournier, 1989). The contribution of the magmatic fluids to the groundwater system appears to be less than a few percent; however, the interpretation of the stable isotope compositions of the thermal fluids is difficult due to the dilution of ascending deep fluids with local meteoric waters and by subsurface boiling, resulting in the fractionation of isotopes between steam and liquid (Craig et al., 1978; Fournier, 1989). The alkaline-chloride waters are calculated to be in the range of 340 to 370°C fluids, rich in dissolved CO₂, H₂S, and with low delta deuterium values. This suggests that these fluids

probably originated from deep regional flow paths where they were either recharged from areas remote from the geyser basins or by ancient precipitation from a cooler climate period (Truesdell et al., 1977; Fournier, 1989; Rye & Truesdell, 2007).

The thermal groundwater reservoirs are recharged by high rates of precipitation (180–200 cm/year), heated by the underlying magma plume where fluids are then buoyed by thermal expansion, and ascend through an open plumbing system toward the surface to be discharged at hot springs (Rinehart, 1980; Yousif, 2002). Within geysers, the process is a bit more complicated. Hydrostatic pressure prevents the thermal groundwater from boiling, but phase change near the water table results in a reduction of hydrostatic pressure, causing the underlying groundwater to flash to steam where it may empty itself catastrophically (Rinehart, 1980). Geyser eruptions are also aided by the presence of gases, such as CO₂, which contribute to vapor pressure during boiling (Hurwitz et al., 2016; Ladd & Ryan, 2016). Geophysical investigations by Vandemeulebrouck et al. (2014) have revealed the presence of a large subsurface cavity laterally offset from the main geyser vents at both Old Faithful and Lone Star geysers, suggesting these cavities act as ‘bubble traps’ where steam generation occurs. A constriction within the Old Faithful geyser vent was detected by Hutchinson (1997) from lowering a video camera into the geyser vent constrictions appear to be another essential feature affecting geyser function within these plumbing systems.

Some geysers erupt with such regularity that their eruptions can be predicted within ranges of minutes or hours. Disruptions in intervals between eruptions are often linked to earthquakes, earth tides, and changes in barometric pressure, climate, and anthropogenic influences such as injecting alkali soaps into geyser vents (Hague, 1889; Hurwitz et al., 2008, 2014). However, at Old Faithful Geyser, these factors appear to be statistically insignificant and geyser variability may be dominated by an interaction between internal processes and interaction between other geysers (Hurwitz et al., 2014). Little is known of the reservoirs beneath the geyser basins, but geophysical investigations have revealed what appears to be a complex 200 m diameter network of fractures and cavities beneath Old Faithful Geyser, extending to the contact with the underlying rhyolite to a depth of approximately 70 m (Wu et al., 2017).

GEOCHEMISTRY

The Upper Geyser Basin is underlain by silica-rich rocks such as rhyolite, consolidated obsidian gravels, and geyserite. Rhyolite is composed of about 70% quartz, which becomes increasingly soluble with increasing temperature and increasing pH, levels off around 350°C, then declines, forming silicic acid (H₄SiO₄) (Bennett et al., 1991; Martini, 2000). Obsidian is composed of the much more soluble non-crystalline (amorphous) silica, with percent silica nearer 80. Geyserite, a massive opaline sinter, is formed when dissolved silica is precipitated during the cooling

and evaporation process around geysers and hot springs. Non-crystalline (amorphous) silica is about 20 times more soluble than quartz and comprises the uppermost cave-bearing strata of the principal geyser basins (Rinehart, 1980; Baunstein & Lowe, 2001; Guidry & Chafetz, 2002; Palmer, 2007). Geyserite is deposited around the geysers and hot springs in thin layers (several cm thick) that are relatively brittle, but may accumulate to several meters in thickness. Approximately 352,000 kg of sinter has been calculated to be deposited in Yellowstone daily (1.32 – 10 g/L) as the thermal waters cool and precipitate excess silica (Rinehart, 1980; Wood, 1986; Knauss & Wolery, 1988).

Hot water is a very potent cave forming agent (Palmer, 2009) and the groundwater beneath the geyser basins is well above the altitude boiling point due to the high hydrostatic pressures in semi-closed convection over the magma plume. Sinter deposits and clear-blue water with pH values >8 are only associated with the more alkaline springs (Rinehart, 1980; Ball et al., 1998; Braunstein & Lowe, 2001). The deep hot spring pools, vent conduits, and subsurface cavities are best known from these clear-blue waters. Brines are present at depths of 5,000 m and at temperatures of 340–370°C. Salinity increases quartz solubility and it is likely that these brines are a contributing factor in deep-seated dissolution (Rinehart, 1980).

GEOMORPHOLOGY

The geomorphology of the Upper Geyser Basin shares a resemblance to traditional karst features in carbonate rocks. Many of the hot springs resemble karst springs such as rise pools and blue hole springs (Figs. 3 and 4). The vent conduits of several geysers resemble vertical cave entrance shafts. Old Faithful contains a vent conduit that would fall into this category.

The plumbing of geysers is mostly unknown, inasmuch as it is out of view and the extreme environment is limiting to most conventional methods of inspection. Where inspected, geysers typically contain vertical vent shafts, in which water ascends and from which steam is ejected. Cameras lowered into geyser vents have revealed the presence of chambers and constrictions within these shafts,

Fig. 3. Karst spring in ambient temperature water in the Texas Hill Country.

Fig. 4. Hot spring in the Upper Geyser Basin in Yellowstone National Park.

and both appear to play an important role in geyser function (Rinehart, 1980; Hutchinson et al., 1997). Geophysical investigations utilizing seismic tomography have revealed the presence of large dome-like chambers beneath and laterally offset from the geyser vents at Old Faithful and Lone Star Geysers (Fig. 5). These chambers are formed beneath the sinter layers within the obsidian gravels and appear to play important roles in geyser function and development (Vandemeulebrouck et al., 2013, 2014). These chambers appear to be partially air-filled, allowing space for steam generation and temporary storage to occur. As such, where geyser eruptions occur in a series of thrusts rather than a single thrust, this may be an indication that the geysers contain multiple chambers and more complex plumbing systems (Rinehart, 1980; Vandemeulebrouck et al., 2013; Quammen, 2016).

Fig. 5. Conceptual graphic of the steam chamber beneath Old Faithful Geyser as interpreted from geophysical investigations modified by Justin Harris from Vandemeulebrouck et al. (2013).

FIELD SURVEY

During this study, most of our field surveys were focused on identifying morphological features within geysers and hot springs. We looked at more than 100 hydrothermal features in total in the Upper Geyser

Basin, but focused mainly on Vault Geyser, Heart Spring, Doublet Pool, Giantess, and Variable Spring; most of which are located in the Geyser Hill Group (Fig. 6). Old Faithful received considerable attention as well, but due to its iconic status, our work there was very limited. From these features, we collected a number of photographs which focused on the interior of the vent conduits and pool walls underwater. The fluid temperatures of these features ranged between 68–88°C which made further inspection of the conduits impossible. Ceiling photographs were the most difficult to collect, but several unnamed fumaroles were inspected near Dome Geyser, where their ceilings were more visible. Dimensional measurements were collected and sketches were made of each of these features. This process was comparable to standing at the entrance of a cave and making a map without actually entering.

Fig. 6. Collecting imagery of Heart Spring near the Lion Geyser Group.

RESULTS

Photographs of the ceilings of conduit vents reveal ceiling features that seem to indicate a greater amount of erosion directed at the ceilings. We interpret this as being caused by ascending thermal fluids.

Photographs of wall features showed a mix of orientations. Some wall features seemed to indicate fluid movement going up, whereas other features within the same pool seemed to indicate fluid movement going down. Direction was interpreted mainly from the orientation of rills and scallops. The long ramp of a scallop occurs on the downstream side while the short ramp occurs on the upstream side (Palmer, 2007). The orientation of scallops and rills in the walls where downward fluid movement is interpreted was inspected using FLIR infrared thermal imagery cameras. Here we noticed that the hottest thermal signatures were occurring on the sides of the pools where scallops indicate upward fluid movement and the coolest thermal signatures were occurring on the sides of the pools where scallops indicate downward fluid movement. We speculate, based on our field observations, that it's possible that the difference in scallop orientation could be attributed to the ascending and descending limbs of convection cells within these hot springs (Figs 7 and 8). However,

some of these springs are also known to function as both 'pulsing springs', in which the water level fluctuates rapidly, or as estavelles by draining surface waters (Rinehart, 1980).

The sketches of the pools and vent conduits are interesting, but do not reveal enough to provide any conclusive information at this particular site with regards to the presence of irregular rooms and isolated chambers. The sketches are more useful for noting the locations of wall and ceiling features. The presence of irregular rooms and isolated chambers is probably best revealed from seismic tomography investigations by Vandemeulebrouck (2013).

Fig. 7. Scallops and rills with a directional orientation indicative of descending fluids into a hot spring.

Fig. 8. A thermographic image of a hot spring showing the hottest water ascending in the center of the pool.

ANALYSIS AND DISCUSSION

To determine if the hydrothermal system of the Upper Geyser Basin might be hypogenic, we compare the system characteristics to the current understanding of hypogene speleogenesis (Table 1). Specifically, we review the flow direction of the thermal fluids; their potential to dissolve silica; pool, chamber, and vent conduit geometries and morphological expressions, and; the regional geologic setting. Our investigations compare accordingly.

Fluid flow direction and the resulting morphological expression

The dominant direction of these thermal fluids discharging at Yellowstone is occurring in the vertical direction as they are heated at depth and buoyed toward the surface by thermal expansion (Rinehart, 1980). Because 'upward' is the dominant direction of these fluids, the resulting morphologies interpreted within the vent conduits and subterranean cavities are indicative of modification by ascending fluids. The most obvious example of ascending fluids is the steam and water that is ejected from the geyser vents ten of meters into the air. The vertical vent conduits of the geysers could have been formed by processes such as tectonic activity, but the modification of the shafts by hot alkaline fluids ascending vertically at high speeds is obvious and undeniable.

Source of fluid aggressiveness

The corrosive agents in the siliceous materials underlying the Upper Geyser Basin are hot alkaline-chloride fluids. Since the meteoric waters that recharge the system obtain their corrosive potential below the water table, we interpret this as an appropriate mechanism which fits within the hypogenic model. The extensive deposits of siliceous sinter are an indication that dissolution is occurring within the thermal groundwater system. It is reasonable to assume that the saturation state of the fluids is in a constant flux between meteoric recharge events and the mixing with thermal fluids is resulting in the dissolution and chemical modification of hot spring pools and vent conduits. As unsaturated waters enter from the surface, mixing with the saturated thermal waters they may form an under-saturated solution with increased dissolution potential. Mixing corrosion is an effective mechanism for cave formation and is recognized as the primary mechanism for the formation of flank margin caves in carbonate rocks of the Bahamas, described by Mylroie & Mylroie in Klimchouck et al. (2017).

The subsurface cavities identified near Old Faithful and Lone Star geysers by Vandemeulebrouck et al. (2014) might also be modified by the mixing of under-saturated meteoric water, but the dome-like structure associated with the Old Faithful chamber may be the result of condensation corrosion. Condensation corrosion has been suggested as an effective mechanism of dissolution in thermal caves in the Amargosa Desert by Dublyanksy et al. (2016). Within the steam chambers of active geysers, such as the subsurface cavities at Old Faithful and Lone Star geysers, air space is known to exist where super-heated liquids flash to steam (Adelstein et al., 2014). The thermal waters within the steam chambers might be expected to be saturated with dissolved silica, but during the phase change from liquid to steam, silica will precipitate out of solution and unsaturated condensates would form on the ceiling of the steam chamber and may dissolve silica by condensation corrosion. However, if the silica that precipitates out of solution is not taken back into solution or expelled from the system during eruption, it might

Table 1. Table comparing and contrasting traditional hypogene speleogenesis to the Upper Geyser Basin of Yellowstone National Park.

	Traditional Hypogene Speleogenesis	Evidence for Hypogene Speleogenesis in the Upper Geyser Basin of Yellowstone National Park.
Geologic Setting	Occurs at the distal end of regional groundwater systems within soluble material.	Groundwater is largely part of a local meteoric system with minor contributions from regional magmatic systems. Occurs in siliceous material that becomes increasingly soluble in alkaline fluids at high temperatures.
Hydrogeology	Manifested by ascending fluids.	Groundwater is buoyed by thermal expansion over a mantle plume, ascends vertically through an open plumbing system, and is discharged at hot springs. In geysers, these fluids are discharged vertically at high velocities in the form of steam and liquid water.
Geochemistry	Source of fluid aggressiveness occurs at or below the water table.	Water is heated to well above the altitude boiling point by an underlying mantle plume. Recharging meteoric fluids increase in alkalinity while circulating within the groundwater system.
Geomorphology	Vertical fluid ascension caves and shafts, cupolas and domes, irregular rooms and isolated chambers.	Limited observations and geophysical surveys indicate the presence of vertical fluid ascension caves and shafts, cupolas and domes, and what appear to be irregular rooms, and isolated chambers.

accumulate within the geyser plumbing and clog the system. If unsaturated waters are able to return to the system, as have been observed in video footage within Old Faithful geyser (Hutchinson et al., 1997), they might mix with the saturated thermal fluids within the steam chambers to form an under-saturated solution to dissolve precipitates of silica and prevent accumulation and clogging within the system.

The development of the steam chamber at Old Faithful by condensation corrosion could be significant in the function and evolution of the geyser. As the chamber expands, it may require more steam to fill it and more time to fill it with steam. We speculate that this could be partly responsible for the increasing intervals between eruptions since the 1950's. According to Hurwitz et al. (2014), the intervals between do not appear to be affected by barometric pressure, earth tides, or earthquakes in any statistical significance. However, a few very large earthquakes did have an effect on eruption intervals. Hurwitz also noted that the response of intervals between eruptions to external forces is relatively small and geyser variability may be dominated by an interaction between internal processes and interaction between other geysers. We further speculate that if the chamber breaches the surface, it might result in the formation of a deep hot spring pool; suggesting that some hot spring pools could share a similar origin and may be related to extinct geysers. We investigated this hypothesis and located a suspicious feature in the Lion Geyser Group near Heart Spring, but due to burial by sinter from neighboring geysers, we could not make a conclusive determination without a damaging and invasive excavation. A similar feature was located in the Norris Geyser Basin in a separate but similar study by the authors (Blackwood et al., 2017).

Due to the hydrogeological and geochemical characteristics, the geomorphology of many of the hydrothermal features within the Upper Geyser Basin share a resemblance to karst features known in carbonate rocks. The presence of irregular rooms and isolated chambers was more difficult to determine from our limited observation point. Here we rely mainly on

an interpretation of subsurface cavities detected using seismic tomography by Vandemeulembrouck (2013). However, the surveys conducted of wall and ceiling features within hot springs and geysers indicates a strong ascending component with a resemblance to common hypogene cave morphologies (Klimchouck et al., 2014, 2017).

Recharge and Setting

The only characteristic of this hydrothermal system that does not fit neatly within the hypogenic model is that of the mode of recharge within the geologic setting. The traditional model for hypogene speleogenesis requires that the groundwater be part of a regional system, but the fluids in the Upper Geyser Basin appear to be part of a predominantly local meteoric circulation with only a minor contribution from regional magmatic sources. However, we do not think the criteria for a regional system is as necessary here at Yellowstone as it is in the traditional hypogenic karst regions. The geologic setting for hypogene speleogenesis occurs at the distal end of regional groundwater systems wherein the hydrogeology is manifested by ascending fluids and/or by geochemical interactions and whereby the source of aggressiveness occurs at or below the water table" (Klimchouk, 2011). In the traditional model, it is necessary that the fluids be decoupled from local surface recharge because the dominant direction of those fluids is downward. Hypogene speleogenesis relies heavily on the hydrogeological mechanism of ascending fluids, typically driven by hydrostatic pressure, to produce the classic hypogene morphologies, which occurs at the distal ends of regional groundwater systems. However, because the fluids at Yellowstone are rising above a mantle plume by thermal expansion, we argue that the regional setting is irrelevant because the mechanism of ascending fluids is occurring locally and allowing the hypogene morphologies to dominate and express themselves. A similar argument is made by Mylroie & Mylroie in Klimchouck et al. (2017) with regards to flank margin caves in the Bahamas as hypogenic caves.

SUMMARY

Based on the strong similarities in hydrogeology and geochemistry, with supporting interpretations of the geomorphology; many of the hydrothermal features of the Upper Geyser Basin fit neatly into the model of hypogene speleogenesis as the process responsible for the formation of the deep hot spring pools, vent conduits, and subsurface cavities and chambers.

The regional setting is not consistent with the traditional model of hypogene speleogenesis which relies on the ascension of fluids by hydrostatic pressure. However, the vertical integration through an open plumbing system situated over a mantle plume may make the regional setting unnecessary at this location. Upon entering the subsurface, the meteoric waters are mixed with alkaline thermal fluids which increase the dissolution potential. Since these hydrothermal features depend mainly on rising alkaline fluids and heat derived from depth, their origin and evolution can be attributed to hypogene speleogenesis or to the modification by hypogenic overprinting.

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