Lithofacies and Microfacies of a Fossil Hot Spring System: McGinness Hills, Nevada

Bonnie Jean Ertel

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LITHOFACIES AND MICROFACIES OF A FOSSIL HOT SPRING SYSTEM,
MCGINNESS HILLS, NEVADA

By
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Bachelor of Arts, Geology, University of Montana, Missoula, MT, 1992

Thesis

presented in partial fulfillment of the requirements
for the degree of

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in Geology, The University of Montana
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Perry Brown, Associate Provost for Graduate Education
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Geosciences
Microfacies and Morphology of a Fossil Hot Spring System, McGinness Hills, Nevada

Chairperson or Co-Chairperson: Dr. Nancy Hinman

The Miocene McGinness Hills sinters are a well-preserved, fossil hot spring system in Nevada. The sinter in McGinness Hills is comparable with the fossil hot spring system in the Drummond Basin, Queensland, Australia (Walter et al., 1996), Artist Point in Yellowstone National Park (Hinman and Walter, 2005) and with modern systems in Yellowstone. The purpose of this study was to further our understanding microfacies preserved in hot springs systems after diagenesis, thus facilitating the identification of epithermal systems in which exposure is limited. It is possible to recognize a range of paleo-hot spring environments from near-vent stratiform geyserite, outflow channels and terraces and distal marsh facies. McGinness Hills is a ‘decapitated’ system in which hydrothermal, eruption breccia is exposed on top of the sinter mound. Based on lithology, macro-features and micro-features the sinter at McGinness Hills was divided into seven microfacies, hydrothermal breccia, massive chalcedonic sinter, flat-laminated sinter, stromatolitic sinter, palisade sinter, palisade sinter, sinter breccia and marsh sinter. The microfacies followed a general bulls-eye pattern with hydrothermal breccia and massive chalcedonic sinter in the center, grading out to the opaline, low temperature marsh facies. Hydrothermal eruption breccia is normally a subsurface feature confined within the throat of the geyser (Browne and Lawless, 2001) hence the breccia at McGinness Hills provides a glimpse into the inner workings of a geyser.
ACKNOWLEDGEMENTS

This work was funded by the Montana Space Grant Consortium, Montana NASA-EPSCoR, and the Geology Department at the University of Montana. I would like to thank Dr. Nancy Hinman for all the help and input she provided. I would also like to thank my field assistants, Bryan Vallett, Francis Hemmah, and Ginger Hemmah for all the encouragement she provided. Lastly, but not least of all I would like to thank my husband, Robert Arfsten for all his patience and support.
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I. INTRODUCTION

Thermal springs are found early in the geologic record. Such occurrences are associated with some of the earliest fossilized evidence of microbial life and hence, thermal springs have been proposed as a locus for the emergence of life on early Earth (Walter and Des Marais 1993). The transfer of biological information from active to ancient springs involves several steps. Through these steps, biological information can be lost by chemical and physical processes, leaving only textural information and lithological relationships. Of the numerous examples of modern thermal springs and their ancient counterparts, few are found at an intermediate stage of preservation.

Hinman and Walter (2005) studied Artist Point, a volcaniclastic deposit, in Yellowstone National Park, WY, report the presence of chalcedonic sinter clasts that show excellent textural preservation but totally lack biological remnants. Sinter clasts exhibit a wide range of textures and are divided into nine microfacies based on their physical characteristics. Such microfacies represent different depositional environments within the hot spring system. The differences in preservation are attributed to different post-depositional histories. In the Yellowstone site, the sinters were probably located on the shores of a former lake. Both subaqueous and subaerial, volcaniclastic flows flooded the lake and the adjacent sinters. The water saturated flow ripped up and transported the sinters, heating them, thus promoting silica diagenesis and burning the organic matter. The sinters of Steamboat Springs, NV, were apparently preserved when an andesitic basalt flow capped the system (Hinman and Walter, 2005).

Devonian sinters within the Drummond Basin, Queensland, Australia Walter et al., 1996, 1998) have similar lithofacies to those of Artist Point. The Drummond Basin
sinters were discovered in the course of exploration for epithermal gold deposits and have been documented by Cunneen and Sillitoe (1989) and Walter et al (1996), and Walter et al (1998). The sinters are hosted by and interbedded with volcaniclastic sediments and sandstone (Cunneen and Sillitoe, 1989; Walter et al. 1996). The post-depositional history presumably had been that of burial within high-temperature volcanic rocks thus providing for rapid diagenesis. The Umukuri sinters studied by Campbell et al (2001) are partially overlain by rhyolitic sands along with approximately 3 meters of Taupo Ash and are interbedded with silicified tuff (Campbell et al. 2001).

Hinman (1995) reports an intermediate degree of diagenesis at a siliceous sinter, Mortar Geyser, Yellowstone National Park, in which some biological material is preserved. The deposit is much younger than the others and is, in fact, cross-cut by an active spring. Presumably this sinter will progress to a higher diagenetic stage, even without the volcanic events that preserved the other two intermediate sinters and would, therefore, represent a normal diagenetic sequence.

It is likely that the sequence of events during early diagenesis has a major effect on the quality of information preserved in the material. The three deposits summarized on Tables 1-4 represent microfacies in four different preservational sequences.

Herein, we describe a siliceous sinter at McGinness Hills, Nevada that progresses from the Mortar Geyser, or non-volcanic, preservational sequence. The field relationships, mineralogical and petrographic characteristics of the sinter, and physical analogues are described.
Table 1: Microfacies reported at Artist Point, Yellowstone National Park, (Hinman and Walter, 2005)

<table>
<thead>
<tr>
<th>Microfacies</th>
<th>Distinguishing Features</th>
<th>Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mound Armor</td>
<td>Chert, well-developed, thinly laminated bedding, 1-2 mm surficial cracks and ripples.</td>
<td>Near-vent, sheet flow.</td>
</tr>
<tr>
<td>Stratiform geyserite</td>
<td>Chert, well-developed, thick bedding, 10-50 cm, surficial cracks and ripples.</td>
<td>near-vent, catchment.</td>
</tr>
<tr>
<td>Streamer Fabric</td>
<td>Chert, well developed, thin-laminated, 1-2 mm, filament ghosts.</td>
<td>Microbial mats in briskly-flowing water</td>
</tr>
<tr>
<td>Columnar Stromatolite</td>
<td>Chert, poorly to well-developed beds, 3-5 mm, vertical fenestae, netting, spikes, ridges, filament ghosts.</td>
<td>Microbial mats in gently flowing to stagnant water.</td>
</tr>
<tr>
<td>Columnar Geyserite with Net Fabrics</td>
<td>Chert, well-developed, thin bedding, 0.5-1 cm, surficial domes.</td>
<td>Microbial mats in gently flowing to stagnant water.</td>
</tr>
<tr>
<td>Generic Columnar Stromatolite</td>
<td>Chert, inconsistent bedding columns &lt; 12 cm, vertical fenestrae, surficial column tops.</td>
<td>Subaerial, intermittently damp.</td>
</tr>
<tr>
<td>Spicular Geyserite</td>
<td>Chert, hemispheric bedding, 1-3 cm, surficial rounding.</td>
<td>Near-vent, splash zones.</td>
</tr>
</tbody>
</table>

Table 2: Microfacies reported at Steamboat Springs, Nevada (*Lynne et al, 2008; Hinman and Walter, 1996)

<table>
<thead>
<tr>
<th>Microfacies</th>
<th>Distinguishing Features</th>
<th>Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>*Fragmental Sinter</td>
<td>Sub-rounded to sub-angular fragments, &lt;5-30 mm, porous, indurated, grey and pink matrix.</td>
<td>NA</td>
</tr>
<tr>
<td>*Fine-grained, no fragments</td>
<td>Fine-grained horizons, brown to orange.</td>
<td>NA</td>
</tr>
<tr>
<td>*Diatomaceous Sinter</td>
<td>Fine-grained, soft/powdery, cream to pink.</td>
<td>NA</td>
</tr>
<tr>
<td>*Laminated</td>
<td>Undulating vitreous laminae, brown/orange/grey.</td>
<td>NA</td>
</tr>
<tr>
<td>*Quartzose</td>
<td>Massive, white, vitreous quartz.</td>
<td>NA</td>
</tr>
<tr>
<td>*Tuffaceous</td>
<td>Fine-grained horizons, no fragments, light brown.</td>
<td>NA</td>
</tr>
<tr>
<td>*Oncoidal</td>
<td>Well-rounded oncoids, vitreous matrix, grey to white.</td>
<td>NA</td>
</tr>
<tr>
<td>*Breccia</td>
<td>Sub-rounded fragments, cross-cutting veins infilled with sinter, strong orange color.</td>
<td>Autobrecciation.</td>
</tr>
<tr>
<td>*Massive/mottled</td>
<td>Indurated, translucent, vitreous sinter.</td>
<td>NA</td>
</tr>
<tr>
<td>**Streamer Fabric</td>
<td>Chert, thin laminated, filament ghosts.</td>
<td>Microbial mats in briskly flowing water.</td>
</tr>
<tr>
<td>**Strataform Stromatolite</td>
<td>Chert, thin laminated, low dome structures, orange stain between laminae.</td>
<td>Microbial mats in gently-flowing to stagnant water.</td>
</tr>
<tr>
<td>**Generic Columnar Stromatolite</td>
<td>Inconsistant bedding, columns, vertical fenestrae.</td>
<td>Subaerial, intermittently damp.</td>
</tr>
</tbody>
</table>
### Table 3: Microfacies reported at Drummond Basin (Walter et al 1996, 1998)

<table>
<thead>
<tr>
<th>Microfacies</th>
<th>Distinguishing Features</th>
<th>Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Massive/mottled/diffusely layered</td>
<td>Subhorizontal laminae, cm-sized vugs and drusy quartz.</td>
<td>NA</td>
</tr>
<tr>
<td>Brecciated</td>
<td>Angular clasts cemented by microgranular quartz associated with massive facies.</td>
<td>NA</td>
</tr>
<tr>
<td>Spicular</td>
<td>Coarsely botyoidal bedform with fan-like, straight, cylindrical features.</td>
<td>Hot, near-vent, splash zones, flowing water</td>
</tr>
<tr>
<td>Oolitic/Pisolitic</td>
<td>Ooids and coated grains in chert.</td>
<td>Turbulent, shallow pools near geyser or spring vents.</td>
</tr>
<tr>
<td>Thin-flat Bedded</td>
<td>White chert with thick, flat, featureless laminae (rare).</td>
<td>Subaqueous, high-temperature geysrite.</td>
</tr>
<tr>
<td>Thin-bedded with Streamers and Fenestrae</td>
<td>Finely-laminated chert, wavy, lenticular beds, elongate filamentous forms.</td>
<td>Filamentous organisms/cyanobacteria <em>Phormidium</em>.</td>
</tr>
<tr>
<td>Thin-bedded with Palisade Bedding</td>
<td>Linear features <em>parallel</em> to bedding.</td>
<td>Sheet-flow in water &lt; few mm-deep, <em>Calothrix</em>.</td>
</tr>
<tr>
<td>Thin-bedded with Pustular Laminae</td>
<td>Large, bushy palisade, &quot;pseudocolumnar stromatolites&quot;.</td>
<td>Shallow ponds, coarsely filamentous <em>Calothrix</em>.</td>
</tr>
<tr>
<td>Thin-bedded with Conical Laminae</td>
<td>Thin-bedded with upward-directed conical features.</td>
<td>Cyanobacterium, <em>Phormidium</em>.</td>
</tr>
<tr>
<td>Thin-bedded with Lycopsids</td>
<td>Thin-bedded chert with silicified stems/molds lying on bedding planes.</td>
<td>Interfluves between channel-ways.</td>
</tr>
<tr>
<td>Encrusted Lycopsids</td>
<td>Irregular, vuggy chert, variously orientated plant stems.</td>
<td>Brush/trees in growth positions engulfed by newly-formed ponds.</td>
</tr>
<tr>
<td>Interclast Grainstone*</td>
<td>Tabular interclasts scattered through thin-bedded sinter (rare).</td>
<td>Breaking of sinter beds through freeze/thaw and trampling by animals. *Dominant feature in modern springs.</td>
</tr>
</tbody>
</table>

### Table 4: Microfacies reported for Umukuri Sinters (Campbell, 2001)

<table>
<thead>
<tr>
<th>Microfacies</th>
<th>Distinguishing Features</th>
<th>Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Palisade</td>
<td>Silicified, erect, fibrous micropillars in horizontally-stacked layers</td>
<td>Low temperature, <em>Calothrix</em>.</td>
</tr>
<tr>
<td>Thinly Laminated</td>
<td>Continuous layers of somewhat undulose, parallel layers</td>
<td><em>Calothrix</em> sheet flow conditions</td>
</tr>
<tr>
<td>Wavy Laminated</td>
<td>Wavy-laminated to tufted, alternating vitreous and porous sinter</td>
<td><em>Phormidium</em>, gas bubble blisters within mats</td>
</tr>
<tr>
<td>Curved Laminae with Lenticular Voids</td>
<td>Smooth, vitreous, silica layers, open voids</td>
<td>Silicified microbial mats, gas from microbial activity</td>
</tr>
<tr>
<td>Clotted</td>
<td>Fine-grained, spheroidal clots of silica</td>
<td>Marsh-like setting marginal to hot spring apron terrace</td>
</tr>
<tr>
<td>Plant-rich</td>
<td>Silicified plant matter</td>
<td>Mid- to low-temperature region of the thermal spring gradient</td>
</tr>
<tr>
<td>Peloidal</td>
<td>Layers and discontinuous lenses of closely-packed, elliptical grains</td>
<td>Cooler, sinter apron</td>
</tr>
<tr>
<td>Pisoidal</td>
<td>Irregular, angular to subrounded grains containing nuclei of fragments</td>
<td>Active, apron terraces</td>
</tr>
<tr>
<td>Breccia</td>
<td>Sinter clasts in matrix</td>
<td>Fragmented, dry sinter</td>
</tr>
</tbody>
</table>
II. McGINNESS HILLS

Location

McGinness Hills are located in Lander County, NV, approximately 19-km northeast of Austin, NV, on the northeastern flank of the Toiyabe Range (Figure 1). Access is via State Route 21, an unimproved gravel road west of the study site. The hills are low to moderate in relief and elevations ranging from 1991 meters along the eastern drainage to 2152 meters at the McGinness Hills VABM station atop the main sinter mound (Figure 1). The climate is arid with annual precipitation averaging 0.36 meters. Primary vegetation is sage brush and prairie grass.

Figure 1: Location map for McGinness Hills.

Previous Geologic Work

Stewart and McKee (1968) mapped the geology and mineral deposits of Lander County at a scale of 1:62,000. Early Cambrian to Holocene sedimentary, igneous and metamorphic rocks are exposed in Lander County. Triassic and Paleozoic strata are cut by Jurassic and Cretaceous igneous rocks which occur scattered throughout Lander County. The largest of these is the Austin pluton which covers an area of about 96 km² approximately 16 km southwest of McGinness
Hills (Stewart and McKee 1968). The region is characterized by basin and range structures, which consist of block-faulted mountain ranges, about 24 km apart trending north-northeast (Stewart and McKee 1968).

Wendell (1985) completed a Master’s thesis on the geology and mineralization of McGinness Hills. He mapped the entire McGinness Hills area and worked out the stratigraphy of the Tertiary volcanic and sedimentary strata and alteration assemblages (Figure 2). Results from this work will be discussed in more detail below.

**Regional Geology**

The Toiyabe Range, south of McGinness Hills is the result of Basin and Range faulting during the Tertiary. Paleozoic strata referred to as the Eastern carbonate and Western siliceous assemblages underlie them. The Western assemblage moved over the Eastern assemblage along the Roberts Mountain thrust during Late Devonian and Early Mississippian Antler Orogeny (Stewart and McKee, 1968; Wendell, 1985).

The granitic Austin pluton intrudes Paleozoic strata to the southwest and north of McGinness Hills. Age dating based on K-Ar give dates of 161 +/- 3 m.y. and 172 +/- 3 7 m.y. for the Austin pluton (Silberman and McKee, 1971; Wendell, 1985).

Tertiary volcanics are the next younger rocks in the region surrounding McGinness Hills. They crop out in Grass Valley directly east of there (Wendell, 1985) and consist mostly of rhyolite ash-flow tuffs, andesite flows and intrusives (Wendell, 1985). K-Ar dates range from 37 to 26 m.y. for those volcanic rocks (Stewart and McKee, 1968; Stewart et al., 1967; Wendell, 1985). Basin and range structures probably began to develop during late Miocene to early Pliocene and continue to be active today.
(Stewart and McKee, 1968). It is during this time period that the siliceous sinters of McGinness Hills formed.

Figure 2: Geologic map of McGinness Hills by Wendell (2005).
Stratigraphy

Ordovician Rocks: The Valmy Formation, a gray orthoquartzite crops out on the west side of the study area (Wendell, 1985). At McGinness Hills, it is locally brecciated and cut by veinlets of chalcedony and minor pyrite (Casaceli et al., 1986). The quartzite is found as xenoliths in Tertiary volcanics (Wendell, 1985) and as clasts in breccia associated with sinter.

Tertiary Rocks

Andesite and Dacite: The oldest volcanic rocks present in McGinness Hills are andesite and dacite (Stewart et al., 1977; Wendell, 1985). This rock has yielded K-Ar dates of 36.3 +/- 1.1 m.y. and 35.4 +/- 1.0 m.y. (McKee and Silberman, 1970; Casaceli et al., 1986). The andesite is dark gray to black with a porphyritic texture. It consists of agglomerates, flows and flow breccias, probable dike rock and minor sedimentary units. The thickness of this unit is estimated to be 152-305 meters (Wendell, 1985).

Bates Mountain Tuff: The Bates Mountain tuff unconformably overlies the andesite and is locally separated from it by several meters of alluvial pebbles and cobbles of chert and quartzite. It is a 61 to 91 m thick sequence of rhyolitic ash-flow tuff that comprises four distinct cooling units (Wendell, 1985; Casaceli et al., 1986). The thickness and distribution of this unit is variable because of irregularities in the paleotopography. K-Ar dates for the Bates Mountain tuff range from 24.7 +/- 1.0 m.y. to 22.1 +/- 0.9 m.y. (Stewart et al., 1977).

Tertiary Alluvium: Tertiary alluvium consists of abundant pebbles and cobbles of chert and quartzite that have been locally altered and silicified by thermal waters (Wendell, 1985). It is locally cut by intrusive breccias and chalcedonic veins derived from hydrothermal fluids (Casaceli et al., 1986).
Sinter: The sinter located in the southern portion of McGinness Hills is up to 24 meters thick, and thins toward the edge of the sinter mounds. It lies directly on top of and interbedded with Tertiary alluvium and is locally in contact with tuff (Casaceli et al., 1986; Wendell, 1985). The sinter consists of massive to laminated chalcedony, opaline sinter and silicified breccia.

Alteration
Alteration assemblages indicate that the two distinct types of hydrothermal activity took place as separate times in the northern and southern parts of McGinness Hills (Wendell, 1985) (Figure 3). A northwest-trending normal fault, dipping to the southwest marks the division between the two alteration zones. Minerals present within each zone suggest that two chemically different hydrothermal fluids were responsible for the alteration (Casaceli et al., 1986). Timing of alteration indicated by K-Ar dating are 34.8 +/- 1.7 m.y. for the northern zone and 2.2 +/- 0.4 m.y. to 3.2 +/- 0.4 m.y. for the southern zone in which the sinter mounds are located.

Circulating fluids in the northern zone were strongly acidic and sulfate-rich resulting in quartz-alunite, illitic, and advanced argillic alteration. Illitic alteration grades laterally to the east and vertically at depth into an argillic-dominant alteration assemblage that consists of kaolinite and minor illite, alunite, cristobalite and pyrite (Casaceli et al., 1986). These mineral assemblages indicate this was an environment of low temperature and moderate depth.

Juxtaposed against that system was the younger geothermal system of the southern zone characterized by K-feldspar, argillic and silica alteration controlled by
north-northeastern trending structures (Wendell, 1985). Fluids were primarily alkaline and sulfate-poor which resulted in quartz-adularia mineral assemblages. Mineral assemblages indicate that this was an environment of low temperature (300ºC) and shallow depth. Evidence for high fluid flow includes intense silicification of surrounding host rocks and feeder zones, intensely silicified hydrothermal breccia and massive, dense chalcedony at the surface (Casaceli et al., 1986). Alteration minerals in the southern zone include quartz, K-feldspar and minor illite. Pyrite occurs in the lowermost tuff and the andesite. Adularia occurs as layers with banded quartz veins in volcanic rock and replacement of tuff in zones of intense silicification. It also occurs near quartz veins and structural feeder zones (Casaceli et al., 1986).
Figure 3: Alteration map of McGinness Hills by Wendell (2005).
III. METHODS

Field mapping at McGinness Hills was done on a 1:2400 scale topographic map by doing radial traverses from known points using a tape and a Brunton compass. Samples were taken along the traverses, and the locations were recorded.

The base map consists of five lithofacies obtained from field observations. These were based on rock type, degree of silicification, and the presence or lack of bedding. Samples were cut and many were polished allowing macro-features to be described and categorized. Thin section analysis was done on a Zeiss petrographic microscope using plane and crossed-polarized light. These were categorized and correlated with the macro-features to obtain microfacies categorizations.

X-Ray diffraction (XRD) analyses were run using an Philips XRG 3100 X Ray Generator. The patterns were run from 10-45 degrees. Scanning was done in steps of 0.1 degrees for 15 seconds. Data from XRD analysis were correlated with macro- and micro-features. Patterns matched to JCPDS files. Mineral determinations were based on work done by Lynne et al (2007), a study tracking crystallinity in siliceous hot springs.
IV. FIELD OBSERVATIONS

The two sinter mounds at McGinness Hills are gently sloping hills with 42 meters relief on the largest hill, herein referred to as the Main Mound, and 18 meters relief for the smaller mound, referred to as the Southeast Mound (Figure 4). Scattered on the flanks of these mounds are what look to be remnants of smaller satellite vents. The sinter at McGinness Hills is of two dominant lithologies: chalcedonic and opaline.

The chalcedonic sinter type is either massive to crudely bedded or medium to thinly laminated. Opaline sinter is rubbly, porous or spongy in texture, and rarely occurs in outcrop except in disturbed areas and prospect pits. Sinter types are distributed in a rough bull’s eye pattern with dense chalcedony in the center of both mounds surrounded by laminated chalcedonic and opaline sinter (Walter, 1976).

Figure 4: Photograph of McGinness Hills, looking northeast.
Satellite vents appear as isolated outcrops of dense chalcedonic and opaline sinter. Lithology distributions of the satellite vents generally display the same pattern as the Main Mound although many contacts are questionable due to lack of outcrop. Gray, silicified, hydrothermal breccia is associated with the two sinter mounds. Breccia of the Southeast Mound lies stratigraphically below the sinter while in the Main Mound it occurs in the center where it is surrounded by dense chalcedonic sinter.

Volcanic tuff and andesite surround the sinter mounds. The contact between the sinter and volcanics is obscured and little field evidence was found to determine age relationships. Most bedding is nearly horizontal to slightly dipping (1 – 5 degrees) although locally dips as great as 45 degrees are found sloping away from the mound. It is on these surfaces where evidence of microbial communities was expected. The three main types of sinter that were mapped are described. They are further subdivided by bedding features of each (Figure 5).

**Hydrothermal Breccia**

Hydrothermal breccia is predominantly gray, matrix-supported material with angular to subangular clasts of black or gray chert and gray quartzite with minor amounts of volcanic rock and buff-colored banded chert. Clast sizes range from 1 mm to several cms in diameter.

**Dense Chalcedony**

Dense chalcedonic sinter is massive to crudely bedded, white to gray fine quartz with a vitreous luster and occurs predominantly on the central tops of the sinter mound. Sedimentary features are faint and overprinted by silicification on fresh surfaces and are most visible on weathered surfaces. Outcrops commonly have a rounded appearance
displaying a cauliflower shape or occur in thick, broken, tabular boulders. Brown and gray patches in the chalcedony occur both randomly and along bedding planes and are most common near weathered surfaces. Porosity within the rock increases and bedding becomes more pronounced distal from and downward on the mound.
**Laminated Sinter**

Laminated sinter comprises both flat, parallel laminations and wavy, stromatolitic beds with the flat laminated sinter occurring at the top of the mound and stromatolitic sinter occurring distal from the center. The rocks become more opaline outward from both mounds, sedimentary structures are more pronounced and porosity between bedding planes increase. In sinter that is more opaline, bedding plane partings increase and sedimentary features are more pronounced.

**Opaline Sinter**

Opaline sinter is predominantly found distal and surrounding outcrops of chalcedonic rock (Figure 5). It is creamy white, pink or gray in color with a waxy luster and of a lower density than that of chalcedony. Red and green-stained opal is found locally. The rock is generally porous and friable, but locally is glassy and massive. Outcrops are rare as opaline sinter is not well-lithified and is less resistant to erosion than is chalcedonic sinter. Textures and fossils in opaline sinter however, are usually well preserved. The dominant bedding feature exhibited is that of fragments of opaline sinter weakly cemented by opaline quartz although undulating to stromatolitic bedding is also present. Details on these textures will be presented below.

**Volcanic Rocks**

Volcanic rocks surrounding the sinter mounds at McGinness Hills have a variety of lithologies. They consist of primarily light colored tuff that is either massive, vesicular or in breccia form, and of andesite. Some tuff displays reddish pink or green hues and locally the tuff is silicified to opal. Brecciated tuff frequently contains angular
chalcedonic clasts resembling sinter indicating tuff deposition may have been simultaneous with sinter formation.

**Quaternary Alluvium**

Loose, incoherent debris found on hill slopes is referred to as colluvium. It contains are small rock fragments most likely derived from the hill slope above and other rocks of unknown origin.
V. MICROFACIES OF MCGINNESS HILLS

Overall Distribution

The McGinness Hills sinter texture classification was based on the hot spring bulls-eye facies model of Walter (1976) that shows the highest temperature facies as the locus and the lower-temperature facies away from the vent (Figure 6).

Subaqueous hot springs support a wide variety of biological communities that occur along temperature gradients controlled by proximity to hot pool or geyser vent (Walter et al, 1998). Within these zones there are a broad spectrum of bacteria and Archaea (Ward et al, 1992). Bacteria are known to exist in water temperatures as high as 92-100°C. These have been shown to form microscopic biofilms that contribute to the microstructural development of subaerial geyserite by providing a filamentous substrate for the precipitation of opal (Cady and Farmer, 1996). Table 5 summarizes the bacterial colonies occurring along the temperature gradient moving away from the vent.

Figure 6: Schematic drawing illustrating biological facies within a modern hot spring, drawn from (Walter, 1976).
<table>
<thead>
<tr>
<th>Environment</th>
<th>Temp.</th>
<th>Bacteria</th>
<th>Distinguishing Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geyser effluent, rims of hot pools.</td>
<td>92-100 C</td>
<td>Unknown</td>
<td>geyserite domes.</td>
</tr>
<tr>
<td>Occurs within stratiform geyserite.</td>
<td>75-85 C</td>
<td>Unknown</td>
<td>Irregular depressions, mat-free sinter.</td>
</tr>
<tr>
<td>Overflow channels, several meters from vent.</td>
<td>57-74 C</td>
<td><em>Chloroflexus aurantiacus</em></td>
<td>Laminated, stratiform.</td>
</tr>
<tr>
<td>Outflow channels, terrace ponds.</td>
<td>30-59 C</td>
<td><em>Phormidium</em></td>
<td>Stromatolitic, preferred filament</td>
</tr>
<tr>
<td></td>
<td>&lt;30 C</td>
<td><em>Calothrix</em></td>
<td>Stratiform, flet-like sheets, vertical</td>
</tr>
</tbody>
</table>

There were seven microfacies mapped at McGinness Hills (Figure 7). Microfacies were classified using field observations, hand sample identification, and thin section analysis. Silica phases were determined via XRD. Mineral determinations were based on work done by (Lynne et al, 2007). The distribution of the microfacies identified at McGinness Hills is shown on Figure 7. Many of the exposures were rubbly preventing the precise determination of microfacies. These areas are marked as ‘Undetermined’. Fragmental and stromatolitic sinter is the most abundant microfacies identified at McGinness Hills. The general distribution is gradational with vent breccia, massive chalcedony and flat laminated occurring at the top or in the center and stromatolitic, palisade, sinter breccia and marsh occurring distally. Petrographic distributions also follow the same outward pattern with chert/chalcedony occurring at the top of the mound. The sinter becomes opaline distally.
Figure 7: Microfacies map of McGinness Hills.
Hydrothermal Breccia

**Distribution:** The breccia body associated with the Main Mound is elongate in a north-south direction. It is found on the central top of the mound surrounded by massive chalcedonic sinter. Contact with the sinter is undulatory with a semi-gradational to sharp transition zone. The hydrothermal breccia associated with the Southeast Mound lies stratigraphically below the sinter and wraps around the south and west flanks of the mound. The breccia bodies associated with both mounds appear similar though upon closer inspection, it is evident that the breccias are different in clast size and matrix composition and in relationship to the surrounding sinter.

*Main Mound Breccia:* In hand sample the breccia is silicified, gray and matrix-supported with angular to subangular, 0.1 to 3.0 cm-sized clasts of black, gray and minor brown chert, gray quartzite and buff-colored banded chert (Figure 8). Locally black or gray chert is incorporated as clasts within the banded chert. Isolated rounded clasts are associated with the banded chert. These clasts show concentric weathering rings and porous siliceous material displays a wavy, stromatolitic texture. Most of the breccia is massive with little indication of bedding or flow banding and appears to have been reworked. The clast to matrix ratio is small in most breccia samples. Matrix composition ranges from a silicified mud comprised of small fragments of clast material to a dense opal or chert.
Southeast Mound

Breccia: In hand sample this breccia is massive, gray and matrix-to clast-supported with a high clast to matrix ratio (Figure 9). The matrix is composed of shiny to chalky, white opal and minor gray chert. Clasts are angular to rounded with sizes ranging from 1 mm to 30 cm in diameter with most falling in the range of 1-5 cm. The largest clasts are rounded and are found on the southwest flank of the mound where the breccia looks alluvial. The breccia/sinter contact is gradational over 0.5 vertical meters (Figure 10). Breccia below the contact is chalky, white, massive, and matrix-supported with subangular clasts. The contact zone is marked by white, porous sinter-like rock in which isolated small (< 1 cm) clasts of black chert are incorporated. Dense chalcedonic sinter lies directly above this zone (Figure 10).

Micro-features: No thin sections were made from samples comprised of hydrothermal breccia.
**Petrography:** Quartz was silica phase present in the breccia associated with the Main Mound. XRD analysis was run on samples representative of the clasts and matrix comprising the Southeast Mound breccia. Samples were also run testing the rocks within the breccia zone and those directly on the contact. The results were quartz/opal C and quartz/opal CT/opal C, respectively.

**Interpretation:** Evidence for explosion breccia at Artist Point was matrix-supported breccia containing angular clasts of stratiform geyserite in a matrix of kaolinite and devitrified glass (Hinman and Walter, 2005). Hydrothermal eruption breccia is typically poorly-sorted, matrix-supported and may contain altered clasts derived from the hydrothermal reservoir. Hydrothermal eruptions typically occur close to the surface due to the rapid formation of steam creating sudden pressure reduction where the steam provides the energy to lift and eject host rock fragments (Browne and Lawless, 2001).

**Main Mound Breccia:** The heavily silicified, matrix-supported breccia on the Main Mound is most likely a hydrothermal eruption breccia hence it is probable the Main Mound breccia was formed by milling and churning of rock within the feeder pipe.

**Southeast Mound Breccia:** The nature and occurrence of the Southeast Mound breccia indicates a different origin that that of the Main Mound. As opposed being spatially confined to the top center of the mound it is in stratiform placement beneath overlying sinter. The contact with the sinter is gradational and undulatory suggesting a disconformal contact with the sinter above. This evidence in addition to localized alluvial appearance and lack of reworking suggest a sedimentary origin for this breccia.

**Massive Chalcedonic sinter**
**Distribution:** The lateral extent of massive chalcedonic sinter is minimal at McGinness Hills. It occurs in the greatest amount on top of the Main Mound where it wraps around vent breccia and is surrounded by stromatolitic sinter. It occurs in a lesser amount on the mound northeast of the Southeast Mound where it is also surrounded by stromatolitic sinter. Small (2-3 m) satellite outcrops of massive chalcedonic sinter are located on the periphery of the Main Mound. Because this facies is resistant to erosion these outcrops are stand-alone and it appears erosion had removed any surrounding any other facies that may have been there.

**Macro-features:** In outcrop, it either occurs as broken, thick, boulders (Figure 11) or locally as botryoidal, cauliflower-shaped outcrop (Figure 12). It is comprised of hard, dense chert that breaks along conchoidal fractures. Bedding features are strongly overprinted with silica and are usually slightly wavy to stromatolitic, 1-2 cm in height (Figure 13). Rarely are flat laminations present in massive chalcedonic sinter. Lenticular porosity occurs locally between bedding planes along with what appears to be opal partings. Brown patches within the
rock occur locally near weathered surfaces. In thin section, this microfacies shows fine-grained quartz.

Micro-features: At McGinness Hills, geyserite was not actually observed in outcrop or hand sample such as the spicular geyserite found at Artist Point, Yellowstone National Park (Hinman et al, 2005). However thin section analysis revealed the presence of what may be geyserite in one sample (Figure 14). The photomicrograph of sample MH10G shows a V-shaped profile of gently, convex, stacked layers in fine-grained quartz with sweeping extinction. The feature shown in Figure 14 is similar to the geyserite described by Walter (1972), Guidry et al (2003), and Jones and Renaut (2005). Geyserite occurs in splash zones that surround geyser and hot spring vents, a subaerial setting that is subjected to periods of wetting and drying, and on the rims of hot spring pools (Walter, 1972; Cady and Farmer, 1996; Jones and Renaut, 1997; Walter et al, 1998; Braunstein and Lowe, 2001; Jones and Renaut, 2005, Guidry et al, 2003). The mineralogy associated with this facies is typically chalcedony (Guidry et al, 2003).
Petrology: XRD analysis of the massive chalcedonic sinter facies was consistent with field descriptions. Quartz was the only mineral present except except for MH_1 taken from the Southeast Mound Vent Breccia contact that showed quartz and opal CT.

Interpretation: Massive chalcedonic sinter appears to be similar to the ‘massive/mottled, diffusely layered’ sinter in Drummond Basin described by Walter et al, (1996) and ‘massive/mottled’ sinter at Steamboat Springs described by Lynne et al., (2008). In the Drummond Basin Walter et al., (1996, 1998) describes the very high temperature microfacies geyserites, vent wall and floor deposits) as being massive to irregularly bedded cherts with alternating layers of fine-grained micro-granular quartz and remnant detrial textures. An interpretation for this microfacies is that of a near-vent facies that was subjected to induration of hot silica-rich water. This is supported by the presence of interstitial geyserite and the high degree of silicification. The presence of relict stromatolitic bedding throughout most of the dense chalcedonic microfacies may indicate the sinter was originally deposited as a lower temperature facies distal from the vent but was subsequently indurated by hot silicieous water due to renewed, increased or shifting geothermal activity.

Flat-Laminated Sinter

Distribution: In outcrop flat-laminated sinter appears as localized patches predominantly in contact with and surrounded by massive chalcedonic sinter and it occurs predominantly on the Southeast Mound except for a small patch associated with a smaller satellite mound southwest of the Main Mound (Figure 7).

Macro-features: In outcrop, horizons of dense, thinly laminated, white, vitreous sinter and are continuous over 0.25 to 1 meter. Beds are both horizontal and dipping
Outcrops are platy and friable due to loosely-cemented, thin bedding horizons (Figure 15). In hand sample the rock is composed of white, vitreous chalcedony and has flat to slightly undulatory beds 0.25-1.0 cm thick. Porous, brown material occurs between bedding planes causing the rock to be friable (Figure 16).

**Micro-features:** In thin section, broad, wavy, parallel bands with a low birefringence and sweeping extinction are observed (Figure 17). Thin, slightly diffuse separations are visible between the layers. Geopetals are also present. A possible microbial texture was found in sample MH5B taken from the top of the Southeast Mound. These appear as weakly layered, branching fenestrae (Figure 18).

**Petrography:** Two samples were run on flat-laminated samples and they both showed strong peaks for quartz. No other mineral was present.
Interpretation: Flat-laminated sinter in McGinness Hills appears to be analogous with the stratiform geyserite described by Hinman and Walter (2005) at Artist Point. Stratiform geyserite is the most abundant microfacies found at Artist Point whereas it occurs only locally and is uncommon at McGinness Hills. It is also described by Walter et al (1996) at Drummond Basin where it is also uncommon. Perhaps due to friable nature of this rock outcrops are not well-preserved in older systems. This facies is similar to the subaqueous high-temperature geyserite from Yellowstone National Park (Walter, 1976) and is interpreted as forming in pools surrounding gently surging hot pools (Hinman and Walter, 2005).

The occurrence of flat-laminated sinter facies in relation to the other sinter facies and the general low abundance in outcrop and in float indicates this facies was not common at McGinness Hills. This suggests the McGinness Hill geothermal system was of predominantly high relief. It could have formed on terraces located near the hot water source.

**Stromatolitic Sinter**

Distribution: Stromatolitic sinter is well-represented both in outcrop and as float at McGinness Hills (Figure 7). Stromatolitic sinter outcrops occur surrounding and distal to massive chalcedony and breccia except on the Southeast Mound where it occurs in a small patch in contact with hydrothermal breccia. Outward contacts with sinter breccia
are gradational as the stromatolitic sinter facies is frequently interbedded with sinter breccia.

Macro-features: Stromatolitic sinter outcrops are generally light colored, tabular to blocky and locally friable depending on the amount of opal present. Horizons are wavy and pinch and swell throughout the rock resembling a stromatolitic or algal texture (Figure 19). Well-pronounced streamer-like features were observed in a smaller satellite mound northeast of Southeast Mound (Figure 20). Locally throughout McGinness Hills rose-like textures (1-2 cm) occur on weathered surfaces (Figure 21). In hand sample this facies is characterized by 2-5 mm-thick horizons of fine (< 1 mm) silica bands. Horizons are continuous and sinuous like that of a stromatolite or broken and rec-cemented. The rock is porous due to coarse, opal partings between bedding planes. White opal and vitreous grey and white chalcedony
occur in varying amounts throughout the rock and appear to occur preferential to bedding (Figure 22).

**Micro-features:** Thin section analysis revealed a wide range of micro-textures associated with the stromatolitic sinter facies. Petrographically the rock appears to be composed of opaque material interbedded and interspersed among varying amounts of fine quartz. The various micro-textures found within McGinness Hills stromatolitic sinter facies include sinuous, stromatolitic banding, broken, bulbous vertical columns (Figure 23), layered, branching domes (Figure 24), and broken, brecciated clasts (Figure 25). Sample MH5D showed a geopetal fill within microcrystalline quartz lined with small quartz crystals (Figure 26).

**Petrography:** Samples were run on stromatolitic sinter include those collected from

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**Figure 22:** Photograph of stromatolitic sinter sample.

**Figure 23:** Photomicrograph of bulbous, vertical columns.

**Figure 24:** Photomicrograph of layered branching domes.

**Figure 24:** Photomicrograph of layered branching domes.
the southeast side of the Main Mound. The result revealed quartz for MH19C and quartz/opal CT for MH10C and MH10G.

Interpretation: Stromatolitic sinter at McGinness Hills appears to be analogous to the ‘streamer fabric’, a chert as having well-developed, thin laminated (1-2mm) bedding with filament ghosts, described by Hinman and Walter (2005) at Artist Point. This facies was interpreted as being indicative of an environment where microbial mats are growing in briskly-flowing water. Hinman and Walter (2005) report this facies is rare at Artist Point. Walter et al., (1996, 1998) designated a ‘thin-bedded with streamers and fenestrae’ facies for Drummond Basin. This facies is described as finely laminated chert with wavy, lenticular beds and elongate filamentous forms (Walter et al., 1996, 1998). The interpretation for this microfacies was that indicative of cyanobacterium, *Phormidium*, and *Chloroflexus*, microbes that live in water within the 32-65ºC range. These bacteria form streamers and grow in the outflow channels and terraces of hot springs (Cady and Farmer, 1996) and in pools 1-10 cm deep (Walter, 1976).
Thin section images of MH5D and MH5A bear resemblance to those of wavy laminated sinter in the Drummond Basin. The domed feature in sample MH5C (Figure 27) was identified by Hinman (personal communication) as being analogous to a feature found in the ‘columnar stromatolite facies with domes. This microfacies at Artist Point is interpreted as having formed under subaqueous conditions in water 32-65ºC (Hinman and Walter, 2005).

The stromatolitic sinter microfacies at McGinness Hills were most likely the mid-temperature facies in the system. It’s proximity in relation to the dense and flat-laminated chalcedony (interpreted as being high-temperature facies) is consistent with this interpretation. Macro-features such as wavy, stromatolitic bedding and streamer-like features are consistent with ‘streamer fabric’ microfacies of Artist Point (Hinman and Walter, 2005) and the ‘thin-bedded with streamers’ microfacies of the Drummond Basin (Walter, 1998). The abundance of stromatolitic sinter on the Main Mound in comparison to that of the denser, more silica-rich facies above may indicate the paleo-geyser mound was a high relief feature from which hot water erupted and spilled down the sides forming numerous outflow channels below. The temperature range for this water was most likely within the 32-65ºC range based on the temperature ranges for Phormidium, the organism likely to have left streamers and
stromatolitic textures. Geopetal features may indicate wetting and drying cycles that could occur due to shifting channels or interruption in water flow.

**Palisade Sinter**

**Distribution:** Outcrops of palisade sinter are not common and occur as localized patches throughout McGinness Hills. The largest of these outcrops occurs northwest from the top of the Main Mound and is in contact with the sinter breccia and marsh microfacies (Figure 7). A limited occurrence of the palisade sinter occurs on the eastern edge, near the top of the Main Mound where it is in contact with stromatolitic sinter on the top and overlies sinter breccia. Contacts with both fragmental and stromatolitic sinter are gradational as these microfacies tend to be interlayered. On the Southeast Mound palisade sinter occurs peripheral to flat laminated sinter where stromatolitic and palisade sinter wrap around a core of flat laminated sinter (Figure 7). The southern-most outcrop of palisade sinter is in direct contact with and overlies hydrothermal breccia.

**Macro-features:** Intact outcrops of palisade sinter are rare at McGinness Hills due to the opaline composition of these rocks. Where present, it occurs as flat laminated, tabular blocks. In hand sample palisade sinter is characterized by perfectly to nearly flat horizons of vertical fenestrae that are interbedded with horizons of chalcedonic and opaline sinter, 0.5 to 2 cms-thick of either massive or stromatolitic texture. Palisade horizons are either continuous or fragmented and range from 1 mm to 2 cms-thick. They consist of thin and rounded (when silicified) columns perpendicular to bedding and spanning from the top of the underlying layer to the bottom of the layer above it (Figure 28). In opaline rocks, these columns appear hair-like and are bent over, like grass in a stream. On bedding plane surfaces, palisade horizons display a rough texture like that of
coarse sandpaper and what appear to be desiccation cracks (Figure 29). The rock is predominantly opal with localized grey, vitreous chalcedony bands. In thin section, vertical, straight and branching columns identify this texture with parallel layers arching toward the top of the column.

**Micro-features:** The thin section for sample MH5B (Figure 30) shows a row of branching, vertical columns growing on and overlain by wavy, pustular laminae. The columns are roughly layered and nondescript. There is a minor amount of quartz and the rock is dominated by opaque material.

**Petrography:** XRD analysis was run for samples MH18A and MH18B collected from a small bed of palisade sinter northeast of the Southeast Mound and MH10, collected from the small palisade sinter outcrop near the top of the Main Mound. Results yielded quartz and opal-C.
**Interpretation:** The closest analogy for the palisade microfacies in McGinness Hills is the ‘thin bedded with palisade fabric observed by Walter et al (1998) in the Drummond Basin. It’s distinguished by the presence of fine, linear features perpendicular to bedding planes. Stratiform, felt-like mats are formed by the cyanobacterium, *Calothrix* in the bottom of low-temperature (<30ºC) pools and terraces in modern hot springs (Walter, 1976). The micro-fabric of these mats consists of vertical palisades which anastomose and branch (Cady and Walter, 1996; Walter et al, 1998). These descriptions are consistent with vertical fenestrae observed in hand sample and, perhaps, that shown by the thin section of sample MH5B. In modern hot spring systems, low temperature terrace pools supporting *Calothrix* bacteria are located distal from the hot water source. The palisade sinter on the northwest flank of the Main Mound crop out distal to the top of the mound (the presumed hot water source) and are in contact with fragmental, opaline sinter and the marsh facies (Figure 7). This is consistent with a low-temperature interpretation for McGinness Hills palisade texture. The palisade sinter on top of the Main Mound and that peripheral to flat-laminated sinter on the Southeast Mound do not fit the low-temperature model. An explanation could be effects from erosion. This seems unlikely as on both the Main Mound and Southeast Mound, the rocks appear to be in place in relation to one another. An explanation for the Main Mound could be that of a tilted mound or an excessive build-up of sinter on the east side of the vent. Either way water would flow predominantly down the west side of the geyser mound leaving the east side as a catchment or overflow thereby allowing a lower temperature facies to develop on the east side.

**Sinter Breccia**
**Distribution:** Sinter breccia is the dominant texture at McGinness Hills comprising 60% of the samples and about 75% of the sinter area (Figure 7). It occurs distal to the central vent facies and is in gradational contact with all other microfacies.

**Macro-features:** Because of the friability of the rock, very few outcrops of sinter breccia exist. In hand sample, the rock is tabular and minor rounded fragments of opaline or chalcedonic sinter indurated by silica cement. The rock can be either porous or dense depending on the degree of silicification. The size of the sinter fragments range from a few mms to 1 cm. Most sinter breccia shows little or no clast sorting or imbrication. Many samples exhibit silica banding interbedded within the breccia. The rock is usually porous and rubbly due to numerous voids between clasts (Figure 31). Minor plant fragments are incorporated in this microfacies as it is commonly interbedded with the marsh facies.

**Micro-Features:** Because the material making up the sinter breccia is most likely derived from elsewhere in the system there are a variety of sinter textures revealed in thin section. The images shown in (Figures 32, 33,
34, 35, 36) show the assortment of features present in sample MH7E collected southwest of the Main Mound.

**Petrology:** Three samples, MH7E, MH14B and MH10C were run for XRD analysis. The results were opal CT and quartz.

**Interpretation:** The sinter breccia facies of McGinness Hills is most analogous with the ‘interclast grainstone’ microfacies observed in the Drummond Basin by Walter et al (1998). They describe this facies as a rock with tabular interclasts, 1-5 mm scattered throughout thin bedded sinter. Lynne et al. (2008) reports ‘fragmental sinter’ at Steamboat Springs and Campbell et al. (2001) reports
identifying ‘sinter breccia at Umukuri. This facies is rare at Drummond Basin (Walter et al, 1998) and non-existent at Artist Point (Hinman and Walter, 2005). This facies is the dominant facies present in modern hot spring systems however and is likely to be the result of desiccation, fracturing due to freeze-thaw cycles and trampling by animals (Walter, 1976; Walter et al, 1998). Sinter breccia is the most extensive microfacies represented both laterally and vertically (Figure 7) at McGinness Hills. Sinter breccia consists of broken clasts of many other sinter types and is commonly interbedded with and in contact with stromatolitic sinter or the marsh facies and occurs predominantly distal to the inner-most silicified vent facies. At McGinness Hills, sinter breccia was most likely the result of numerous abandoned out flow channels that were subject to periods of wetting and drying due to the waxing and waning of geyser activity and the shifting of outflow channels.

Marsh

**Distribution:** The marsh microfacies at McGinness Hills occur distal to the more chalcedonic facies and are usually spatially the outermost facies (Figure 7). Outcrops displaying the marsh microfacies are not common as the rock tends to be porous and friable.

**Macro-features:** Marsh texture is defined primarily by the presence of fossilized organic material. In hand sample, the rock has a porous, spongy texture depending on degree of silicification. Discontinuous water lines are present within many samples. Plant fossils include marsh vegetation consisting of reeds, grass, and roots. The stems in cross section show a dicot pattern. Reeds are well preserved and lie at various angles to bedding (Figure 37). Many occur in vertical bunches that originate and radiate from a
common origin with diameter of the stems ranging from 1 to 6 mms. Two types of roots were observed. The most common form consists of small, branched, thread-like fragments that occur randomly throughout the rock. The other type is bulbous taproot, 0.5 to 1 cm in diameter covered with root hairs. Associated with this type of root are large, 1 to 1.5 cm-thick stems with a woody texture.

Micro-features: Thin section analysis for the marsh microfacies at McGinness Hills revealed amorphous material, very little quartz and nondescript features that may have been organically derived. Round concentric voids most likely the cross sectional view of reeds (Figure 38).

Petrography: XRD analysis for the marsh microfacies revealed a broad peak characteristic for opal A. A sample ran from the silicified water line from sample gave a strong peak for quartz.

Interpretation: The microfacies, ‘thin-bedded with Lycopsids’ and ‘encrusted Lycopsids’ described by Walter et al. (1998) appears to be the best analogy for the marsh microfacies at McGinness...
Hills. In the Drummond Basin, it was described as irregular to vuggy, thin-bedded chert with variously-orientated silicified stems and molds lying on bedding planes. The marsh facies in modern systems are distal, siliceous marshes where the temperature (<30ºC) was low enough to allow vegetation to grow (Walter, 1976). These are environments characterized by low-energy pools and water-logged soils. At McGinness Hills, the marsh facies occur distal to and downward from the central, chalcedonic, near-vent facies. The spatial distribution of and the textures preserved in the marsh facies point to that of a siliceous marsh fed by run-off channels in which the water had cooled enough to allow vegetation to grow.

<table>
<thead>
<tr>
<th>Microfacies</th>
<th>Distinguishing Features</th>
<th>Silica Mineral</th>
<th>Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrothermal Breccia</td>
<td>Grey, matrix-supported, angular to sub-angular clasts of various lithologies.</td>
<td>qtz</td>
<td>Main Mound: eruption breccia</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Southeast Mound: unknown</td>
</tr>
<tr>
<td>Massive Chaledony</td>
<td>Rounded to thick, tabular outcrop, dense chalcedony with faint overprinted textures.</td>
<td>qtz</td>
<td>High temp. subaerial, constant induration by hot water</td>
</tr>
<tr>
<td>Flat Laminated</td>
<td>Thinly-laminated, dense chert</td>
<td>qtz</td>
<td>75-85°C, stratiform geyserite</td>
</tr>
<tr>
<td>Stromatolitic</td>
<td>Wavy, stromatolitic bedding, surficial streamers</td>
<td>qtz&gt;opal C</td>
<td>30-59°C, outflow channels, Phormidium</td>
</tr>
<tr>
<td>Palisade Fabric</td>
<td>Flat-laminated sinter with vertical fenestrae</td>
<td>qtz/opal C</td>
<td>&lt;30°C, pools and terraces, Calothrix</td>
</tr>
<tr>
<td>Fragmental Sinter</td>
<td>Tabular fragments of sinter indurated with Si-cement, either massive or interbedded wavy bands</td>
<td>opal CT/htz</td>
<td>Abandoned outflow channels and pools.</td>
</tr>
<tr>
<td>Marsh</td>
<td>Porous, spongy in texture, plant fragments, reeds and silicified organic matter</td>
<td>Opal A/htz</td>
<td>Marshes outward from the hot water source.</td>
</tr>
</tbody>
</table>

**VI. EFFECTS OF EROSION**

It appears that large portions of the sinter at McGinness Hills have been removed and hence it is likely McGinness Hill is a decapitated system in which the top has been removed thereby exposing the inner workings of the system. The most compelling evidence for this is the hydrothermal breccia occurrence on top of the Main Mound where the breccia occurs at the top and forms an elongate, oval-shaped core in sharp contact with surrounding dense and laminated chalcedonic sinter. No evidence for mixing of the
two rock types was found in the sinter or the breccia. It appears the breccia of the Main Mound has hydrothermal origins therefore it is likely to have been deposited within the subsurface confines of a geyser throat where the material was milled, churned and brecciated due repeated episodes of pressure release (Browne and Lawless, 2001). It is possible that what is present at the surface today represents a cross section through the subsurface feeder pipe of a geyser or hot spring (Figure 39).

Figure 39: Interpretive cross section (not to scale) through the Main Mound. A) present day surface, B) paleosurface.
VII. RECONSTRUCTING THE MCGINNESS HILLS HOT SPRING SYSTEM

Although both the Main and the Southeast Mounds at McGinness Hills are part of the same system, are both siliceous hot spring systems and display similar sinter microfacies, I have chosen to break the two out as separate entities. This decision was based on 1) their spatial distribution; they don’t appear to intermix and are separated by volcanics, 2) different character of the breccias, and 3) slightly different nature and distribution of sinter microfacies.

The hot spring facies that were most likely present at the McGinness Hills are best described by analogies to modern systems. A modern system analogous to the Main Mound is Castle Geyser in Yellowstone National Park. Castle Geyser consists of a large geyserite cone, over 3.6 meters high, and is estimated to have been active for at least 5,000 years (Bryan, 1991). The cone is built on a large sloping geyserite mound that was formed during earlier hot spring activity (Bryan, 1991). Eruptions from Castle Geyser reach heights of 9 to 24 meters and are followed by a steam phase. Along the sides of the cone, are numerous holes through which water appeared to have flowed previously. Nearly horizontal beds of platy, sheet-flow sinter surround the cone. Shallow, wide outflow channels emanate from the mound although these do not support an abundance of bacterial mats due to the sporadic nature of the runoff. Sinter breccia is also present between runoff channels. Marshes exist outward from the mound (Bryan, 1991).

The vent facies of the geyser is represented by the dense chalcedonic sinter on top, however the chalcedonic sinter exposed presently may have been overlain by subsequent deposits that have since eroded. The top of Main Mound may have looked
similar to the top of Castle Geyser with ramparts of siliceous sinter that are frequently
inundated with silica-saturated water.

Reconstruction of the Main Mound

The Main Mound hot spring system was most likely composed of one larger, high-profile
geyser mound and numerous smaller vents on the periphery (Figure 40). The whole
system had a general north-northeast trend following that of a major north-south structure
to the west of the hot spring area. The elongate nature of the largest mound and the
secondary mound to the southwest indicate geothermal activity was structurally
controlled. The paleotopography was most likely similar to that of today as the sinter
deposits built up and merely added to the existing vertical relief. Drilling data indicated
the sinter build up is 24 m on the top of the mound and thins toward the edge of the
mound (Casaceli et al, 1986; Wendell, 1985). Geothermal activity most likely began on
the western top side of the hill and the effluent flowed down the western side of the hill.
Evidence for this is the large lateral extent of sinter and numerous sinter microfacies on
the west side. All the sinter microfacies exist to east of the main vent except for the marsh
microfacies. However the extent of the sinter on the east side is much less than that of the
west side and is contact with volcanic rock mid-slope on the present day topography. The
marsh facies is absent from the east side of the hill indicating the relief was too high to
support a marsh.

In an ideal system, dense chalcedony would form in an area of high fluid flow and
opal would dominate away from feeder zones (White, 1964). This appears to be the case
at McGinness Hills where the dense chalcedonic sinter grades outward to more opaline
facies. In this case, there would have to have been at least 4 satellites to the largest vent.
Evidence for this is the east-west, elongated patch of dense chalcedonic sinter surrounded by more opaline sinter a few meters to the southwest, two smaller systems to the north and numerous, stand-alone outcrops of dense, rounded chalcedony.

Figure 40: Interpretive drawing showing microfacies of the Main Mound during time of deposition. A) large geyser surrounded by geyserite, B) flat-laminated sinter, sheet flow, C) satellite geyser vents or hot pools, D) mid-temperature (32-74°C) facies, outflow channels and terraces, E) Low-temperature (<32°C) ponds, F) desiccated sinter from abandoned outflow channels, G) marshes.
The Main sinter mound was most likely a system of intense geyser activity and high fluid flow. The Main sinter mound was undoubtedly a highly active feature with explosive eruptions and high discharges of hot siliceous water depositing large amounts of sinter (Figure 41). The throat was laterally elongated in a north-south direction. The reworked nature of the hydrothermal breccia indicates that this may have been a zone of milling and churning within the geyser tube and may possibly marks the zone within the geyser’s throat where the water flashed to steam, causing the eruption. The depth at which the breccia originated was possibly near or at the bottom of the sinter pile. Evidence for this is the grey quartzite and black chert clasts derived from the alluvium directly below the sinter. Most of the discharge water from the Main Mound flowed in a
westerly to southwest direction. Evidence for this is the lateral extent of the sinter on the west side as opposed to the east side.

Outward from the geyser vent, meandering outflow channels formed a sinter apron on which the water temperatures had cooled to 32-65°C, the temperature range optimal for the growth of *Phormidium*. In turn, these bacteria created filamentous mats that formed wavy, sinuous laminations and streamer-like textures associated with the stromatolitic microfacies. The outflow channel on the Main Mound probably saw sporadic runoff similar to Castle Geyser. Geopetal fills observed in thin section and the presence of interbedded sinter breccia is evidence for this. However it appears that locally there may have been enough water to support biological activity.

Further from the source the meandering runoff channels were forming low temperature (<30°C) pools with terrace dams. Within these pools *Calothrix* would likely form stratiform felt-like sheets. Evidence for these sheets is the well-defined fenestrae present in many of the rocks representing the palisade microfacies.

Sinter breccia was probably widespread within the Main Mound hot spring system. It most likely formed between runoff channels as it does on Castle Geyser in addition to abandoned runoff channels and terraces and inactive geyser cones. All these features would be subject to breakage due to desiccation, erosion, freeze-thaw cycles or perhaps faunal activity such as the modern sinters in Yellowstone.

Marshes surrounded the western periphery of the Main Mound geothermal system where they were probably fed by silica-rich water cool enough to have supported higher vegetation. The abundance of opal-A associated with this microfacies is further evidence that it formed furthest from the hot, siliceous source.
Reconstruction of the Southeast Mound

The Southeast Mound is located southeast of the Main Mound and consists of two or three geothermal features. The system has a general north-south trend suggesting the geothermal activity that drove the Southeast Mound system has structural origins. It appears the Southeast Mound system was a low-relief feature with less eruptive geyser activity and lower discharge. It consists of a larger feature located on the southern end and a smaller feature on the northern end of the system. The tabular nature of the breccia body beneath and the undulatory contact with the overlying sinter, and the alluvial nature of the breccia make interpretation problematic. The breccia appears to have had some hydrothermal reworking due to the lack of sorting and the presence of angular clasts. The breccia may be a combination of silicified alluvium and hydrothermal breccia (Figure 42).

Figure 42: Vertical stratigraphy column on the west side of the Southeast Mound showing the breccia/sinter contact.
The larger of the two features on the Southeast Mound may have started out as a boiling, perhaps surging pool that could have erupted at least once during its existence. The flat laminated sinter on the Southeast Mound is analogous to the stratiform geyserite or mound armor described by Hinman and Walter (2005) at Artist Point, Yellowstone National Park, who interpreted the microfacies as resulting from hot silica-rich fluids bathing the surface or hot surging pools. Over time, it appears that the heat fueling the hot spring subsided and the temperature of the effluent cooled to a range to support *Phormidium* and *Calothrix* on the outer edges. Evidence for this is the semi-circular occurrence of stromatolitic and palisade sinter directly overlying flat laminated chalcedony (Figure 43).

Figure 43: Interpretive cross section (not to scale) the Southeast Mound during time of deposition. A) present-day topography, B) paleosurface.
VIII. SUMMARY

McGinness Hills is a relatively, well-preserved fossil hot spring system. The microfacies therein represent a wide variety of textures from the high temperature near-vent facies to distal marsh facies that are found in modern systems today. McGinness Hills is a decapitated geothermal system thereby giving us a glimpse of the inner workings of an active geyser.
IX. REFERENCES


