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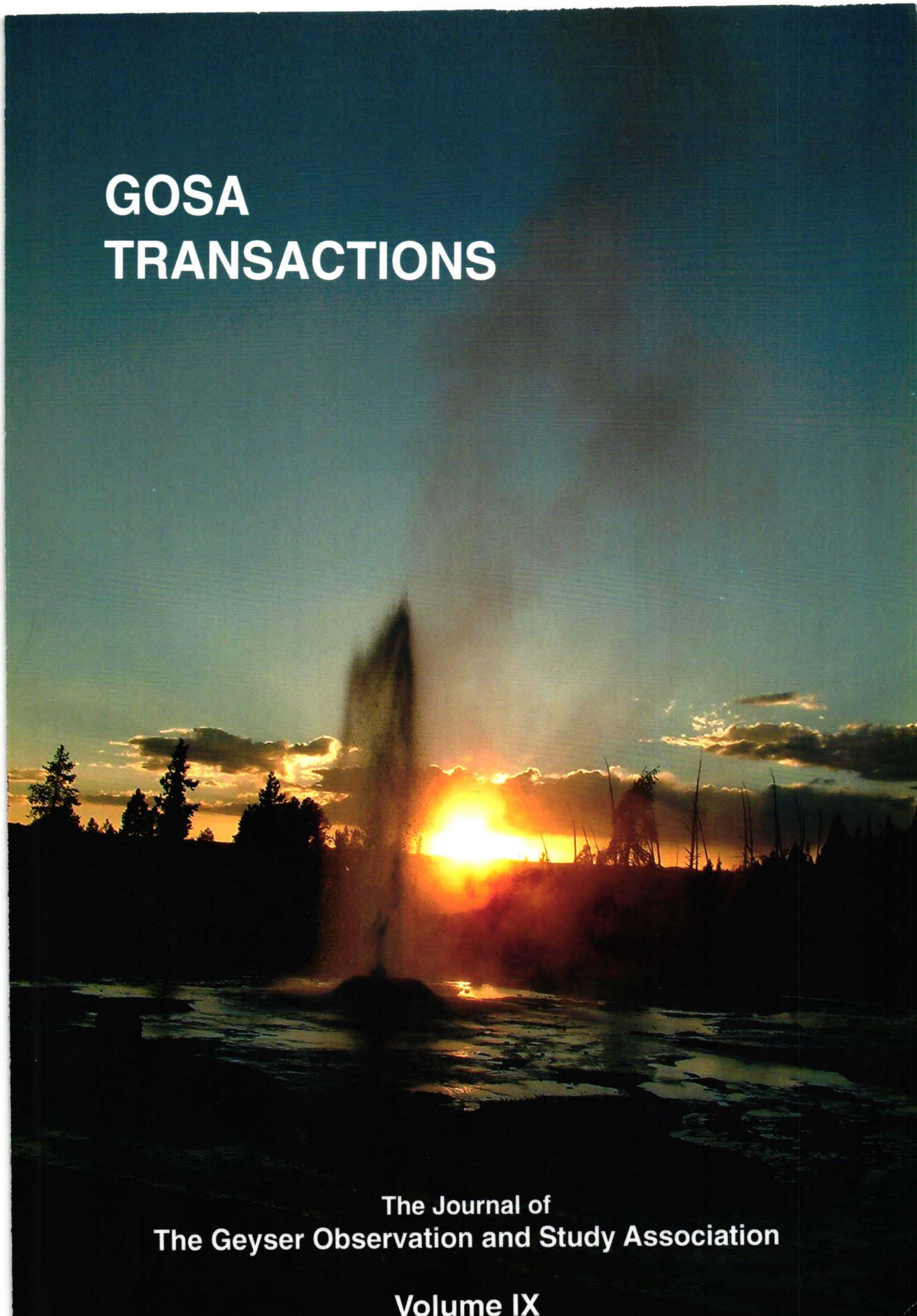

The Journal of
The Geyser Observation and Study Association

Volume IX
2005

The GOSA Transactions

The Journal of The Geyser Observation and Study Association

Volume IX
Published January 2005

The GOSA Transactions are published on an irregular basis, as merited by the volume of submissions received by the editors. Numbered volumes contain articles reporting on original or historical research about geyser activity worldwide.

The price of each issue is set separately, according to its size. In keeping with GOSA's non–profit goals, this price is substantially less than the cost of production.

Cover Photograph:
Pink Cone Geyser is immediately adjacent to the Firehole Lake Drive in Yellowstone's Lower Geyser Basin. It erupts from a small geyserite cone stained pink by a small content of manganese oxide mineralization. During 2003 the intervals between eruptions varied between about 19 and 22 hours. Cover photo by Bill Masella, July 03, 2003.

Printed by:
Four Star Printing
Palmdale, California

The GOSA Transactions publishes articles, research notes, short notices, reviews and photographs of both general and technical interest on any aspect of the physics, chemistry, geology or behavioral aspects of geysers and related geothermal phenomena, as well as social and historical studies related to these phenomena.

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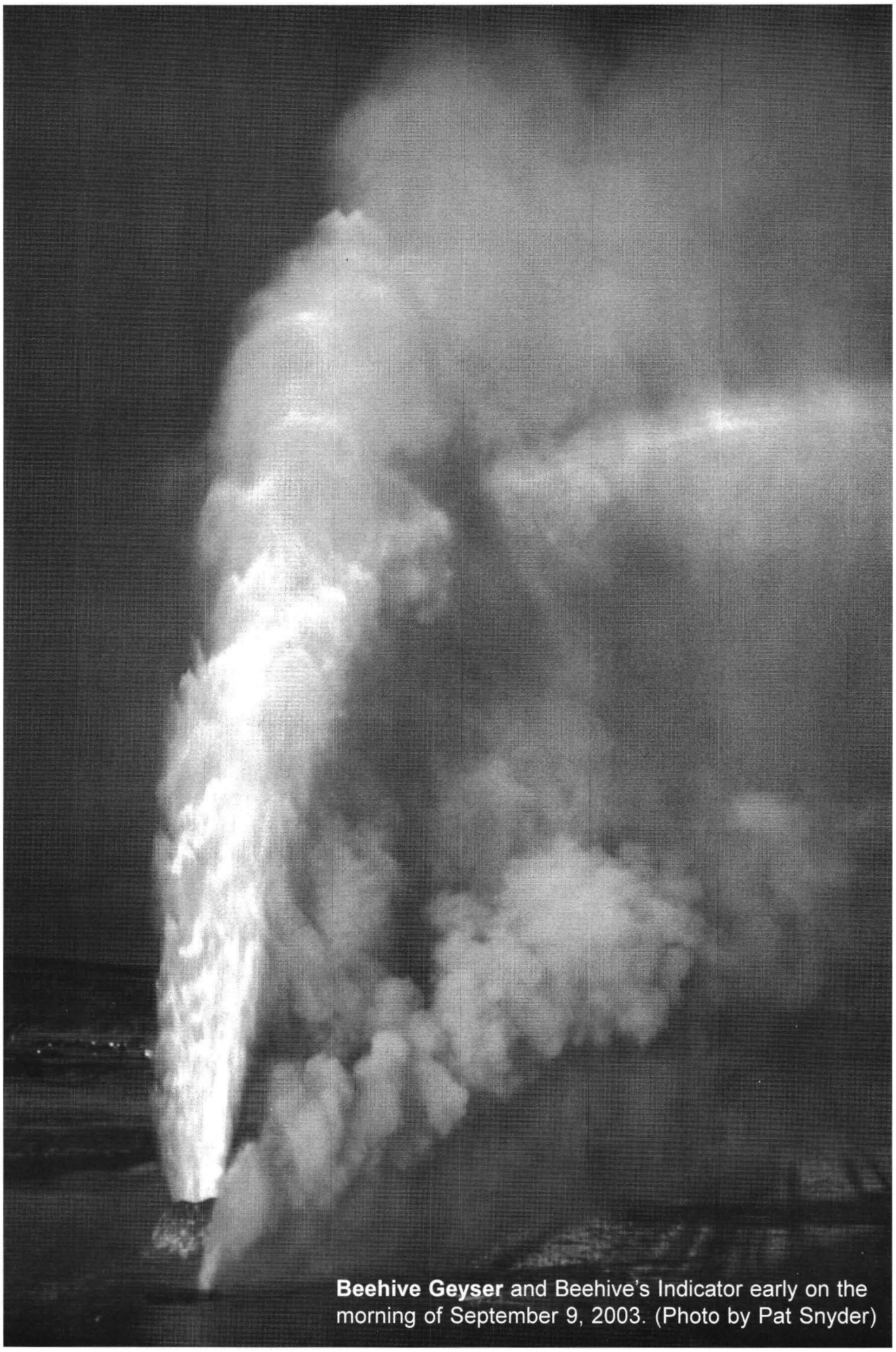

Beehive Geyser and Beehive's Indicator early on the morning of September 9, 2003. (Photo by Pat Snyder)

The Journal of
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An Explanation of GOSA Measurement and Language Conventions

To assure consistency and the understandability of the articles published in *The GOSA Transactions*, a number of standards have been adopted. It should be noted that these are only the editorially preferred usage. Individual authors may use other measurement values as they wish.

Distance and Height Measurements

The goal of this publication is for readers to understand the information contained in these articles without being bogged down or confused by unfamiliar measurement units. Therefore, GOSA publications prefer the use of the English system of measuring distances and heights (that is, units of feet, yards and miles) over the metric system. Although some feel that we should adopt the metric system, the simple fact is that the most Americans (the majority of our readers) do not readily understand metric units. Note that articles that do use the metric system will always be accepted.

To avoid possible confusion, punctuation–type abbreviations (such as ' for feet, " for inches and m for meters) should not be used.

Time Measurements and Their Abbreviations

Units of time are straightforward in nearly all cases (the use of inventions, such as the "famous" microdays and millihours, will not be accepted for publication). In general discussions, where specific data is not involved, it is preferred that time units be spelled in full ("hours" or "minutes," for example). Within specific data, however, the use of abbreviations is preferred. These units should be shown as follows: "d" = days; "h" = hours; "m" = minutes; "s" = seconds.

To avoid confusion, punctuation–type abbreviations (' for minutes and " for seconds) should not be used, and longer units of time, such as "years" and "months," should always be spelled in full.

Other Abbreviations

A number of additional, geyser–standard abbreviations may be used within articles, most commonly within data tables or in text where directly associated with specific data. These include:

"I" or "i" = interval; "IBE" = interval between eruptions; "D" or "d" = duration; "ie" = observed in eruption; the tilde ("~") may be used to note an approximate time value.

In situations where there is only isolated usage of these terms, they should be spelled in full rather than abbreviated.

Past Tense versus Present Tense

Almost without exception, a discussion about geyser activity will be based on what was observed at some time in the past. Therefore, the use of past tense is strongly preferred for all articles.

Giant and Mastiff Geysers
"Normal Function" Eruption
August 2, 2004

The eruptive activity of Giant Geyser was erratic during 2003 and 2004, and most of the eruptions were of the "Normal function," that is, *not* accompanied by adjacent Mastiff Geyser. These eruptions tend to be of lower maximum heights than when joined by Mastiff, and in this case Giant reached perehaps 'only' 170 feet high. [Photo by Joe Erlanger and contributed by Debby Stahl]

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The GOSA Transactions

Volume IX, January 2005

A Special Report

The Geysers of Lake Bogoria,
Kenya Rift Valley, Africa

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Abstract

At least 13 geysers have been active at Lake Bogoria in the Kenya Rift Valley during the past 25 years. The alkaline (pH 8-9.8) Na-HCO_3 fluids are discharged from vents in volcanic rocks or littoral sediments located along the shoreline at Loburu, Chemurkeu, Koibobei, and Losaramat. Few of the geysers are predictable. Their behavior is strongly influenced by the prevailing lake level, which is controlled mainly by climatic changes. Rises in lake level increase discharge at some vents, while suppressing geyser activity at others. Falling levels can induce eruptions by exposing formerly submerged vents. Unlike most other geyser localities, siliceous sinter is absent around most of the vents because most of the discharged fluids are initially undersaturated with respect to amorphous silica. Travertine deposits, however, are present at most active geysers and spouting springs at Loburu and Chemurkeu. The geysers at Bogoria are probably the largest single group in Africa.

INTRODUCTION

Geysers are rare in Africa. Except for sporadic reports of geyser activity at Yirrigue volcanic centre in the Tibesti Mountains of Chad (Bryan 1995), all known examples lie within the volcanic regions of the East African Rift system, which extends 3,500 km southward from the Red Sea through Ethiopia, Kenya, Tanzania, and into Malawi and Mozambique. Geysers have been reported from several parts of the Ethiopian Rift (e.g., Aluto-Langano, Tendaho: UNDP 1973; Bryan 1995), although details of their activity are sparse. In the Kenya Rift Valley (Figure 1A), however, several geysers are known to be active or dormant. They are most abundant in the Lake Bogoria National Reserve, which lies just north of the equator.

At least 13 active or dormant geysers are known at Lake Bogoria. The geysers and their activity differ in many respects from more familiar geothermal fields, such as those at Yellowstone and the Taupo Volcanic Zone of North Island, New Zealand. Geyser activity in Kenya is not linked to rhyolitic volcanism, but rather to extensional tectonics, high regional heat flow associated with magmatic intrusion, and high local recharge on the elevated rift shoulders and rift floor. Siliceous sinter and geyserite deposits, which typify most geyser fields (e.g., Renaut and Jones 2000; Jones and Renaut 2003), are almost absent at active Kenyan geothermal sites, whereas travertine is found around many of the vents. Furthermore, the hydrothermal processes, including geyser activity, are strongly influenced by short and long term climatic changes.

Aspects of the geyser behavior at Bogoria were first mentioned briefly by McCall (1967). Glover (1972), Allen et al. (1989) and Cioni et al. (1992) discussed the origins of the hot spring and geyser fluids. Jones and Renaut (1995, 1996) and Renaut and Jones (1997) described the travertine deposits found around their vents. No previous studies, however, have focused specifically on the geysers and their activity. The aim of this paper is to describe the geysers at Lake Bogoria and to discuss some of the unusual influences on their behavior. Observations are based mainly on eight field trips to the Bogoria region between 1976 and 2002.

THE LAKE BOGORIA GEOTHERMAL FIELD

Lake Bogoria occupies an asymmetric half-graben basin in a structurally complex part of the Kenya Rift Valley, just north of the equator (Le Turdu et al. 1995). The lake, which is 22 km long by up to 3.5 km wide, lies in a catchment composed almost entirely of basalts, trachytes and phonolite lavas of Miocene to Pleistocene age (Figure 1B). East and

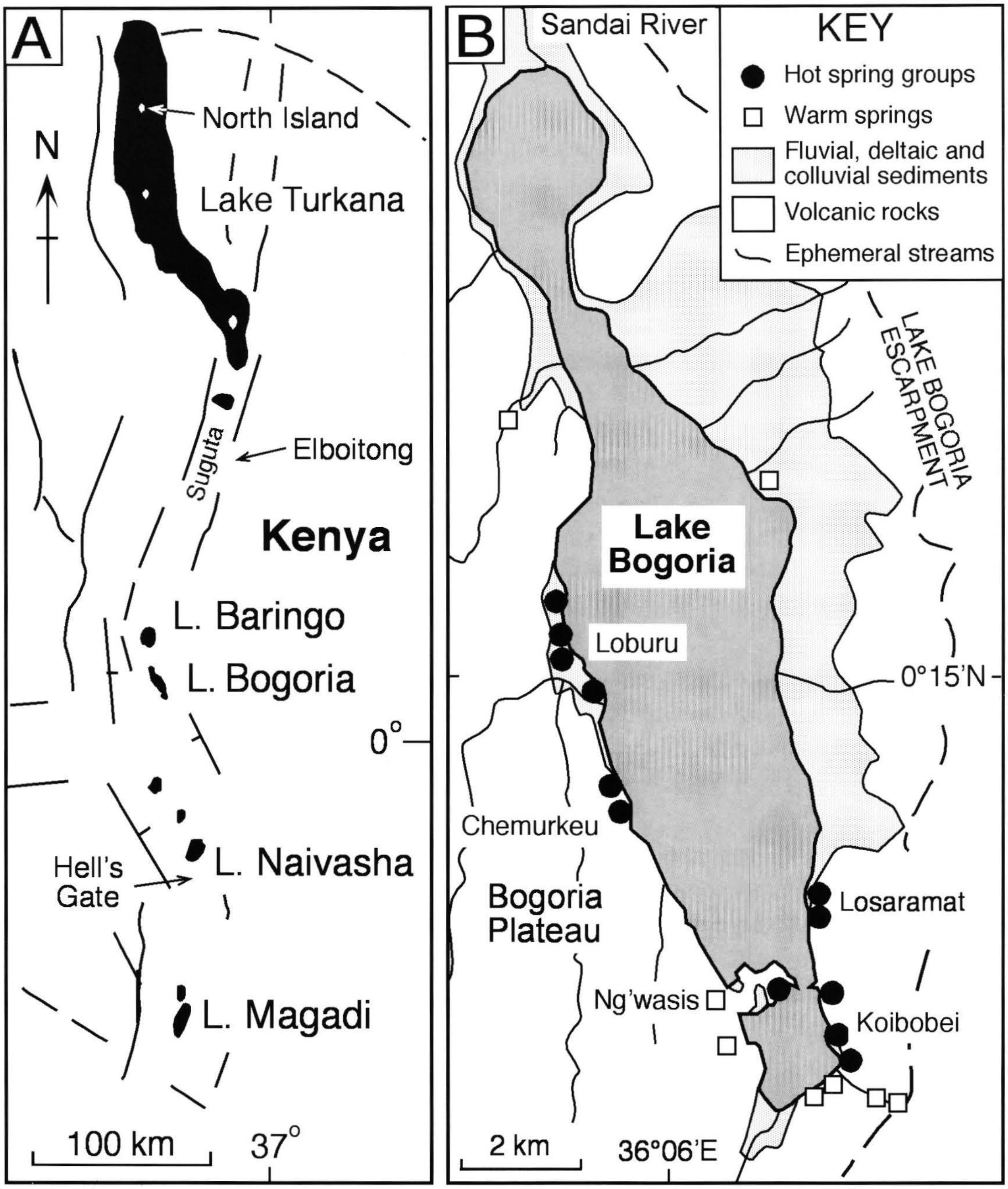


Figure 1A (left). The Kenya Rift Valley, showing the location of Lake Bogoria and other locations mentioned in the text.

Figure 1B (right). Lake Bogoria geothermal field, showing the distribution of thermal spring groups south of the lake, the Lake Bogoria and Emsos fault escarpments rise abruptly up to 700 m above the lake surface. To the west lies the more subdued Bogoria Plateau, a northward-dipping platform of trachyphonolites and basaltic lavas that were erupted on the rift floor during the Pleistocene (~1 Ma). The plateau surface is broken by numerous closely spaced north–south trending grid–faults.

Lake Bogoria is fed by the ephemeral Sandai River, which flows into the lake at its northern shoreline, several smaller ephemeral streams, direct rainfall on the lake surface, and by both subaerial and sublacustrine hot springs. The lake is shallow (~10 m maximum depth in central sub-basin), has no surface outflow, and is hydrologically closed. The present climate is semi–arid, with annual evaporation (~2,500 mm per year) greatly exceeding precipitation (~700 mm per year). Most of the water that flows into the lake is therefore lost by evaporation. As a result, the lake waters have become highly saline (up to 90 g/l Total Dissolved Solids: TDS) and alkaline (pH: 10.5), and are of Na-HCO_3-CO_3-Cl composition, acquired mainly through weathering of silicate minerals in the volcanic rocks. A further consequence is that the surface level of the lake is controlled mainly by changes in the precipitation to evaporation budget rather than the height of any outlet. Lake level (~990 m elevation) fluctuates frequently over a vertical range of several metres in response to climatic variability (Renaut and Tiercelin 1994). As will be shown, such changes in lake level, which occur over timescales of years to thousands of years, can have a major impact on the behavior of the hot springs and geyser activity.

Approximately 200 individual hot spring vents are present near Lake Bogoria. The hot springs (73–99°C) are clustered in three main groups, all of which are located near the shoreline. Loburu and Chemurkeu lie on the mid–western shore; the south Bogoria group lies in a structurally complex area near the southern end of the lake (Figure 1B). Several outlying warm springs lie on fault-line sites away from the shoreline, but these are significantly cooler (35–45°C) and fresher (440–650 mg/l TDS; pH: 6.5–7.5) than the springs near the lake shore.

Lake–bottom temperature surveys have shown that hot springs also discharge directly from the lake floor, mainly in the southern half of the central basin of the lake (Naylor 1972).

The hot spring waters in each of the three groups have similar chemical compositions and temperature ranges, but different salinities. All the spring waters, including the geyser fluids, are alkaline (pH: 8.0–9.8) and of Na-HCO_3 composition. The Loburu waters have salinities of approximately 4.5–5.0 g/l TDS, whereas those at Chemurkeu are 5–6 g/l TDS. In contrast, most waters of the southern group (except some dilute fumarole condensates) are more saline, ranging from 14 to 26 g/l TDS. The chloride concentrations at Loburu and Chemurkeu are ~220–330 mg/l Cl, compared to 1100–1750 mg/l for the southern group. All the hot spring waters have low Ca (<2 mg/l) and Mg (< 1 mg/l) concentrations. Silica concentrations at Loburu and Chemurkeu are 105–135 mg/l SiO_2, but rise to 180–230 mg/l SiO_2 in the springs and geysers of the southern group. The relatively low silica concentrations compared to most other sites with active geysers suggest that the reservoir fluids are probably in equilibrium with chalcedony rather than quartz (Glover 1972; Cioni et al. 1992).

The geothermal aquifers probably lie in fractured or brecciated lavas and (or) the interbedded sediments or paleosols between lava flows. Calculated temperatures of the reservoir fluids, using Si and alkali geothermometers, range from ~100°C at Loburu to ~170°C at Koibobei. The origin of the spring waters is uncertain. Allen et al. (1989) proposed that the Loburu and Chemurkeu springs derive from local groundwater drawn rapidly into a CO_2–rich geothermal upflow that has cooled adiabatically, but suggested that steam heating was not involved. In contrast, Cioni et al. (1992) suggested that the fluids at Loburu and Chemurkeu originate mainly by steam heating of shallow, relatively dilute groundwaters that have mixed with a small component of lake water, then boiled upon ascent. The more saline fluids of Koibobei and Losaramat may be derived, in part, from a deeper geothermal reservoir with a higher chloride content.

Photo 1. General view of northern Loburu, showing hot springs with Lake Bogoria and the Lake Bogoria Escarpment in the background. [All photos in this article provided by Robin Renaut]

Geothermal sites and geyser activity

North Bogoria hot springs

Loburu

Loburu (formerly known as Kiboriit) is a small delta located on the midwestern shoreline of Lake Bogoria. Two linear groups of hot springs emerge on the delta plain and are aligned along extensions of normal faults that cut the volcanic rocks west and southwest of the delta (Figure 2, Photo 1). The northern group consists of approximately 40 hot spring vents; the southern group has about 20 hot spring vents. The number of springs visible at any time varies with prevailing lake level. When lake level rises, many submerged vents continue to discharge below the lake surface.

Most of the hot springs at Loburu discharge from subcircular pools that range in diameter from <1 m to about 10 m. Many pools emerge in littoral marsh, but a recent (1997–1998) rise in lake level associated with an El Niño event eroded much of the shoreline and obliterated much of the marsh that was present in the 1980s to mid 1990s. Maximum temperatures at the vent range from 73° to 98.9°C. Several springs have extensive deposits of travertine (mainly dendritic calcite) around their vents, but siliceous sinter is largely absent. Much of the travertine is fossil and being eroded; only minor $CaCO_3$ is precipitating from the Ca-poor waters. Minor silica (opal-A) precipitates as friable white crusts on subaerial surfaces of microbial mats by capillary rise and wicking around the perimeter of most spring pools, and along the subaerial margins of their outflow channels where water temperatures are <70°C (Renaut et al. 1998). No subaqueous silica precipitation is taking place in the pools and outflow channels.

The two most prominent springs in the northern group at Loburu both have deposits of travertine surrounding their vents. Spring KL6 (Photo 2; spring numbering system follows Renaut 1982),

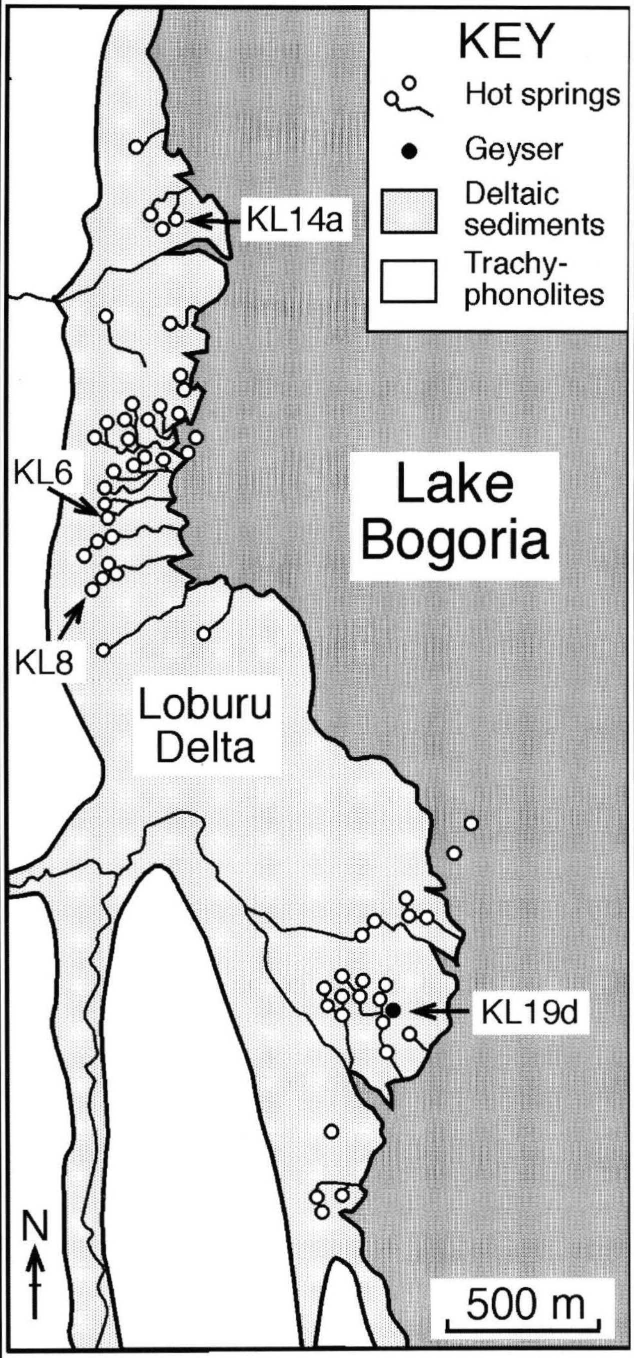


Figure 2. Loburu delta, showing location of the hot springs and geysers. The linear distribution reflects the faults that cut the lavas south and west of the delta.

although often referred to as a geyser, has been a perpetual spouter probably for the past 25 years. A jet of boiling water and steam discharges continuously up to 3.5 m in the air from a platform of low travertine terraces composed mainly of calcite. An ebullient boiling spring, partly rimmed by fossil travertine, lies directly north of the spouter, adjacent to the platform. During the mid-1970s and possibly earlier, the spouting spring exhibited geyser–like periodicity in discharge. When first observed in July 1976, the spring was a perpetual spouter, but the jet of water underwent cyclic variations in height. At times, it attained a height of only ~1.2 m, but periodically underwent periodic "surges", reaching a height of >3 m. The intervals between these surges were typically 4 to 5 minutes, and their duration ranged from 60 to 95 seconds before returning to the initial level. By summer 1977, the spring was a perpetual spouter behaving essentially the same as it does today. Observations over 25 years have shown that the maximum height of the spring jet responds to prevailing lake level, decreasing to ~1 m or less during periods of drought when lake level drops (e.g., cover photograph of Allen et al. 1989). Anecdotal reports from local elders at Loboi village claim that the spring was a true geyser during periods of low lake level in the 1960s and early 1970s.

Spring KL8 (Photo 3), which lies ~200 m south of KL6, is also a perpetual spouter and appears to have maintained this state since at least 1976. Water and steam are continually ejected to a height of ~2–3 m, with occasional brief pulses of up to 4 m. The jet of water emerges from a platform of pale–brown, calcite travertine that lies approximately 0.5 m below the delta–plain surface. Eroded travertine mounds near the spring vent are evidence of a long history of activity. Two mounds lie adjacent to the vent. The larger, older mound of dark gray to brown, bedded travertine is the eroded remnant of a former, more extensive deposit. A smaller (1 m

Photo 2. Spring KL6 (perpetual spouter, former geyser) spouting from a platform of fossil travertine.

Photo 3. Spring KL8 (perpetual spouter). The mound is fossil travertine.

high), pale brown mound with a domal, mammillary surface lies in the spray zone of the modern jet. Dendritic calcite is actively precipitating on the substrate from the spray as CO_2 exsolves from the fluids. The history of this spring is unknown, so it is unclear whether it was ever a true geyser. A photograph by McCall (1967, his Plate III) shows the spring to have been little different in appearance in the early 1960s from that active today.

Spring KL14a (Photo 4) at northern Loburu is a small perpetual spouter emerging from a mound of fossil travertine. It ejects a jet of water up to 30 cm in the air from a small (5 cm diameter) circular vent at the top of the mound. Remnant travertine blocks near the vent mound, some of which are partly buried along the margins of the outflow channel, suggest that the spring formerly erupted into a pool, most of which has been eroded. However, the present temperature (94–96°C) of the spring is below local boiling point (~ 98.5°C), and the spring is unlikely to have been a true geyser during the past 50 years.

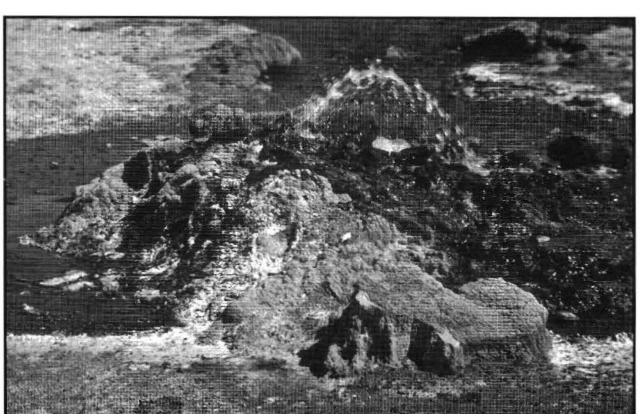
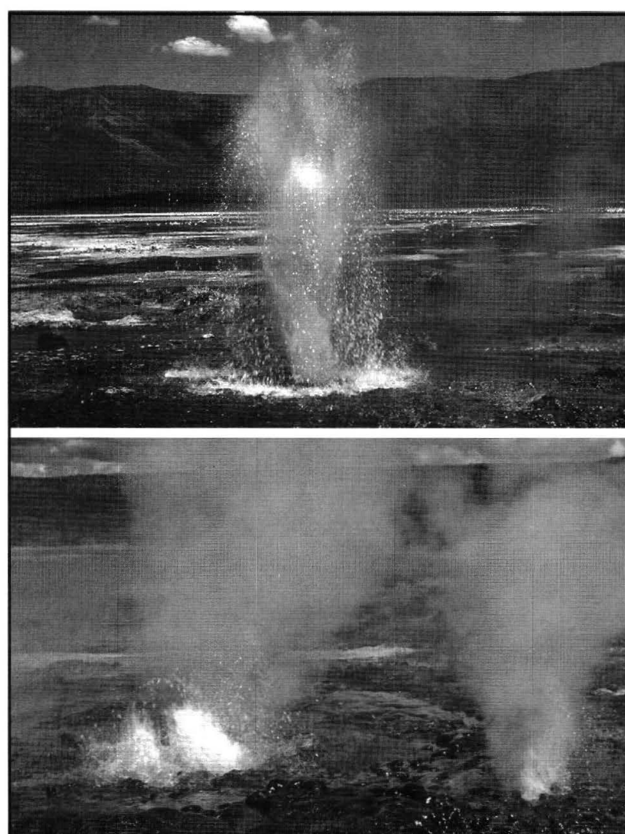


Photo 4. Spring 14a (perpetual spouter).

During spring 1994, a geyser (KL19d) became active in the southern group of springs at Loburu. Before 1994, the spring was an ebullient pool of boiling water. Activity began abruptly with the eruption of boiling water to heights of 3.5 m with strong audible emissions of steam and gas (mainly CO_2). At times during summer 1994, KL19d behaved as a true geyser (Photo 5a), with eruptions of 60–90 second duration and intervals of 5 to 8 minutes; at other times, it behaved as a perpetual spouter to heights of ~1.5 m. In summer 1995, the geyser was still active, but the large eruptions had been replaced by smaller eruptions up to 1.5 m in height from two adjacent vents (Photo 5b). By summer 1996, geyser activity had ceased, and in 2001 the vent was occupied by a vigorously boiling spring. Unlike other vents in southern Loburu, pale brown travertine crusts surround the vent of KL19d. No other geysers have been reported in the southern group at Loburu, but several springs undergo periodic surges every four to five minutes,



Photos 5a and 5b. Geyser KL19d during eruption in June 1994 (top) and in June 1995 (bottom).

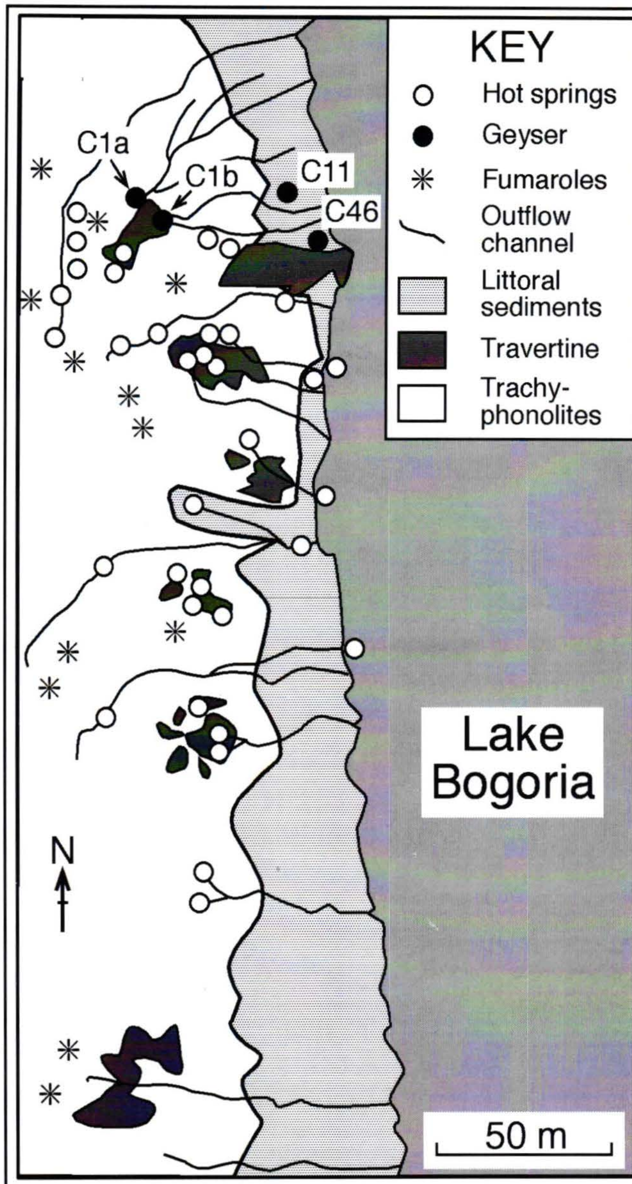


Figure 3. Chemurkeu, showing the main geothermal features. Very small springs are not shown.

many synchronously, associated with subsurface boiling.

Chemurkeu

At Chemurkeu (formerly known as Mawe Moto and "Loburu" in older literature), which lies about 1.5 km south of Loburu, about 40 hot springs discharge directly from open joints and fractures in volcanic bedrock. The site extends north–south along the steep rugged shoreline over a distance of 200 m and is up to 70 m wide (Figure 3).

Much of the surface is composed of fractured and fissile trachyphonolite lavas, but travertine is abundant, particularly at the northern and southern ends of the site. The travertine forms coarsely crystalline beds at the land surface and eroded mounds, and fills or lines open fractures in the lava bedrock. As at Loburu, the travertine, which is composed of both calcite and aragonite, is a fossil deposit. Very little $CaCO_3$ is actively precipitating from the Ca-poor spring waters (Jones and Renaut 1996, 1998; Renaut and Jones 1997).

Most of the active hot springs are small, emerging from shallow (<50 cm deep) pools in the fractured lavas; others seep quietly from vents in the travertine and are recognized by the microbial mats that line their outflow paths. Present activity is concentrated in the northern half of the site. Temperatures at the vent range from 73° to 99°C, with most >95°C.

Four geysers have been active at the northern part of Chemurkeu during the past 25 years. Geyser C1a erupts from a vent in the fractured lavas (Photo 6). The vent, which is approximately 60 cm across, lies directly below a mound of lava bedrock. Eruptions take place at intervals varying from 2.5 to 3 minutes, and typically last 30–50 seconds. The water, which is ejected to a height of up to 1.5 m, flows across a discharge apron of lava and fossil travertine that is extensively covered by microbial mats. In the main outflow channel network within 10 m of the geyser vent, parts of the substrate have a rippled surface of thin (1 cm), purplish brown crusts composed of Mg-rich silicates that are probably clay minerals such as smectite or sepiolite (Jones et al. 2003). These Mg-silicates have precipitated directly from the geyser fluids.

Photo 6. Geyser C1a during the early stage of an eruption in June 1995.

Photo 7. Geyser C1b.

Geyser C1a is believed to be the "Loburu Geyser" reported in earlier literature. Loburu is a former name for Chemurkeu.

A second geyser, C1b (Photo 7), lies ~8 m southeast of the vent of C1a. This geyser erupts directly from a small vent in fractured lavas and travertine to a height of about 50 cm. Eruptions commonly alternate with eruptions of C1a, suggesting that the two vents share a common conduit. In one feeder cavern, steam bubbles form, reducing the hydrostatic pressure of the overlying water column until the whole cavern empties rapidly in a geyser–like eruption. During the eruption, the other cavern is filling up until it too boils and repeats the cycle. Geyser C1b was active in the mid–1970s, 1991 and 1996. Its activity had declined by 2001, although small cyclic eruptions were observed.

The third geyser, C11, discharges a jet of water up to 50 cm high, directly from fractured lavas approximately 30 m east of C1a (Photo 8). Intervals between eruptions also range from 2–5 minutes, with durations of 15–30 seconds. At times, both C1a and C2 play simultaneously; at other times, eruptions are asynchronous. No surface precipitates are found at geyser C11. Geyser C1a has been active since at least 1976. Geyser C11 was inactive when the site was visited in the mid–1970s, but was playing in November 1991. It appears to have been active since then, except when submerged by lake water.

Photo 8. Geyser C11 during an eruption in 1994.

Geyser C46 is a small geyser that erupts from fractured lavas near the shoreline to a height of 50 cm (Photo 9). This geyser was active in 1977 and 1994, but no eruptions were seen in 1996 and 2001. The interval between eruptions varied (1994) from 4 to 35 minutes, with only about 30 seconds of play.

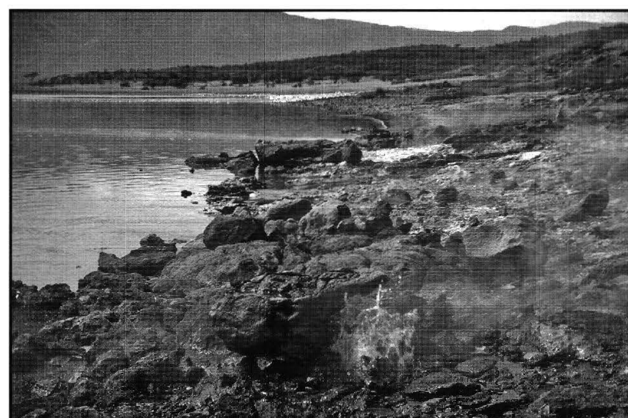


Photo 9. Geyser C46 in eruption, June 1994.

Several of the small springs at northern Chemurkeu show temporal variations in discharge without being geysers. These are evident as changes in the level of water in the pools, increases in steam venting, and cyclic variations in ebullience within the pools. Periodic sprays of water droplets have been observed escaping from fractures at northern Chemurkeu that at other times discharge only vapor. These are akin to small geysers that are nearly starved of water. Some of the sprays occur with similar periodicities to those observed at the two geysers, implying a variable response to common subsurface boiling events.

Siliceous sinter is absent at Chemurkeu, although thin silica crusts line the margins of many vents (including fumaroles) and their outflow channels. As at Loburu, most silica precipitates as opal-A directly on and in cyanobacterial mats.

The 1:50,000 Kenya Survey topographic map for the southern half of Lake Bogoria (Sheet 105/3: Solai, Edition 6, 1973) shows two geysers on the shoreline south of Chemurkeu. The first is marked on a small promontory 100 m south of Chemurkeu, where a small group of hot (>90°C) springs bubble up through littoral gravels. The second is shown in an ephemeral stream channel 500 m further south, where a weak hot (82°C) spring discharges on the channel floor. No geyser activity has been seen at either of these sites.

South Bogoria hot springs

The southern group of hot springs includes at least eight geysers. Geothermal activity takes place at three main sites — Ng'wasis, Koibobei, and Losaramat (Figure 4). These sites lie in a zone of complex cross fracturing and faulting. The fluids discharged are the hottest and most saline (chloride-rich) in the basin, implying that they have a different, and probably deeper, source(s) than those at Loburu and Chemurkeu.

Ng'wasis

Ng'wasis, also called Mwanasis, is a rugged peninsula of Pleistocene (0.3 Ma) volcanic rocks (mainly trachytes) that projects eastward from the southwestern shoreline, nearly isolating the southernmost part of the lake. A group of about 20 hot springs and several strong fumaroles discharge along a fault line that forms the southeastern shoreline of the peninsula and along a faulted ridge at its eastern margin. Temperatures range from 76° to 98°C, with most >96°C. Most springs flow from small shallow pools, 5–60 cm in diameter, in littoral gravels and coarse sands. White opaline silica crusts and bluish-gray gelatinous silica are present around the margins of most of the modern pools, but true sin-

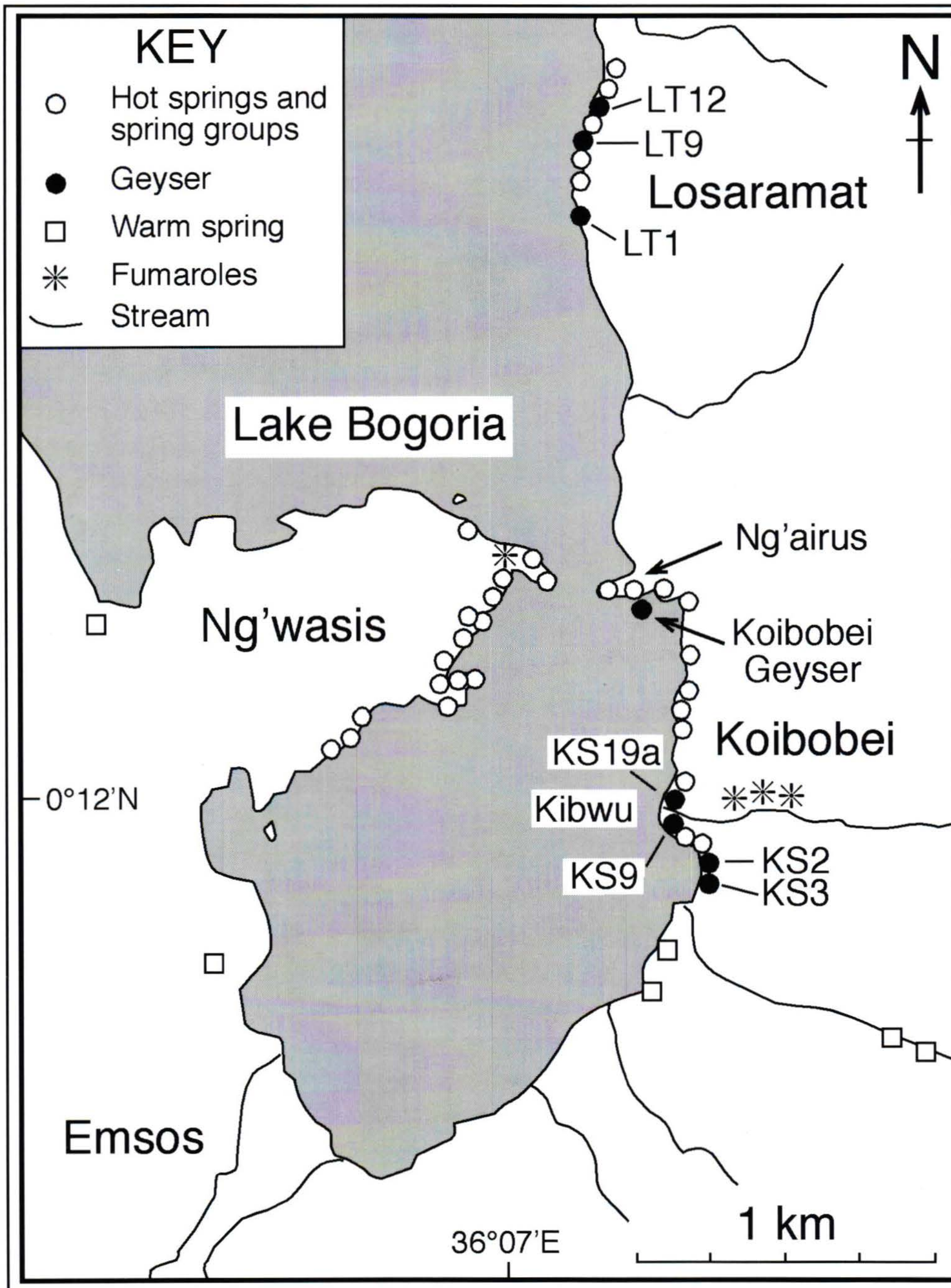


Figure 4. South Bogoria hot springs, showing the locations of the hot springs and geysers.

ters are absent. Fossil sinters and silica-cemented gravels, however, are locally present along the shoreline. These sinters contain fossil diatoms and gastropods that show that they formed around submerged hot springs during times when lake level was much higher than today (Renaut and Owen 1988; Renaut et al. 2002). No geyser activity has been reported at Ng'wasis.

Koibobei

Koibobei (formerly Kwaipopei) lies along the steep southeastern lake shore, and stretches from Ng'airus, a narrow peninsula directly opposite Ng'wasis, to the southeastern corner of the lake. Thermal activity in this zone includes about 30 hot spring vents and several strong fumaroles emitting steam and CO_2, mainly at higher elevation than the springs. Spring temperatures range from 86° to 98°C, with most >97°C. At least five active geysers have been observed in this area since 1976. Most geysers and hot springs discharge from vents up to 2 m in diameter that lie in volcanic gravels. The gravels include coarse beach deposits and the bedded gravels of a small alluvial fan (Kibwu). Some of the bedded gravels are cemented by iron-stained opaline silica and cristobalite, and are clearly fossil deposits. These silica cements are similar to those cementing gravels at Ng'wasis, and some have formed while the springs were submerged by the lake. Diatoms, however, are poorly preserved or absent because of recrystallization of the silica.

The Koibobei (Kwaipopei) Geyser, when active, is the largest geyser at Lake Bogoria, discharging water to a height of at least 3.5 m. The vent lies on the southern shore of Ng'airus (Figure 4), but frequently has been submerged below lake water during the past decade. The geyser was observed in eruption during the summers of 1976, 1991, and 1996 but was inactive in June 1977 when lake level was relatively high. Although a water plume was not confirmed, high steam discharge was observed from the opposite shoreline in June 2001 that also probably represented an eruption. The site of the vent was located in 1996 by the high discharge of gas bubbles in water >1 m deep, approximately 3 m offshore. The vent appears to lie in a fissure in volcanic rocks along a fracture or small fault parallel to the southern shore of Ng'airus. The geyser periodicity is unknown but recent eruptions seem to have been very irregular. McCall (1967, his Plate IIIb) illustrated the geyser in eruption during the 1960s. At that time, eruptions occurred at 10–minute intervals. Activity appears to be suppressed except when lake level is low and the vent becomes subaerially exposed or lies in very shallow water.

Two geysers are periodically active on the Kibwu alluvial fan, one on the southern part (KS9), and the other to the north (KS19a). Both discharge from depressions up to 1 m deep in alluvial gravels.

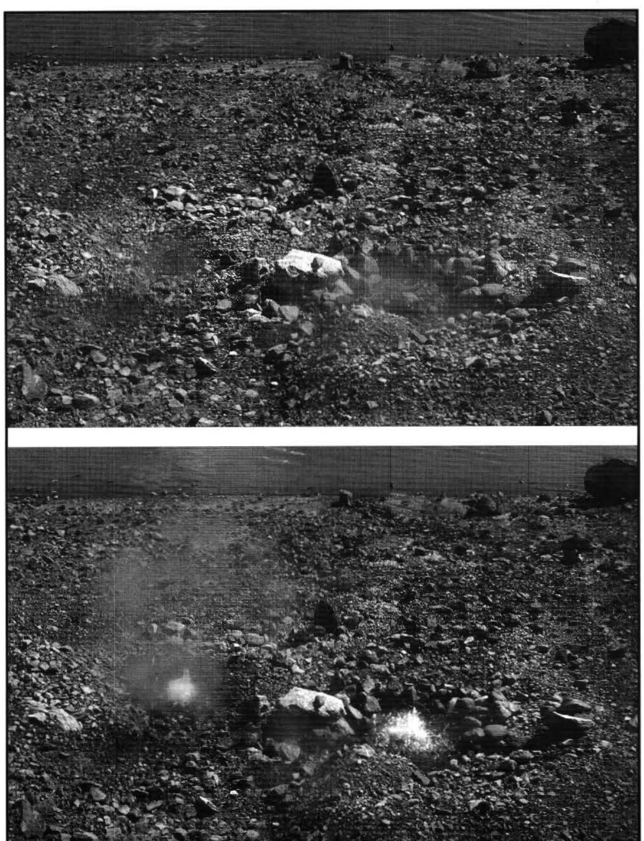
In August 1995 and August 1996, Geyser KS19a discharged for about 30 seconds to ~70 cm high every 3 minutes (Photo 10), whereas Geyser KS9 erupted to about 70–80 cm for 30 seconds every 3–4 minutes. In July 2001, Geyser K19a was

Photo 10. Geyser KS19a, Koibobei, in eruption in July 2001.

Photo 11. Geyser K9 Koibobei, during a passive state in July 2001. During eruptions, the geyser will play up to 80 cm high.

still active, but K9 (Photo 11) was then a periodically surging hot spring.

Two geysers (KS2 and KS3) discharge from small (40 cm diameter) vents 1 m apart on the gravelly shoreline at the southern part of Koibobei. Although they discharging water only to a height of about 25 cm, they are true geysers (Photos 12a and 12b). Eruptions took place over intervals of 3–5 minutes during June 2001 with both vents discharging simultaneously for about 35 seconds.



Photos 12a and 12b. Small geysers KS2 and KS3, on the foreshore at Koibobei, before (top) and during eruption (bottom).

Losaramat

The Losaramat site is located 1.3 km north of Koibobei and consists of a group of about 17 hot springs that lies along the shoreline at the foot of a steep slope of volcanic rocks (trachytes). Several more springs discharge in shallow waters offshore. Temperatures measured in 1995 were between 95° and 99°C. At least three of the springs are known to behave as geysers (LT1, LT9 and LT12). When observed in eruption in 1995 and 1996, their vents were approximately 10–20 cm above lake level. The vents are about 40–60 cm in diameter and >30 cm deep, lying within trachytic lavas that are overlain by coarse colluvial gravels. Eruptions are relatively modest, with discharge of water to height of 30–50 cm for about 30–40 seconds, but with the release of abundant steam and gas (Geyser LT9, Photo 13). Intervals between eruptions in summer 1996 ranged from 4 to about 20 minutes.

Other geysers in the Kenya Rift Valley

Several other major geothermal areas are present in the arid rift valley between Lake Bogoria and Lake Turkana, many of which are associated with dormant or extinct volcanoes (Allen and Darling 1992; Dunkley et al. 1993; Renaut et al. 1999, 2002). Access to the region north of Lake Baringo (Figure 1A) is extremely difficult and confirmed reports of geyser activity are rare. With the present arid climate, water tables are regionally low. Although hot springs are locally present along faults, steam vents and fumaroles are more common at the sites of recent volcanic activity. Nonetheless, siliceous sinter and fossil geyserite have been found at several volcanoes (Dunkley et al. 1993) indicating that many geysers were probably once active, most likely during wetter climatic phases of the late Pleistocene when water tables were regionally higher than today (Sturchio et al. 1993).

Several hot springs discharge from the northeastern part of Ol Kokwe, a volcanic island near

Photo 13. Geyser LT9, at Losaramat, during eruption in July 1996.

the center of Lake Baringo, which lies 20 km north of Lake Bogoria (Dunkley et al. 1993; Renaut et al. 2002). No geysers have been observed recently on Ol Kokwe, but Powell-Cotton (1904) reported that some springs "throw out only an intermittent jet", implying that geysers may have been active during his visit in 1902. A new artificial geyser, the "Baringo Geyser", located near the shoreline of Lake Baringo, was formed on April 8, 2004, during drilling of a water well that penetrated a thermal reservoir at ~75 m below the land surface. The artificial geyser erupted acidic water (pH 4.3) continuously for several weeks from the wellbore, reaching a height variably estimated at 50 to 80 m.

The only confirmed geyser in the northern Kenya Rift is the Logipi Geyser, which lies at Elboitong on the eastern margin of the Suguta Valley. At Elboitong, numerous hot springs lie along the base of a fault scarp over a distance of 5.5 km and include the hottest springs (100.2°C) recorded in Kenya (Dunkley et al. 1993). The Logipi Geyser was first reported by Champion (1935, 1937), who visited the area in the early 1930s. The geyser then erupted at regular intervals (unspecified) to a height of 4 feet (1.3 m) from a platform of sinter. Dunkley et al. (1993) revisited and sampled the springs in 1990, but did not report any geyser activity. They noted that activity at Elboitong appeared to have declined since the 1930s. It is likely, therefore, that the Logipi Geyser is either dormant or no longer active.

A geyser has also been reported by local fisherman on the southern shore of North Island, an extinct volcano in northern Lake Turkana (Figure 1A). Although hot springs and many steam vents are active on the island (Dunkley et al. 1993), the existence of a geyser has yet to be confirmed.

Major geothermal fields and isolated groups of hot and boiling springs extend southward along the rift valley from Lake Bogoria to the Tanzanian border, and continue into Tanzania (Allen et al. 1989; Clarke et al. 1990). These include hot springs at Lake Elmenteita and Lake Magadi, and fumaroles and steam vents at Arus, Eburru and Olkaria. No geysers are known from this region. Reports of geyser activity at Hell's Gate, south of Lake Naivasha (Figure 1A), appear from time to time but are unconfirmed. This site lies near the Olkaria Geothermal Power Station. Strong steam jets are locally common in that area, and superficially may resemble geysers.

Discussion

The geysers at Lake Bogoria are probably the largest single group in Africa, although there remains the possibility of undiscovered sites in the remote volcanic regions of the Ethiopia, Djibouti, and central north Africa. The Bogoria geysers are not associated with acidic (rhyolitic) volcanism. Instead, they are associated with the volcanic rocks (basalts, trachytes, phonolites) and extensional faulting linked to continental rifting. Their waters are exclusively alkaline and acidic surface waters are absent. The geological setting of the geysers at Bogoria perhaps has most in common with the geothermal areas of Iceland, most of which lie in extensional rift settings.

The most unusual feature about the Bogoria geysers is the paucity of siliceous sinter. The fluids are undersaturated with respect to amorphous silica when discharged, so no geyserite is present around their vents. Silica is only precipitated on and in microbial mats along the subaerial margins of pools and outflow channels, where silica–bearing fluids undergo cooling, capillary rise and evaporation (Renaut et al. 1998). Some silica has been precipitated subaqueously in the south Bogoria group, where rising thermal fluids encountered cool lake water around submerged vents (Renaut and Owen 1988). The paucity of siliceous sinter at Lake

Bogoria is unusual, particularly because alkaline fluids normally precipitate large quantities of sinter around geyser vents, and can play an important role in geyser dynamics by forming local seals and constrictions in the geothermal reservoirs (Bryan 1995). In general, however, a reservoir temperature of >235°C is required for fluids to precipitate amorphous silica at ~100°C at the surface (Rimstidt and Cole 1983). The predicted reservoir temperatures at Bogoria are much lower (~170°C). The travertine deposits at the surface appear to have poor sealing properties. They are initially highly porous, although the porosity gradually declines with the precipitation of intercrystalline calcite and fluorite (CaF_2) cements. Despite the lack of sinter, favorable hydrogeological conditions for geysers clearly exist at shallow depths around Lake Bogoria.

The geyser sites are underlain predominantly by the trachyphonolites and trachytes, which are dense finely crystalline lavas typically ~150 m thick, with little porosity unless they are fractured. These, in turn, overlie basalts and older series of phonolites (Griffiths and Gibson 1980). Exposures of Pleistocene trachyphonolites on the track to Maji Moto, approximately 200 m west of Loburu, show white and orange quartz veining that fills fractures up to 30 cm wide in the lavas. Similar quartz veins are seen in mugearite lavas near Soro, a small geothermal site on Ol Kokwe Island near the center of Lake Baringo, and in fractures in the Baringo Trachyte near Kampi-Ya-Samaki, west of Lake Baringo (Le Gall et al. 2000). These quartz veins were precipitated from hot fluids in hydrothermal systems that are now extinct; all are located near sites of present hydrothermal activity. Hydrothermal alteration is associated with some of the quartz veins. This demonstrates that silica is likely being precipitated in the subsurface roots of the present geothermal sites. Subsurface silica precipitation in fractured dense lavas may help to provide favorable plumbing systems that host the geyser reservoirs. The role of the carbonates in geyser activity is unclear, because without drilling, their subsurface extent cannot be known. However, shoreline exposures of fossil travertine at northern Chemurkeu show fractures in trachyphonolites that are lined by calcite and aragonite cements (Jones and Renaut 1996, 1998; Renaut and Jones 1997). The carbonates precipitate with exsolution of CO_2 upon pressure release and boiling of ascending fluids (Simmons and Christenson 1994). It is possible, therefore, that sealing of conduits by subsurface carbonate precipitation could also be a factor in providing favorable conditions for geyser formation. All the geysers and spouting springs at Loburu have travertine deposits at their vents. Spring carbonates, however, may only play a role at Loburu and Chemurkeu, and are sparse at Koibobei and Losaramat.

Periodic observations over 25 years have shown that activity at the Bogoria hot springs and geysers undergoes rapid and frequent change. Although frequent changes characterize most geothermal sites, the location of all the geysers near the lake shore means that their activity is strong influenced by changes in lake level, which in turn are mainly controlled by climate. McCall (1967) first proposed a hydrostatic connection between the springs and lake level, and argued that their shoreline locations reflect their hotter, less saline fluids, which are less dense than the highly saline lake water. This relationship is reasonable, with faults and fractures providing permeable conduits for the rising fluids.

Rising and falling lake levels have variable effects on geyser activity. When lake level rises, many of the subaerial vents are drowned. Direct observations are clearly difficult, but most submerged vents continue to discharge underwater, as shown by rising gas bubbles and plumes of water breaking the lake surface. Activity at the Kobobei (Kwaipopei) Geyser is clearly suppressed by high lake level and the geyser only erupts when the fluid pressure of rising plume can exceed that exerted by the overlying lake water column. Its eruptions, therefore, tend to be most common during relatively dry years when the vent is exposed or in shallow water. In contrast, some geysers, such as C1a at Chemurkeu, tend to have increased activity or higher eruptions when lake water level is higher. This presumably is related to pressure changes and variable water levels in the shallow part of the plumbing system. Similarly, some perpetual spouters (e.g., KL6) have higher spring jets during high lake level, at least until the vents become submerged. Many small fumaroles may discharge water, temporarily becoming springs when lake level is high.

Low and falling lake level leads to declining activity at many shoreline springs. Those with travertine deposits at Loburu and Chemurkeu, however, tend to maintain their flow even during dry climatic phases. This implies that they are probably the oldest springs at those sites, and that they have mature plumbing systems that can maintain recharge even during periods of aridity.

Tectonic activity may also have an impact on spring and geyser behavior, but its importance is difficult to judge. Microearthquakes are abundant throughout the region (Young et al. 1991), but the last major earthquake (M 6.9) was in 1928 (Ambraseys 1991). Changes in hydrothermal plumbing caused by earthquakes are well known at Yellowstone and in the Taupo Volcanic Zone. The sudden eruption of geyser KL19d at Loburu in 1994 could have been triggered by minor fault movements, but direct evidence is lacking.

Conclusions

Study of the hydrothermal activity at Lake Bogoria in the central Kenya Rift Valley over 25 years has shown that at least 13 geysers have been historically active, making this probably the largest geyser locality in Africa. All the geysers discharge alkaline Na-HCO_3 fluids but most of their waters are undersaturated with respect to amorphous silica when discharged, so little siliceous sinter has formed around their subaerial vents. In contrast, travertine lines the vents of several geysers and spouting hot springs at Loburu and Chemurkeu. Activity is strongly controlled by changes in the level of Lake Bogoria, which in some cases suppresses, and in other cases, enhances the geyser activity.

Acknowledgements

Research at Lake Bogoria has been supported by grants from the Natural Sciences and Engineering Research Council of Canada (NSERC).

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GOSA

In Memory

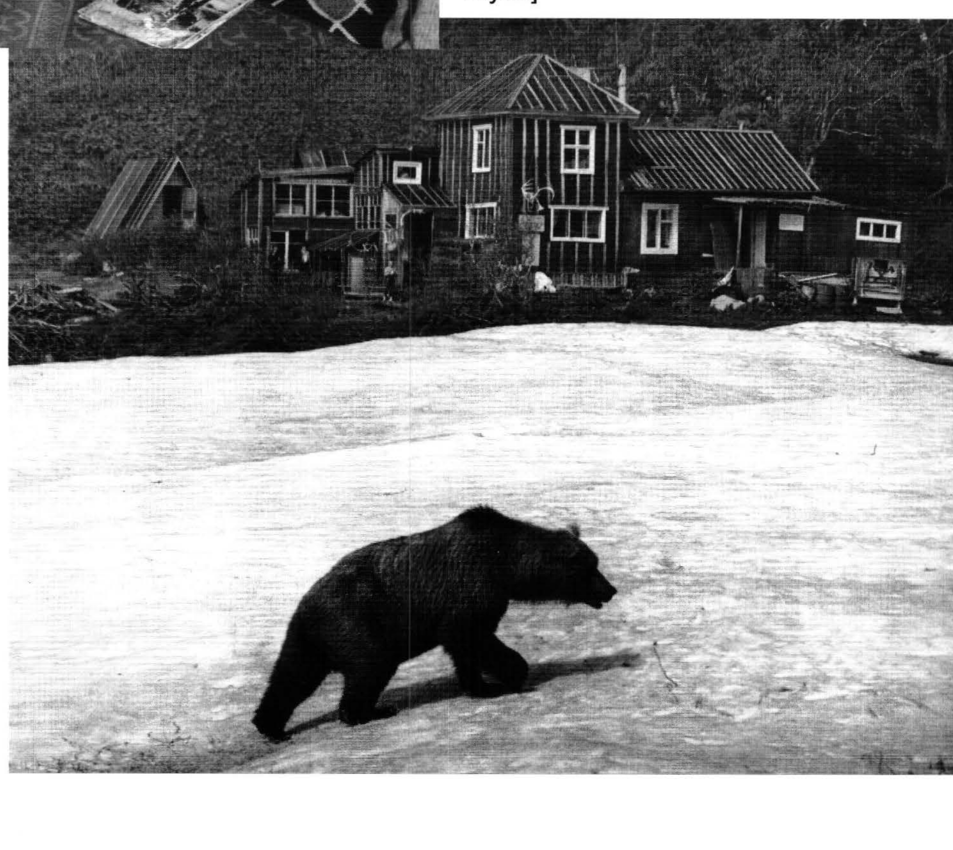
Photographs Remembering
Vitalii A. Nikolayenko
1937 – 2003

On December 31, 2003, the American news media reported the death of Vitalii A. Nikolayeno. Although he was perhaps better acquainted than anybody else with the geysers of Dolina Geizerov, in the Kronotski Nature Reserve of Russia's Kamchatka Peninsula, Vitalii was considered to be one of the pre–eminent bear researchers in Russia. After 25 years of study, however, he was killed on December 26, 2003, when mauled by one of those bears.

Vitalii served as the resident host of the GOSA expeditions that visited Dolina Geizerov (the "Valley of Geysers") on Russia's Kamchatka Peninsula, in 1991 and 1996. I believe he enjoyed our presence as much as we benefitted from his open and graceful friendship, extensive knowledge and unending stories. I, at least, will never forget him.

Here, some memorial photos from the 1991 trip. — *Scott Bryan*

Left — Vitalii presented the 1991 travelers (left to right, Jack Hobart, Bill Warnock and Martha Fenimore) with many gifts. Included were numerous photos of the Kamchatka brown bear, better known as grizzly bear and probably the same species as that in Yellowstone but not the same as the actual Alaskan brown bear. Here Vitalii was sorting and autographing those pictures. Jack and I both attempted to generate American publicity of Vitalii's work, and perhaps that helped gain him an invitation to a bear conference in Missoula; unfortunately, travel funds were not to be had. [Photo by Scott Bryan]



Right — One of the many bear photos that Vitalii gave to members of the 1991 expedition. Vitalii disliked the use of telephoto lenses, a philosophy that may have led to his death... In the background of this photo is the house that Vitalii built piecemeal through the years, and which was destroyed by fire sometime after the 1991 trip. [Photo by Vitalii Nikolayenko]

Долина Гейзеров.
4.06.91.

Right — On the first full day in Dolina Geizerov, Vitalii led a long hike up–valley. Although numerous hot spring groups were visited, the primary goal was to try to find a bear. We never saw one, but we did find warm bear scat. Here Vitalii was telling one of his many stories to (left to right) Bob Colvin, Martha Fenimore, Katie Sauter, Jack Hobart and Bill Warnock. The central portion of Dolina Geizerov, including the area of Velikan Geyser, is behind Vitalii. [Photo by Scott Bryan]

Left — I cannot recall any 4th of July Celebration more enjoyable than that presented by our Russian hosts. Here Vitalii and Vladimir ('Volodia') Petrushen (behind Vitalii) use rescue flares as fireworks. Lying as Kamchatka does in the far north, in early summer the sky remains light until near midnight. This photo was taken at about 11:00 pm; note the snowy mountain in the background. [Photo by John Rinehart]

Right — No matter where we were in the valley, lunch was brought to us by Vladimir ('Volodia') Petruschen and Mikhail ('Misha') Selefonov. This particular repast of lettuce and tomato sandwiches, smoked salmon and beer was being enjoyed by (left to right) Katie Sauter, Misha, Scott Bryan, Vitalii Martha Fenimore, Volodia, Bob Colvin and Jack Hobart while waiting for an eruption of Troynoy Geyser (geyserite formation in the right background). [Photo by Bill Warnock on Scott Bryan's camera]

GOSA

"Monthly" Interval Variations by Beehive Geyser and Vicinity, Summer 2004

by T. Scott Bryan

Abstract
The intervals of Beehive Geyser and of other geysers whose activity is known to be related to that of Beehive were monitored throughout the summer season of 2004. The result was the discovery of a number of complex relationships dominated by a previously unknown "monthly" cycle.

Introduction I — The Known "Weekly" Geyser Hill Wave

Most of the hot springs on Geyser Hill (Upper Geyser Basin, Yellowstone National Park) are interconnected at depth, so that variations in activity are often widespread and contemporaneous. One such process that is readily observable is known as the "Geyser Hill Wave", and the Summer 2004 study that resulted in this paper was aimed at confirming the continued existence of the Wave.

Although its cause is entirely unknown, the Wave has been observed to produce predictably regular variations in the water levels and eruption intervals in several geysers, most notably Beehive Geyser, Plume Geyser, Silver Spring, Bronze Spring and Little Squirt Geyser. Most obvious to casual observers is the eruption of Little Squirt. It normally takes place only at the time of "Smax", when the water level within in the southern portion of Geyser Hill is at its highest. This general time (plus–or–minus a day or so) is often accompanied by unusually short intervals by Beehive and Plume Geysers, is the most likely time for there to be eruptive episodes by Bronze Spring, and has been related to activity in Giantess Geyser and other, even more distant Geyser Hill features.

All of the above, however, was observed when the Smax of the Geyser Hill Wave recurred at intervals of about one week. In 2004 the interval was only around 2½ days. This was evidently too small a time frame for short Wave–controlled interval cycles to be apparent. In essence, the Wave was not clearly observable except in the guise of Little Squirt's eruptions, which at times were almost predictably regular.

Introduction II — The New "Monthly" Cycle

Throughout the summer of 2004, the average of Beehive Geyser's intervals was less than 16 hours; specific to this study, the mean was 15h 42m for 231 closed intervals. In general, Beehive was remarkably regular and on the cusp of predictability for much of the season after June 20. The complete record of Beehive's activity from April 16 through November 2, 2004 is appended at the end of this paper as Table 3.

It was in June, however, that I began to realize there were long term variations in these intervals, and that this cyclic action was punctuated by extraordinarily long (20–plus) hour intervals that seemed to repeat about once per month. After such an episode took place on June 20, I predicted that a similarly long interval would occur about July 20. When it did so (on July 23), I successfully made even more accurate predictions for August and September; I was not in the Park in October.

These episodes are listed in Table 1, and they are shown on the activity chart of Figure 1 where the cycle peaks are indicated by arrows. That the cycle affected at least the southern portion of Geyser Hill is obvious. Each of the six observed cycles is summarized in the following paragraphs.

Observed Cycle Effects

April 25, 2004
cycle duration unknown

The long Beehive interval of this peak was 25h 45m. This occurred approximately 4¼ days

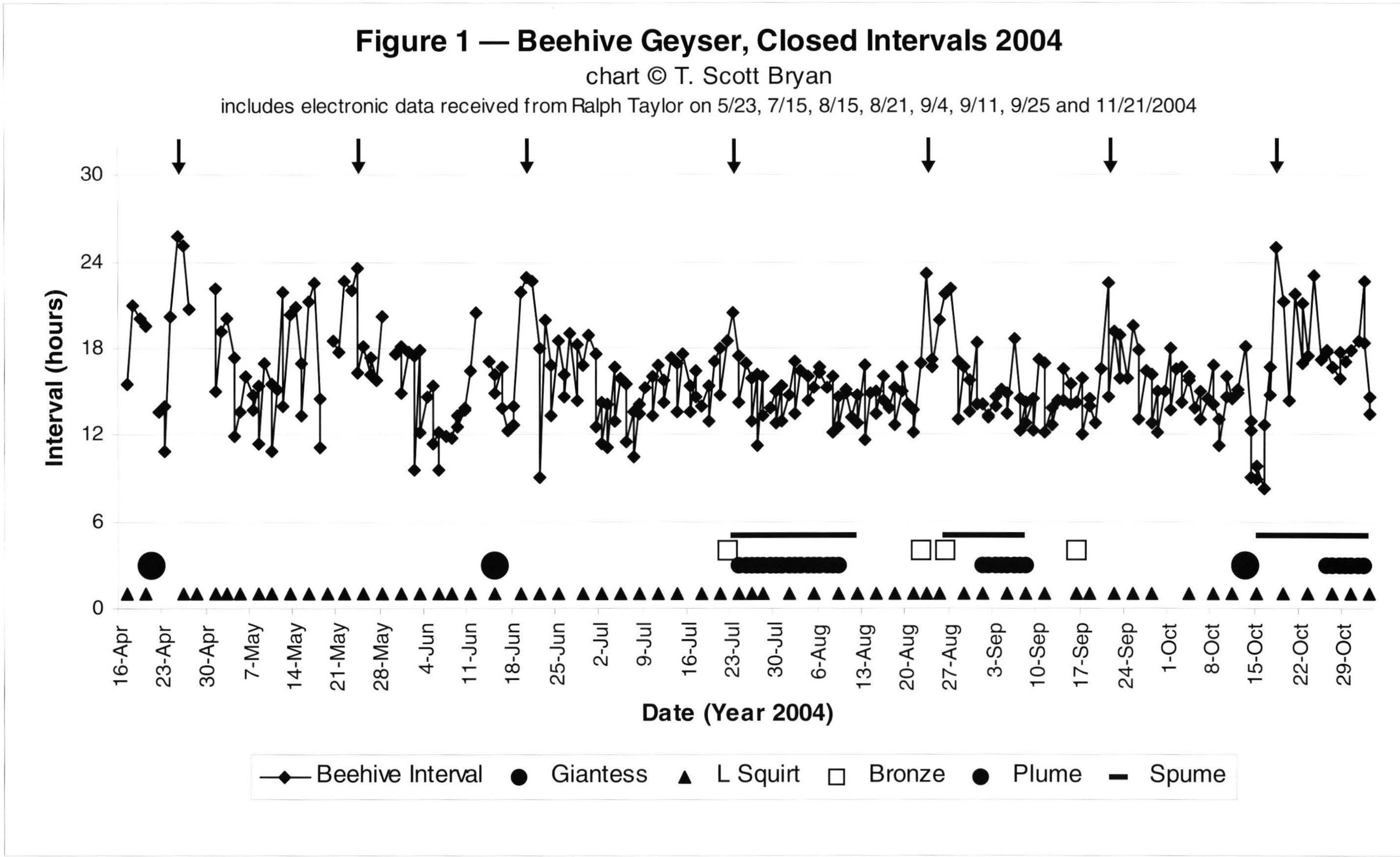


Figure 1. Intervals of Beehive Geyser from April 16 through November 2, 2004 are shown on the vertical scale. Also shown are individual eruptions of Little Squirt Geyser (diamonds on the 1–hour line), and eruptive episodes of Giantess Geyser (large circles on the 3–hour line), Plume Geyser (small circles on the 3–hour line), Bronze Spring (open squares on the 4–hour line) and Spume Geyser (lines on the 5–hour line). The monthly cycle peaks are indicated by arrows along the top of the chart.

Table 1: Cycle Intervals and Observed Associated Effects, Beehive Geyser, 2004

Date and Time	Beehive Interval	Cycle Peak to Cycle Peak Duration		Observed Effects
	hours:minutes	days:hours:minutes	decimal days	
4/25/04 @13:02	25h 45m	unknown	unknown	Giantess 4 days previous
5/24/04 @01:48	23h 37m	28d 12h 46m	28.532 days	None observed except Plume overflow
6/20/04 @11:01	22h 53m	27d 09h 13m	27.384 days	Giantess 5 days previous
7/23/04 @07:57	20h 29m	32d 20h 56m	32.872 days	Bronze, Plume and Spume active after
8/23/04 @07:59	23h 08m	31d 00h 02m	31.001 days	Bronze and Spume, later Plume active
9/21/04 @01:25	22h 32m	28d 17h 26m	28.726 days	Bronze 5 days previous
10/18/04 @22:56	24h 58m	27d 21h 31m	27.896 days	Giantess 5 days previous
Mean Cycle Interval		29d 16h 52m	29.402 days	3h 07m (0.44%) shorter than mean synodic period
Mean Synodic Period			29.532 days	

after the start of eruptions by Giantess Geyser. Following the onset of Giantess, Little Squirt experienced an interval nearly double the seasonal average, its 145h 51m not ending until 18 hours after Beehive's peak. Eruptive action, if any, by other geysers, and especially of Plume, Spume or Bronze, is unknown due to the early season date when few or no geyser gazers were present. It is believed, however, the Plume did overflow during Giantess' activity. Also unknown is the duration of the cycle leading to this peak. (At that time, the electronic recorder was located in a position where it failed to detect many Beehive eruptions. Data for the appropriate part of March, when the park was additionally closed, is unavailable.)

May 24, 2004
cycle duration 28d 12h 46m

Although this long Beehive interval was quite extreme, at 23h 37m, the peak itself was somewhat subdued, marked by what is simply the longest single interval among a series of "longer than usual intervals" (as compared to the following part of 2004). The gentle nature of this cycle might account for the fact that no associated effects were noted among any other geysers.

June 20, 2004
cycle duration 27d 09h 13m

This cycle peak was sharp, the data set showing three long Beehive intervals bound by unusually short intervals both before and after the peak. The longest of these Beehive intervals was 22h 53m. In a fashion very similar to the peak in April, Giantess Geyser began an active phase just less than 5 days prior to the peak. There was absolutely no evident response in Plume Geyser, and allied events in other geysers also were not observed.

July 23, 2004
cycle duration 32d 20h 56m

This was the longest cycle peak–to–peak duration, and was culminated by the least extreme of the long Beehive intervals: "only" 20h 29m. However, this peak was accompanied by dramatic activity in the related geysers. Bronze Spring underwent its first known activity of 2004 almost exactly 24 hours earlier, and then played every few minutes with bursts up to 6 feet high. Roughly 7 hours after the specific peak time, Plume and Spume Geysers began erupting; neither had played since February 2004, but now they persisted until August 10.

August 23, 2004
cycle duration 31d 00h 02m

This appears to have been a double peak. The longest Beehive interval, on August 23, was 23h 08m. The peak was preceded by a little less than 1 day by eruptions of Bronze Spring, which was active for less than 12 hours. The secondary peak, with a Beehive interval of 22h 08m, was late on August 27, a little more than 4½ days following the primary peak. As seemed to be a rule, this peak was also preceded by activity in Bronze Spring, which began 1½ days before the peak, and was quickly joined by Spume Geyser. Plume eventually responded, on September 1, and continued activity until September 8.

September 21, 2004
cycle duration 28d 17h 26m

Beehive's long interval that marked this peak was 22h 32m. It was preceded by a brief eruptive phase by Bronze Spring that occurred on September 16, about 4½ days before the peak. Although this episode of activity was brief and ended before the cycle peak, the eruptions were strong and some bursts over 12 feet high were seen.

October 18, 2004
cycle duration 27d 21h 31m

This was the longest Beehive peak interval since that of April, at 24h 58m. As was the case in both April and June, The peak was preceeded by about 5 days by activity in Giantess Geyser, as was the case in both April (4 days) and June (5 days). Somewhat different was the fact that those earlier Giantess eruptions were *not* accompanied or followed by eruptions in Plume, Bronze or Spume, whereas on this occasion both Spume, then Plume became temporarily active.

Table 2. Time Relationship Between New Moon and Monthly Cycle Events

New Moon Date & Time [1]	Associated Event Name, Date & Time	Difference from New Moon [2]	Beehive Peak Date & Time	Difference from New Moon [2]
4/19/04 @07:21	Giantess, 4/21 @07:30	+ 2d 02h 09m	4/25 @13:02	+ 6d 05h 41m
5/18/04 @22:52	none observed	-----	5/24 @01:48	+ 5d 02h 56m
6/17/04 @14:27	Giantess, 6/15 @12:43	– 2d 01h 44m	6/20 @11:01	+ 2d 20h 34m
7/17/04 @05:24	Bronze, 7/22 @08:00 ie	+ 5d 02h 46m	7/23 @07:57	+ 6d 02h 33m
8/15/04 @19:24	Bronze, 8/22 @12:00ie	+ 6d 16h 46m	8/23 @07:59	+ 7d 12h 35m
9/14/04 @08:29	Bronze, 9/16 @12:00 ie	+2d 03h 31m	9/21 @01:25	+ 6d 16h 56m
10/13/04 @20:48	Giantess, 10/13 @13:34 ie	– 0d 07h 14m	10/18 @22:46	+5d 01h 58m

1. Source: www.aa.usno.navy.mil/data/docs/MoonPhase.html, Astronomical Applications Department, U.S. Naval Observatory; times corrected to Mountain Daylight Time.
2. Negative values (–) represent event prior to date and time of New Moon; plus values (+) represent event after the date and time of New Moon.

A Hypothetical Cause of the "Monthly" Cycles

The following is highly conjectural and will not be discussed in detail. It is clear, however, that cyclic action was occuring within Geyser Hill, and that the cycles repeated grossly similar events on an average basis remarkably close to one lunar month (the synodic period, which itself can vary by several hours from its 29.532 day mean value). As shown in Table 1, the mean cycle interval was only 3h 07m (or 0.44%) shorter than the mean synodic period. Thus, the thought that varying lunar tidal stresses serve as a control of Geyser Hill activity seems reasonable.

Therefore, a comparison was made between the actual dates and times of lunar phases versus the Geyser Hill events and Beehive peaks. The result is shown in Table 2. In fact, four of the six observed Geyser Hill events and six of the seven Beehive peaks took place between New Moon and 1st Quarter Moon; that is, during the first 25% of the complete synodic period. Furthermore, the two events and the one Beehive Peak that fell outside this interval did so by small amounts; indeed that one Beehive peak missed the interval by only 3h 23m.

Is this conjecture valid; can this apparent relationship be tested statistically? That I cannot answer. There are only seven "data points," and in any case I do not personally have a background in statistics sufficient to allow me to conduct such tests. For others who may with to do so, the dates and times of the Summer 2004 New Moons are included here in Table 2, and the complete record of Beehive Geyser's eruptions comprises Table 3.

So, the thought that the Moon's tidal stress might have a direct influence on Geyser Hill events is a conjecture, and nothing more. However, I think it is important to note that this has been hypothesized before. Dr. John Rinehart felt that he could show a short term lunar control at Riverside Geyser. I have always been puzzled by Dr. Donald E. White's rejection of that idea, since in 1952 he showed a strong lunar control in an erupting well at Steamboat Hot Springs, Nevada. So as hypothetical as this idea is, I believe it bears future attention.

On the Relationship Between Giantess Geyser and Bronze Spring

In the course of previous studies of geyser activity on Geyser Hill, I inferred that several relatively small geysers can ursurp activity by much larger Giantess Geyser. Other observers have made similar observations. In summary here, it has been shown that at least Dome Geyser, or Beehive Geyser or Plume Geyser have apparently erupted "instead of" Giantess.

In the course of Summer 2004, the obvious cyclic activity on Geyser Hill was marked by long "peak intervals" by Beehive Geyser, and also by activity in *either* Giantess Geyser *or* Bronze Spring. It seems remarkable that two hot springs apparently so different from one another are able to play the same, or perhaps exchange, roles within the geothermal system, but such again seems to be the case.

Acknowledgements

Numerous geyser gazers provided eruption data that contributed to this paper, but the greatest of thanks are due to NPS volunteer Ralph Taylor, who provided electronic data for the activity of Beehive, Plume and Little Squirt Geysers in electronic files dated May 23, July 15, August 15, August 21, September 11 and September 25, 2004. The completion of this paper would have been impossible without that data.

Notes about the data and some nomenclature.

Although it is known that the electronic recorder commonly "sees" an eruption about 2 minutes after the actual start time, such data has not been corrected for this paper. All times, whether visual or electronic, are taken as being exact.

Noted in this paper are eruptive episodes by Spume Geyser. The hot spring crater that includes the vent of Spume also contains the vent of Spew Spouter, which clearly is a separate hot spring. A possible third vent in that same crater is informally named "Scuba Geyser." Most 2004 eruptions by this complex were reported as being by Scuba. However, it is not clear that Scuba actually exists as a different or new vent, so this activity is reported here as by Spume.

Table 3. Beehive Geyser, April 16 – November 2, 2004

Note: "gap in record" notes occasions when it was positively known that an unseen and/or unrecorded eruption took place during the time between known records.

Date Time	Interval
4/17/04 2:45	
4/17/04 18:21	15:36
4/18/04 15:18	20:57
4/19/04 11:24	20:06
4/20/04 7:01	19:37
4/21/04	gap in record
4/22/04 0:39	gap in record
4/22/04 14:14	13:35
4/23/04 4:12	13:58
4/23/04 15:03	10:51
4/24/04 11:17	20:14
4/25/04 13:02	25:45
4/26/04 14:10	25:08
4/27/04 10:53	20:43
4/28/04	gap in record
4/29/04	gap in record
4/30/04 4:25	gap in record
5/1/04 2:35	22:10
5/1/04 17:33	14:59
5/2/04 12:40	19:07
5/3/04 8:48	20:08
5/4/04 2:10	17:22
5/4/04 14:02	11:52
5/5/04 3:41	13:39
5/5/04 17:20	13:39
5/6/04 9:22	16:02
5/7/04 0:12	14:50
5/7/04 13:56	13:42
5/8/04 5:19	15:23
5/8/04 16:40	11:21
5/9/04 9:38	16:58
5/10/04 1:14	15:36
5/10/04 12:08	10:54
5/11/04 3:15	15:07
5/12/04 1:07	21:52
5/12/04 15:05	13:58
5/13/04 11:26	20:21
5/14/04 8:16	20:50
5/15/04 1:15	16:59
5/15/04 14:34	13:17
5/16/04 11:52	21:18
5/17/04 10:21	22:29
5/18/04 0:53	14:32
5/18/04 12:00	11:07
5/19/04 17:06	gap in record
5/20/04 11:41	18:33
5/21/04 5:25	17:44
5/22/04 4:07	22:42
5/23/04 2:08	22:01
5/24/04 1:48	23:37
5/24/04 18:11	16:23
5/25/04 12:18	18:07
5/26/04 4:33	16:15
5/26/04 22:52	17:19
5/27/04 14:39	15:47
5/28/04 10:49	20:10
5/29/04 14:29	gap in record
5/30/04 8:10	17:41
5/31/04 2:18	18:08
5/31/04 17:09	14:51
6/1/04 10:55	17:46
6/2/04 4:22	17:27
6/2/04 13:57	9:32
6/3/04 7:47	17:50
6/3/04 20:58	12:11
6/4/04 11:34	14:36
6/5/04 2:59	15:25
6/5/04 14:25	11:26
6/6/04 2:33	12:08
6/6/04 12:10	9:37
6/7/04 11:53	gap in record
6/7/04 23:50	11:57
6/8/04 11:37	11:47
6/9/04 0:54	13:17
6/9/04 13:27	12:33
6/10/04 3:12	13:45
6/10/04 19:01	13:49
6/11/04 11:26	16:25
6/12/04 7:55	20:26
6/13/04 17:11	gap in record
6/14/04 10:18	17:07
6/15/04 2:33	16:15
6/15/04 16:29	14:56
6/16/04 9:12	16:43
6/16/04 23:06	13:54
6/17/04 11:28	12:22
6/18/04 0:11	12:43
6/18/04 14:12	14:01
6/19/04 12:08	21:56
6/20/04 11:01	22:53
6/21/04 9:41	22:40
6/22/04 3:45	18:04
6/22/04 12:48	9:03
6/23/04 8:43	19:55
6/24/04 0:36	16:53
6/24/04 13:57	13:21
6/25/04 8:28	18:31
6/26/04 0:39	16:11
6/26/04 15:17	14:38
6/27/04 10:19	19:02
6/28/04 0:39	14:20
6/28/04 18:55	18:16
6/29/04 11:49	16:54
6/30/04 6:45	18:56
7/1/04 0:24	17:39
7/1/04 12:58	12:34
7/2/04 3:14	14:16
7/2/04 14:41	11:27
7/3/04 4:52	14:11
7/3/04 15:59	11:07
7/4/04 8:38	16:39
7/4/04 21:33	12:55
7/5/04 13:00	15:57
7/6/04 4:32	15:32
7/6/04 16:04	11:32
7/7/04 5:38	13:34

7/7/04 16:06	10:28	8/16/04 7:57	16:05
7/8/04 6:10	14:04	8/16/04 22:23	14:26
7/8/04 19:42	13:32	8/17/04 12:11	13:48
7/9/04 10:56	15:14	8/18/04 3:30	15:19
7/10/04 2:59	16:03	8/18/04 16:08	12:38
7/10/04 16:20	13:21	8/19/04 7:07	14:59
7/11/04 9:10	16:50	8/19/04 23:49	16:42
7/12/04 1:00	15:50	8/20/04 13:59	14:10
7/12/04 15:17	14:17	8/21/04 3:40	13:41
7/13/04 8:35	17:18	8/21/04 15:52	12:12
7/14/04 1:30	16:55	8/22/04 8:51	16:59
7/14/04 15:06	13:36	8/23/04 7:59	23:08
7/15/04 8:40	17:34	8/24/04 1:12	17:13
7/16/04 0:06	15:26	8/24/04 17:53	16:41
7/16/04 13:41	13:35	8/25/04 13:49	19:56
7/17/04 6:05	16:24	8/26/04 11:38	21:49
7/17/04 20:47	14:42	8/27/04 9:46	22:08
7/18/04 10:43	13:56	8/28/04 2:55	17:09
7/19/04 2:05	15:22	8/28/04 15:59	13:04
7/19/04 15:03	12:58	8/29/04 8:38	16:39
7/20/04 8:12	17:08	8/30/04 0:29	15:51
7/21/04 2:11	17:59	8/30/04 14:02	13:33
7/21/04 17:00	14:49	8/31/04 8:25	18:23
7/22/04 11:28	18:28	8/31/04 22:30	14:05
7/23/04 7:57	20:29	9/1/04 12:35	14:05
7/24/04 1:30	17:30	9/2/04 1:44	13:09
7/24/04 15:47	14:17	9/2/04 15:03	13:19
7/25/04 8:46	16:59	9/3/04 5:38	14:35
7/26/04 0:41	15:55	9/3/04 19:34	13:56
7/26/04 13:39	12:58	9/4/04 10:44	15:10
7/27/04 5:53	16:14	9/5/04 1:40	14:56
7/27/04 17:06	11:13	9/5/04 15:07	13:27
7/28/04 9:10	16:04	9/6/04 9:43	18:36
7/28/04 22:33	13:23	9/7/04 0:17	14:34
7/29/04 12:27	13:54	9/7/04 12:32	12:15
7/30/04 3:30	15:03	9/8/04 2:48	14:16
7/30/04 16:23	12:53	9/8/04 15:40	12:52
7/31/04 7:49	15:26	9/9/04 6:15	14:32
7/31/04 20:49	13:00	9/9/04 18:37	12:22
8/1/04 11:36	14:47	9/10/04 11:52	17:13
8/2/04 4:42	17:06	9/11/04 4:53	16:59
8/2/04 18:10	13:28	9/11/04 17:01	12:08
8/3/04 10:41	16:31	9/12/04 6:53	13:52
8/4/04 2:44	16:03	9/12/04 19:34	12:41
8/4/04 17:05	14:21	9/13/04 9:57	14:23
8/5/04 9:25	15:20	9/14/04 0:23	14:26
8/6/04 2:10	16:45	9/14/04 16:56	16:33
8/6/04 18:27	16:17	9/15/04 8:29	15:30
8/7/04 9:45	15:18	9/15/04 22:40	14:09
8/8/04 1:46	16:01	9/16/04 12:56	14:16
8/8/04 13:54	12:08	9/17/04 4:56	15:58
8/9/04 4:33	14:39	9/17/04 16:58	12:02
8/9/04 17:04	12:31	9/18/04 7:29	14:31
8/10/04 8:10	15:06	9/18/04 21:25	13:56
8/10/04 23:01	14:51	9/19/04 10:16	12:51
8/11/04 12:16	13:15	9/20/04 2:53	16:37
8/12/04 3:04	14:48	9/21/04 1:25	22:32
8/12/04 15:51	12:47	9/21/04 16:00	14:35
8/13/04 8:44	16:53	9/22/04 11:09	19:09
8/13/04 20:26	11:42	9/23/04 3:08	15:59
8/14/04 11:20	14:54	9/23/04 22:02	18:54
8/15/04 2:23	15:03	9/24/04 13:50	15:58
8/15/04 15:52	13:29	9/25/04 9:25	19:35

9/26/04 3:18	17:53
9/26/04 16:25	13:07
9/27/04 8:53	0.69
9/28/04 1:08	16:15
9/28/04 13:56	12:48
9/29/04 4:47	15:01
9/29/04 17:05	12:08
9/30/04 8:06	15:01
10/1/04 2:04	17:58
10/1/04 15:49	13:45
10/2/04 8:24	16:35
10/3/04 1:05	16:41
10/3/04 15:22	14:17
10/4/04 7:29	16:07
10/4/04 23:16	15:47
10/5/04 13:05	13:49
10/6/04 4:03	14:58
10/6/04 17:08	13:05
10/7/04 7:42	14:34
10/8/04 0:29	16:47
10/8/04 14:39	14:10
10/9/04 3:45	13:06
10/9/04 14:59	11:14
10/10/04 5:35	14:36
10/10/04 21:39	16:04
10/11/04 12:13	14:34
10/12/04 3:08	14:55
10/12/04 18:15	15:07
10/13/04 12:20	18:05
10/14/04 1:16	12:56
10/14/04 13:36	12:20
10/14/04 22:43	9:07
10/15/04 7:39	8:56
10/15/04 17:30	9:51
10/16/04 1:49	8:19
10/16/04 14:33	12:44
10/17/04 7:12	16:39
10/17/04 21:58	14:46
10/18/04 22:56	24:58
10/19/04 20:11	21:15
10/20/04 10:32	14:21
10/21/04 8:21	21:49
10/22/04 1:23	17:02
10/22/04 22:32	21:09
10/23/04 16:05	17:33
10/24/04 15:08	23:03
10/25/04 8:25	17:17
10/26/04 2:08	17:43
10/26/04 20:03	17:55
10/27/04 12:42	16:39
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10/28/04 22:21	17:46
10/29/04 15:27	17:06
10/30/04 9:20	17:53
10/31/04 2:48	18:28
11/1/04 1:31	22:43
11/1/04 19:52	18:21
11/2/04 10:29	14:37
11/2/04 23:58	13:29
Mean Interval	15:43
Number Intervals	291

Herbert C. Warren

b. February 12, 1910,
in Colorado
d. August 25, 1998,
in Colorado Springs, Colorado

Hardly a Yellowstone geyser gazer is unfamiliar with the concept of a "Herb Warren splash" at Beehive Geyser, a huge surge from Beehive's cone that often is a portent that Beehive's Indicator will start playing within a short time. At the time of this October 1984 photo, Herb was encouraging photographer Andy Casterline to hurry, since the Indicator was playing (visible in the background).

Relatively few existing gazers knew Herb and those who did have often wondered about his fate, since he seldom or never visited Yellowstone after the death of J. Randolph Railey. Herb is known to have resided in Colorado Springs, and it was an Internet search of Social Security Administration birth–death records that revealed the above dates.

The Relationship Between the Timing of Rift Geyser Eruption Starts and the Length of Grand Geyser's Intervals

by Vicki Whitledge

Abstract

A relationship between the length of Grand Geyser's interval and eruptions of Rift Geyser has long been suspected. The electronic data from 2003 was analyzed to investigate and attempt to quantify this relationship. A sample of 310 Grand eruption cycles was studied in more detail to determine the nature of the relationship between Grand and Rift Geysers. These data provide evidence of a statistical relationship between the timing of a Rift eruption start and the length of Grand's interval. The nature of this relationship is discussed.

Introduction

It is commonly believed that eruptions of Rift Geyser delay eruptions of Grand Geyser. This effect was noted in a study conducted by Suzanne Strasser in 1978. Although the delaying effect of Rift Geyser was discussed in that report, it noted that the effect was not guaranteed. Of the eleven Rift eruptions observed during the Strasser study, "seven significantly delayed Grand, while the other four had no apparent effect" [Strasser, 1989]. Some years Grand seems to be delayed by Rift and in other years, such as 1993, Rift seems to have only a small impact [Bryan, 1995]. More recently, the influence appears less specific. In general, more frequent activity by Rift appears to be associated with longer intervals of Grand rather than causing a specific delay in Grand's eruption [Schwarz, 2004a]. To account for some of these variations, the belief that Rift delays Grand is sometimes refined to claim that only eruptions early in Grand's eruption cycle (or only ones that are late) delay Grand's eruption [Taylor, 2004a]. However, more recently, it seems that Rift eruptions that occur near an eruption of Grand have less of an influence than those that occur at other times [Schwarz, 2004a]. From these observations, it appears that there are two issues of interest when investigating the effects of Rift on Grand. The first issue is to determine what evidence exists to support the idea of a connection between the activity of Rift and the activity of Grand. The second issue is to determine the nature of the connection and if the time-location of a Rift eruption start is important.

In 2003, both Grand Geyser and Rift Geyser were electronically monitored for the entire year. This data was analyzed to see if there was evidence that Rift was influencing Grand in 2003 and, if it was, to estimate the size of the effect. A sample of data from 2003 was analyzed in more detail to determine if there was evidence that the timing of a Rift eruption start relative to Grand's eruption cycle made a difference in the effect and, if it did, what the nature of this difference was.

Source and Quality of Data

The data analyzed for this article is the electronic data recorded by the data loggers that are deployed on Grand and Rift Geysers. The Geology Group, under Supervisory Geologist Henry Heasler, coordinates the collection of the raw data. The raw data consists of temperature readings of the water in the run-off channel of the geyser that is monitored. Ralph Taylor, working as a volunteer for YCR, conducted the initial analysis of the raw data. This initial analysis extracted the date and time of eruption starts from the raw temperature data. The eruption intervals were then computed from these times. The data files containing the raw temperature data, extracted date and time of eruption starts, and intervals used for this article were provided to the author by Ralph Taylor. For a further discussion of the data collection see "Geyser Data Logger Background" by Ralph Taylor [Taylor, 2004 online].

The possible errors that are of concern while looking at this data come in three different types:

missing data, errors in the temperature data, and errors in the eruption times and intervals that were calculated from the temperature data.

The first type of error, missing data, occured when the data logger failed to collect any temperature data. This type of error, while unfortunate, can usually be compensated for in an analysis, typically by simply excluding the time period for which there is no data from the analysis. For 2003, the temperature data from Rift Geyser is complete. There are no gaps in the data collection. For Grand Geyser, there are two short periods where data was not collected. These two periods were from May 22, 09:44 to May 23, 09:40 and from May 24, 11:44 to May 25, 08:29. (All times are recorded using a 24–hour clock.)

The second type of error, errors in the temperature data, occured when the data logger is collecting temperature data, but the data did not reflect the true behavior of the geyser being monitored. For example, some geysers use more than one run-off channel. A sensor placed in one channel may entirely miss eruptions when the run-off flows in other channels. Another problem occurs when more than one geyser produce run-off in the same channel. This may lead to the conclusion that a geyser is more active than it is in reality. This type of error can be very serious if there are no artifacts in the temperature trace to indicate that the data do not reflect the true state of the geyser. Fortunately, in some cases, errors of this type can be detected by examining the data. Signals from multiple geysers are not a problem when the signals can be differentiated from each other. An example of this occurs with Grand and Turban Geysers. The runoff from both geysers uses the same runoff channel and is detected by the sensor for Grand. This does not cause any difficulties, however, because the signal for a Grand eruption is significantly stronger than the signal produced by a Turban eruption. Another type of error in the temperature data that can usually be detected is error due to ice dams. When this happens the sensor does not detect the temperature of the runoff, but instead records the temperature of the ice. This type of error typically produces a distinctive flat-line trace. Errors in the temperature data that are not detectable by simple inspection of the temperature trace should be considered the most serious type of error because these are errors that cannot be compensated for.

The third type of error, errors in eruption times and intervals, occured as data processing errors. The temperature data must be analyzed to extract the eruption times, which are then used to calculate the intervals. Eruption starts are identified by locating distinctive changes in the temperature trace. Because of the immense quantity of data collected by the data loggers, the temperature data must be analyzed by computer. Although each geyser tends to produce temperature signatures that are characteristic of its eruptions, errors occur in this analysis because many factors can introduce changes in the temperature profile of a given eruption. Air temperature and the weather can effect the temperature data, especially if the temperature sensor is located a long distance from the geyser. Another issue for some geysers is the natural variation that can occur from eruption to eruption. These changes in the eruption signature can cause the detection program to miss or misplace eruption start times. Data processing errors are bothersome because they introduce another opportunity for errors to enter the data set. However, as long as the temperature data does not have fundamental errors in it, these errors can be corrected, if necessary, before an analysis is performed. The eruption start times generated by computer analysis will be referred to as "extracted data" in the rest of the paper when it is necessary to differentiate them from data obtained by other methods.

To check for the second and third types of errors, the extracted times of the eruption starts of both Grand and Rift were compared to the Old Faithful Visitor Center (OFVC) Logbook which has been transcribed by Lynn Stephens and is available on-line [Stephens, 2003]. For Grand Geyser, the OFVC logbook contains times of Grand starts that were witnessed visually and, frequently when visual times were not available, electronic start times for Grand. These electronic times were obtained by interpretive rangers looking at graphs of the temperature traces [Taylor, 2004b]. For Rift Geyser, the entries in the OFVC logbook are all from visual observations.

Any differences between the OFVC logbook and the extracted times were further investigated by looking at the original temperature data. In most cases, the temperature trace verified the visual time as the correct time. In checking both Grand and Rift, there were ten instances where the temperature trace verified an extracted time and contradicted a visual time. These instances were looked at closely. Of the ten, two were denoted as visitor reports, indicating that the times entered in the logbook may be inaccurate. Seven had indications that some type of copying error may have occurred. For example, the "minutes" of the eruption start were consistent between the logbook and extracted times but the "hour" time was off by one or two hours. The last instance was a Rift eruption that was denoted in the logbook by "e" for electronic even though it was not consistent with the electronic data and no other electronic times had been entered for Rift for the entire year. Furthermore, the eruption time indicated was inconsistent with the two *visually* observed (and electronically verified) eruptions that bracketed it and Rift's known typical behavior. Therefore, I believe that this logbook entry is in error.

From the above inspections, there is no indication that entire eruptions were ever missed by the temperature probes in the run-off channels of either Grand or Rift. In addition to the comparison with the OFVC logbook, nineteen weeks of temperature data were independently plotted in Excel along with the times of the eruption starts, and these were inspected visually to determine the accuracy of the eruption start times. This error check, of course, would not indicate any errors in the temperature data but would reveal errors that occurred during the extraction process.

The extracted Rift data for 2003 appears to be of very high quality. The two methods of error checking did not reveal a single error in the extracted eruption start times for Rift. This claim, however, is tempered by the fact that only a limited amount of data could be checked. The OFVC logbook contained only 121 entries for Rift during 2003. Of these, there were only 41 instances where the time of a Rift start was noted. The other 80 entry times were denoted as "in eruption". All logbook entries were consistent with the extracted data. For comparison, the electronic data detected 553 Rift eruption starts in 2003. This means that only 7.4% of start times could be verified. When the "in eruption" times were included 21.9% of the year's eruptions were checked. Independent checking of the graphs verified 202 eruption start times. This was 36.5% of the year's eruptions.

The Grand Geyser eruption times contained some errors, but were still of high quality. Approximately, 6% of the eruption times of Grand Geyser were in error in 2003, meaning that 94% of the times were accurate. For Grand Geyser, 316 extracted start times could be compared to visual start times, an additional 31 log entries had times labeled "in eruption" and 443 "electronic" times were entered. This means that 35.7% of extracted start times could be compared to visual start times. When the "in eruption" and "electronic" logbook times are included 88.1% of the extracted times were checked.

The errors that were found in the Grand data occurred when a large pre-eruption spike in the temperature of the overflow was detected as the eruption start instead of the true eruption start. These produced inaccurate eruption starts that were one half to two hours before the actual eruption start. The errors in the eruption times produced corresponding errors in the interval times for Grand Geyser. There was a single instance where a Grand eruption was missed by the eruption detection algorithm. This error occurred because ice dams around the sensor weakened the temperature spike of the eruption. This eruption was able to be seen by visual inspection of a graph of the temperature trace.

Initial Analysis of Extracted Data

For 2003, the Grand Geyser extracted data had 884 intervals with the following statistics: Minimum 5h54m, Mean 9h50m, Median 9h53m, Maximum 14h31m, Standard Deviation 1h24m, and a Coefficient of Variation 14.19%. For Rift Geyser, the extracted data had 553 intervals with the following statistics: Minimum 3h00m, Mean 15h51m, Median 15h54m, Maximum 40h55m, Standard Deviation 4h05m, and a Coefficient of Variation 25.76%. The maximum interval of 14h31m for Grand Geyser is known to be accurate as it occurred in July and was witnessed by many observers. The minimum interval for Rift Geyser of 3h00m occurred when a prior eruption of Rift had an extremely short duration of 5 minutes or less. Although rare, this type of behavior, where a very short duration eruption leads to a very short subsequent interval, was seen a total of six times throughout the year with Rift Geyser. In these cases, the subsequent intervals, sorted by increasing length, were as follows: 3h00m, 3h05m, 3h20m, 4h20m, 5h10m, and 5h48m.

An initial analysis of the entire data set was carried out as follows. The intervals of Grand were separated into two classes based on whether or not a Rift eruption occurred during the interval, the interval being the time between the prior eruption start and the current eruption start. The mean and median interval length of each class was then computed. The intervals of Grand which contained the start of a Rift eruption had a mean *and* median length of 10h09m, rounded to the nearest minute. The intervals of Grand which did not contain the start of a Rift eruption had a mean length of 9h19m and a median length of 9h12m, rounded to the nearest minute. Thus the intervals of Grand that had a Rift eruption start in them had a mean length that was 50 minutes longer than the intervals which did not have a Rift eruption start in them. A problem with interpreting the above statistic is that, even if Rift eruptions were completely independent of Grand eruptions, longer Grand intervals would be more likely to contain the start of a Rift eruption. Thus, even if there were no effect of Rift on Grand, one should still see a difference between the mean interval lengths when they are separated into classes this way. Furthermore, it should be kept in mind that this is a difference of averages. It is entirely possible that Rift Geyser could have a large effect on some eruptions and no effect on others. To address these issues a more detailed analysis which took into account the location of a Rift eruption start was conducted.

Table 1 — Weeks included in the Sample
13/Jan/03 to 19/Jan/03
01/Feb/03 to 07/Feb/03
10/Feb/03 to 16/Feb/03
10/Mar/03 to 16/Mar/03
17/Mar/03 to 23/Mar/03
24/Mar/03 to 30/Mar/03
03/Apr/03 to 09/Apr/03
24/Apr/03 to 30/Apr/03
05/May/03 to 11/May/03
12/May/03 to 18/May/03
09/Jun/03 to 15/Jun/03
14/Jul/03 to 20/Jul/03
11/Aug/03 to 17/Aug/03
08/Sep/03 to 14/Sep/03
13/Oct/03 to 19/Oct/03
10/Nov/03 to 16/Nov/03
03/Dec/03 to 09/Dec/03
16/Dec/03 to 22/Dec/03
23/Dec/03 to 29/Dec/03

Analysis of the Relationship between the Location of a Rift Eruption Start and Grand's Interval Lengths

Methods

To analyze the relationship between the location of a Rift eruption start and Grand's interval lengths, a sample of 310 eruptions from 2003 was examined. The entire data set was not inspected for this analysis because the work involved in this analysis is time–consuming. The 310 eruptions occur in 19–week–long blocks. Each month had at least one week selected from it. These twelve weeks usually started with the second Monday in the month. In some cases, the week chosen this way was adjusted so that gaps in the data were avoided. The seven additional weeks were chosen to inspect any unusually long intervals of both geysers and any unusually short intervals of Grand Geyser. This sample is not random, but it does contain data that represents behavior across the entire year and extreme events. Table 1 has a list of the weeks that were chosen. The statistics of the 310 Grand intervals included in the sample were as follows: Minimum 5h54m, Mean 9h41m, Median 9h51m, Maximum 14h31m and a Coefficient of Variation 16.52%.

For each day in the chosen weeks, the temperature traces and eruptions start times of the geysers were plotted. Figure 1 shows a daily graph of the temperature traces of Grand and Rift from March 12, 2003. This graph shows two eruptions of Grand and a single eruption of Rift. The temperature data is plotted with a solid line for Grand and a dotted line for Rift. The extracted eruption times are plotted with a circle for Grand and a triangle for Rift. The temperature trace of Grand Geyser was plotted in degrees Fahrenheit and the temperature trace of Rift Geyser was plotted in degrees Celsius. The Grand Geyser temperatures are much lower than the Rift Geyser temperatures because the sensor is much farther away from the geyser than the sensor that is monitoring Rift. Plotting the traces in two different units allows for easier visual inspection since the Rift trace cuts across the trace of Grand whenever Rift starts an eruption. This made it easier to visually place the timing of a Rift start relative to the behavior of Grand.

In 2003, Rift Geyser produced a very clean trace. Eruption starts and stops are typically sharp. When Rift is not erupting, little activity is seen in the trace. The trace from Grand, however, is much

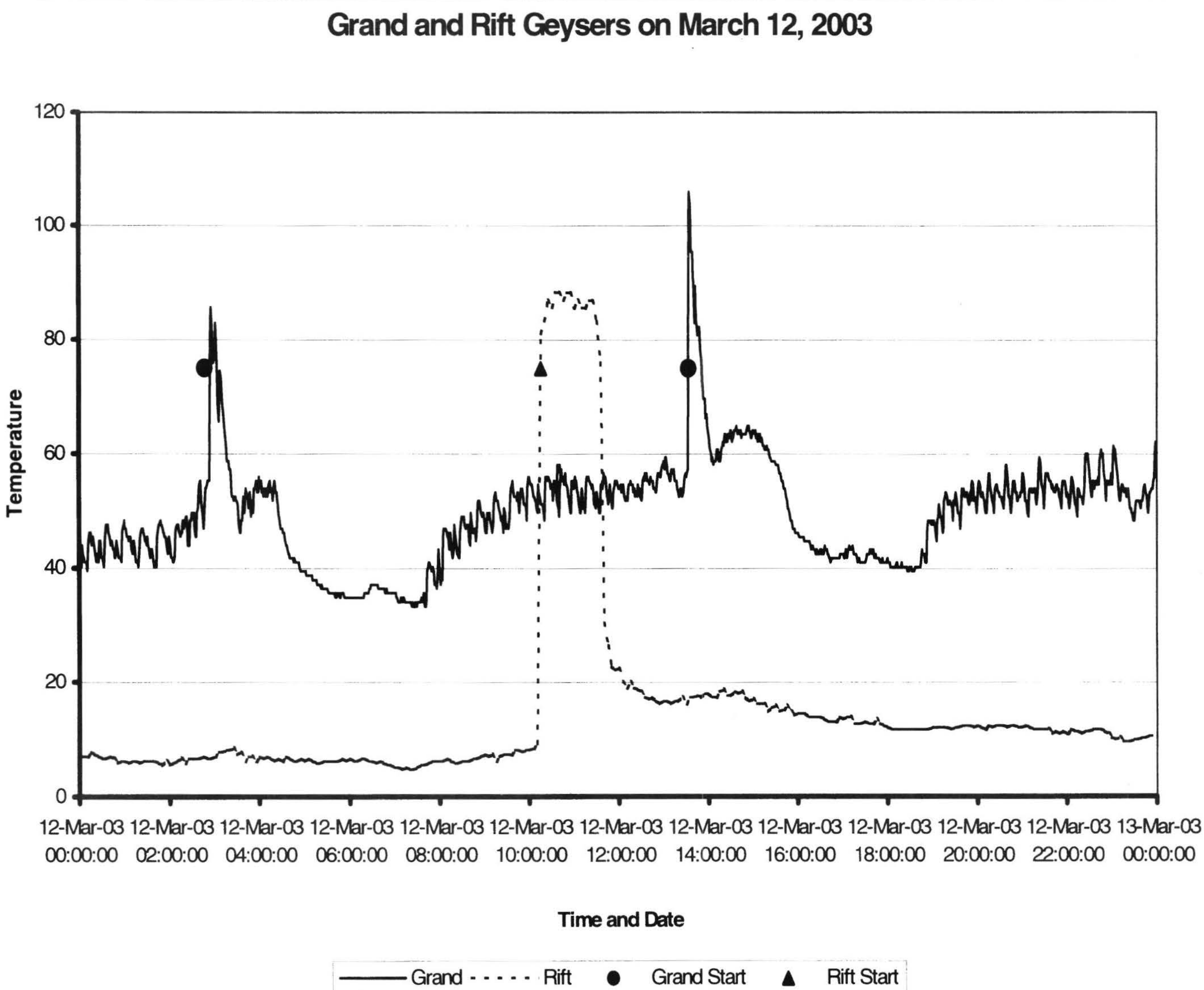

Figure 1. An example of a daily graph used in the analysis. Temperatures for Grand Geyser are in degrees Farenheit and temperatures for Rift Geyser are in degrees Celsius. These are themperatures of the runoff water at the sensor. Temperatures closer to the geysers are much higher.

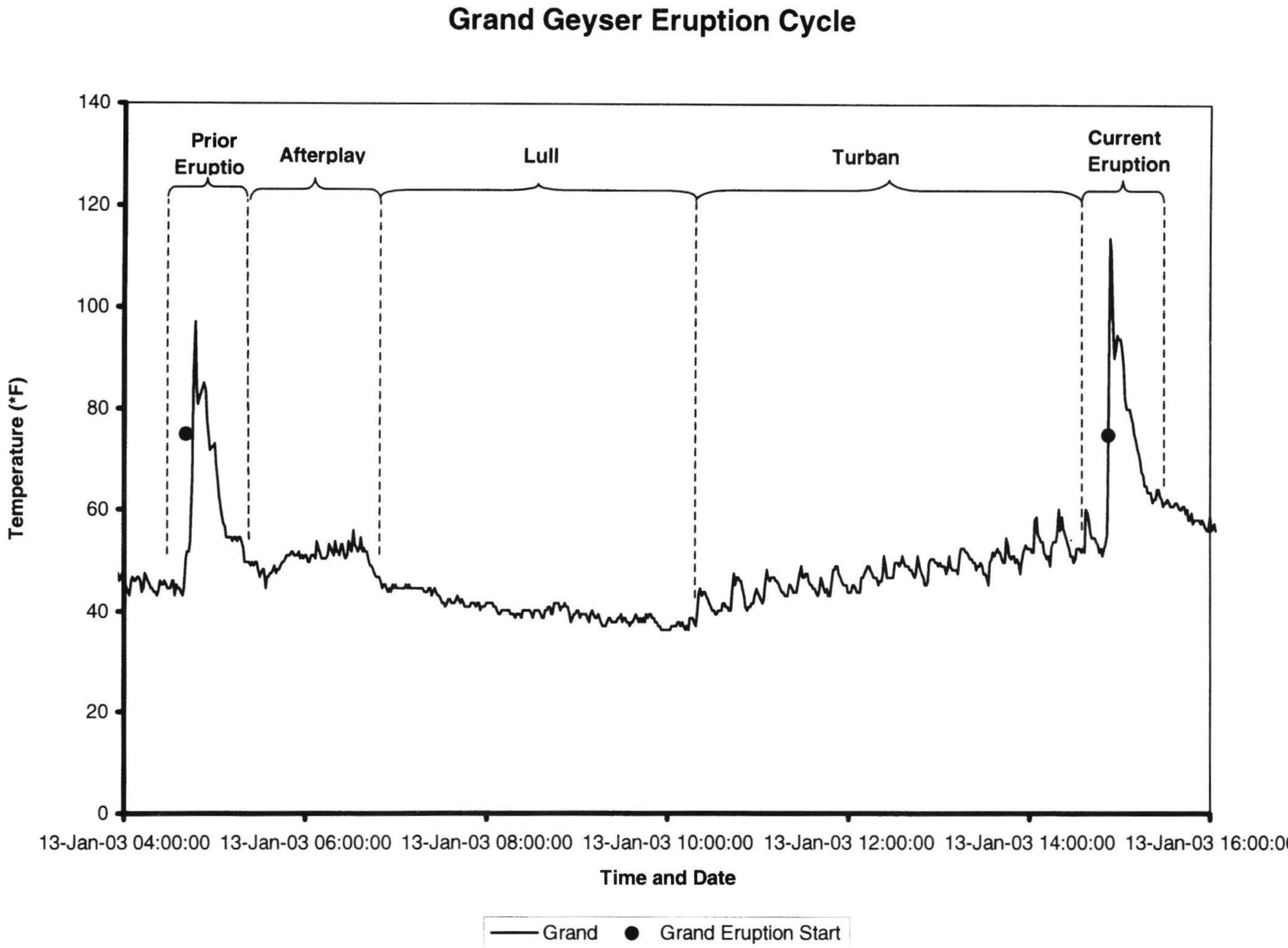

Figure 2. The "named" periods within Grand Geyser's eruption cycle.

more complicated. This is because the runoff channel that was monitored also carries water from Turban and Vent Geysers. Fortunately, eruptions of Grand clearly stand out from the other activity. Grand eruption starts can be accurately determined from this trace but duration of eruptions and the number of bursts cannot. This trace can also frequently be used to roughly determine whether Turban and Vent are active based on known typical eruption patterns. It cannot be used, though, to accurately determine the timing of eruptions or other details about the eruptions of Turban and Vent geysers.

The graphs were visually inspected and a class designation assigned to the eruption of Grand and its associated interval. This class designation depended on where, in relation to the parts of Grand's eruption cycle, a Rift eruption start occurred.

A Grand eruption cycle is the period between the start of the prior Grand eruption and that of the eruption that is currently of interest. Thus every classification of a Grand eruption considers two eruptions of Grand: the one currently of interest and the one that is prior to it. In the descriptions of these classes these will be referred to as "current" and "prior". Figure 2 illustrates the different periods of Grand's eruption cycle. Because it was not possible to accurately determine the end of a Grand eruption, it was decided to consider a region "near" an eruption, both before and after, as belonging to the eruption. This region typically started about 15 to 20 minutes before the start of Grand's eruption and ended usually about 45 minutes after the start of Grand's eruption. The actual length of this region varied somewhat depending on the length of Grand's interval. For longer inter-

Table 2 — Definitions of Grand Interval Classifications

Classification	Description
Class 0	No Rift eruption start occurred in any of the locations listed for Classes 1-7
Class 1	A Rift eruption start occurred during the Prior Eruption period. A designation of "b" means that Rift started before the start of the eruption of Grand and "a" means that it started after Grand's eruption start.
Class 2	A Rift eruption start occurred during the Afterplay period.
Class 3	A Rift eruption start occurred during the Lull period.
Class 4	A Rift eruption start occurred during the first part of the Turban Cycles period.
Class 5	A Rift eruption start occurred during the middle of the Turban Cycles period.
Class 6	A Rift eruption start occurred during the last part of the time Turban Cycles period.
Class 7	A Rift eruption start occurred during the Current Eruption period. A designation of "b" means that Rift started before the start of the eruption of Grand and "a" means that it started after Grand's eruption start.
Class Pair	Two Rift eruptions starts occurred during a single Grand eruption cycle.

vals, this region would be larger and for shorter intervals, this region would be shorter. This method is somewhat subjective. This issue is discussed during the analysis. These two periods are labeled as Prior Eruption and Current Eruption on Figure 2. After the prior Grand eruption, Turban and Vent either continue to erupt, or they may stop for a short time of 2 to 24 minutes [Schwarz, 2004b] after Grand ends before restarting. This part of the eruption cycle will be referred to as the "Afterplay period." After Turban and Vent end, there is a period of little activity in the system. This part of the eruption cycle will be referred to as the "Lull period." The next type of activity seen on Figure 2 occurs when Turban Geyser begins to cycle through its series of eruptions prior to the next eruption of Grand Geyser. This part of the eruption cycle will be referred to as the Turban Cycles period. Finally, the "Current Eruption" occurs to end the eruption cycle. The temperature traces did vary from eruption to eruption and throughout the year. The regions indicated in Figure 2 have different lengths and display variations in the characteristics of the traces for different eruptions of Grand. However, it was usually possible to determine the different periods of the eruption cycle.

The definitions used for the class designations are as follows:

• Class 1 was assigned if a Rift eruption started in the region designated as "Prior Eruption". Two sub-classes were also used for this category. Class 1b was used if the Rift eruption start occurred before the eruption start of Grand and Class 1a was used if it occurred after the eruption start. It should be noted that intervals given the Class 1b designation do not technically have a Rift eruption start occurring during that eruption cycle of Grand. However, Rift eruptions are frequently of long duration and at least part of the eruption of Rift occurred during the current Grand eruption cycle.

• Class 2 was used if a Rift eruption start occurred during the Afterplay period.

• Class 3 was used if a Rift eruption occurred during the Lull period.

• Classes 4, 5 and 6 were used if a Rift eruption start occurred during the Turban Cycles period. Class 4 was used if Rift occurred in approximately the first 25% of the Turban Cycles period. Class 5 Rift occurred in approximately the middle 50%, and Class 6 if Rift occurred in approximately the last 25%.

• Class 7 was used if a Rift eruption started in the region designated as "Current Eruption" of Grand. This class also had two subcategories: 7b if Rift occurred before start of the current Grand eruption and 7a if it occurred after the current Grand eruption start.

Two other classes were also used.

• Class 0 was used when no Rift eruption occurred, so that a Grand eruption had no classification under the previously defined classes.

• Class Pair was used if a Grand eruption had two classifications because two separate Rift eruptions occurred in the same Grand eruption cycle. Table 2 contains a summary of these classifications and definitions.

More than 310 eruptions of Grand occurred during the 19 weeks that were selected for inspection. However, a Grand eruption was not classified unless all the regions used for the classification could be completely seen on the graph that was constructed. Thus eruptions at the beginning or end of the week may not have been classified. For the Grand eruptions classified, it was always possible to reasonably determine the class designation, even if some of the features of the Grand eruption cycle were indistinct on the temperature trace. It should be emphasized, however, that these classifications were done by visual inspection and are somewhat subjective. In addition, some of the boundaries between classes are not always well-defined, for example the boundaries between Classes 4, 5, and 6 or the boundaries between Classes 6 and 7b. However, this technique provides a useful first analysis of the data and, as will be seen from the results and discussion, some of these problems became irrelevant during analysis.

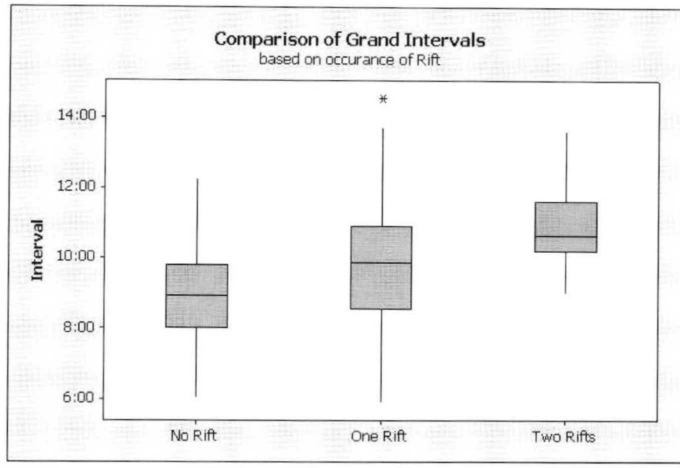

Figure 3. Comparison of Grand intervals based on the number of Rift eruptions during the interval.

After the Grand eruptions were classified, the eruption times and dates and associated intervals were sorted based on their class designation. Appropriate statistics were calculated for the intervals in each class. Table 3 lists these statistics. The statistics have been rounded off to the nearest minute. Since the temperature data were graphed with the extracted eruption start times, any errors in the extracted eruption times and dates and intervals were corrected before doing this analysis. This correction depends on the assumption that the temperature data has no errors in it. There is no evidence from the OFVC logbook or the temperature

Table 3 — Statistics of Grand Intervals based on Classification

Class:	0	1b	1a	2	3	4	5	6	7b	7a	Pair
Number	43	12	54	14	5	26	52	8	12	64	20
Percent	13.9%	3.9%	17.4%	4.5%	1.6%	8.4%	16.8%	2.6%	3.9%	20.6%	6.5%
Mean	8:57	9:34	9:26	9:47	9:08	10:55	10:31	10:26	9:46	8:58	10:55
Standard Deviation	1:20	1:46	1:35	1:50	1:29	1:03	1:31	1:01	1:12	1:34	1:03
Minimum	6:01	6:22	5:55	6:09	7:53	8:33	7:18	8:57	6:30	5:54	9:00
Q_1	8:02	8:10	8:22	8:31	7:57	9:31	9:32	9:23	9:41	7:43	10:13
Median	8:57	9:44	9:28	10:31	8:24	10:37	10:39	10:35	9:54	9:08	10:38
Q_3	9:49	10:50	10:23	11:06	10:40	11:19	11:26	11:29	10:21	10:09	11:38
Maximum	12:17	12:53	12:45	11:41	11:20	12:09	14:31	11:35	11:18	12:20	13:37

data itself to suggest that these corrected values were in error.

Results and Discussion

The interval statistics for the classes that are in Table 3 have been rounded to the nearest minute. Many of the statistics listed in Table 3 are likely familiar to the reader. Two statistics that may be less familiar are the first and third quartiles, denoted Q_1 and Q_3 respectively. The first quartile is another name for the 25th percentile. The third quartile is the 75th percentile and the median is, of course, the 50th percentile. The median and quartiles are less affected by extreme data values and by deviations from a normal distribution than are the mean and standard deviation. For this reason, they are often the preferred statistics when describing data that have outliers or that are skewed.

For a broad view of the relationship between eruptions of Rift and Grand's interval, first consider the relationship between intervals with no Rift eruptions, intervals that are associated with a single Rift eruption, and intervals that are associated with two eruptions of Rift. This relationship is presented using boxplots in Figure 3. Each part of the boxplot represents a different feature of the data or statistics. Asterisks represent outliers. The top end of the line protruding from the top of the box extends to the largest value in the data that is not an outlier. If no outliers are present, it extends to the maximum value. The top of the box occurs at the third quartile. The line in the box occurs at the median. The bottom of the box occurs at the first quartile and the line extending from the bottom of the box goes to the smallest value that is not an outlier or, in the absence of outliers, the minimum. The vertical axis is the interval in hours and minutes. From the plot, it can be seen that the medians increase as the number of Rift eruptions associated with a Grand interval increase.

The boxplot labeled "No Rift" represents the data from intervals with a Class 0 designation and the statistics for this data are in Table 3.

The boxplot labeled "One Rift" was constructed by compiling all the data from Class 1 (b and a) to Class 7 (b and a). For reference, the statistics, rounded to the nearest minute, for this data are as follows: Number of Intervals 247, Mean 9h44m, Standard Deviation 1h37m, Minimum 5h54m, First Quartile 8h33m, Median 9h53m, Third Quartile 10h55m, and Maximum 14h32m. This boxplot does have a median that is between the medians of the other two boxplots but it also shows a large amount of variability. Its minimum value is smaller than the minimum of the intervals associated with no Rift eruptions and its maximum is an outlier that was the maximum interval for the entire year.

The boxplot labeled "Two Rifts" represents the data from the intervals with a Class Pair designation and the statistics for this data are in Table 3. These intervals were almost all intervals in which the current and prior Grand eruptions had a Rift eruption start nearby. Thus the interval was designated as both classes 1 and 7. Seventeen of the twenty Class Pair intervals were of this type. Of the remaining three intervals, two had classes 2 and 7, so the first eruption of Rift was still within the period of Turban and Vent afterplay. The remaining interval was comprised of classes 4 and 7, meaning that the first Rift eruption occurred at the start of the Turban Cycles period and then another one occurred near the actual eruption of Grand itself. It should be noted that the first eruption of this pair had an extremely short duration of 5 minutes or less.

Because of the variability in the intervals associated with a single Rift, it is necessary to take a closer look at how the individual classes within this

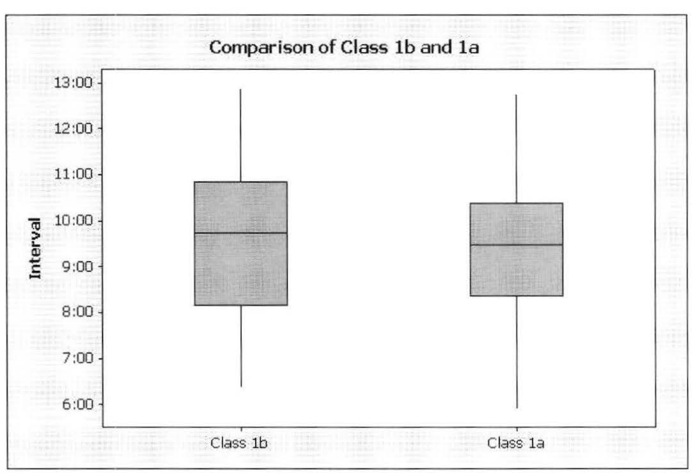

Figure 4. Comparison of the Grand intervals in the subclasses of Class I.

group compare with each other. The subclasses of Class 1 are compared in Figure 4. From these boxplots, there appears to be very little difference between the statistical properties of the Grand interval if a Rift occurred just before or just after the prior Grand. It is interesting to note that if Rift is going to erupt near a Grand eruption, it appears to prefer to erupt shortly after instead of shortly before Grand's eruption. Table 3 shows that only 12 Class 1 intervals had a Rift eruption before Grand erupted (Class 1b) while 54 had the Rift eruption occurring after the Grand eruption (Class 1a). This means that approximately 82% of the eruptions that occurred near a prior Grand, started after Grand had begun erupting. Since there is no evidence that there is a difference between these two subclasses, they will be grouped together and referred to as Class 1 for the rest of the paper.

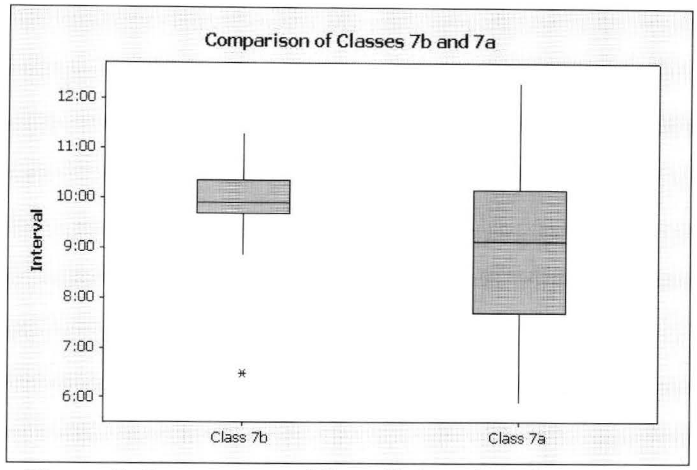

Figure 6. Comparison of Grand intervals in the subclasses of Class 7.

Class 2 data had a median that is much larger than the median for the intervals associated with no Rift eruptions (Class 0). Class 2 had a median of 10h31m versus a median of 8h57m for Class 0. However, there are very few intervals in Class 2, only 12 or 4.5% of the whole sample. Because the number in this class is so small, drawing any conclusions about the effect of a Rift eruption during the Turban and Vent afterplay period would be questionable. This is especially true since the division between Class 1a and Class 2 is highly subjective. A more careful examination of a larger sample is needed to define this class more clearly and to determine the properties of the intervals with this classification. If there is a true relationship between Rift eruptions at this time and longer Grand intervals, it would be very interesting and could be potentially useful for predicting the length of the Grand interval. Because of its small size, this class will not be included in any further analysis at this time.

The Class 3 data is interesting in that there are so few intervals in this category. Only 5 Grand eruptions had a Rift eruption start in the period of little activity between the end of the afterplay and the start of the Turban Cycles. This is only 1.6% of the eruptions studied. Because of its small size, this class will not be included in any further analysis.

The data from Classes 4, 5, and 6 are compared in Figure 5. From the boxplots and from the statistics in Table 3, there appears to be no important difference in the statistics of the intervals in these three classes. (These categories were originally created to see if there was a difference in the effect of Rift based on how close it erupted to a Grand start. The analysis was left in even after the result was negative [that is, no difference], because negative results themselves can be interesting.) The Class 5 data shows more variability than the other two but this is not surprising since Class 5 was used if any Rift eruption occurred in the middle 50% of the Turban Cycles period. The other classes were only used if Rift occurred during the first or last 25% of that period. The larger region means more data in Class 5 and, thus, more chance for variabil-

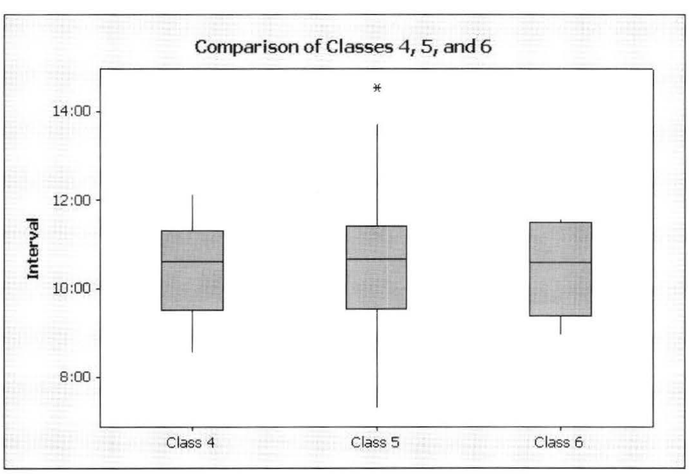

Figure 5. Comparison of Grand intervals in Classes 4, 5, and 6.

Table 4 — Statistics of Grand Intervals based on Classification

Class:	0	1	TC	7a	Pair
Number	43	66	86	64	20
Percent	13.9%	21.3%	27.7%	20.6%	6.5%
Mean	8:57	9:27	10:29	8:58	10:55
Standard Deviation	1:20	1:36	1:21	1:34	1:03
Minimum	6:01	5:55	7:18	5:54	9:00
Q_1	8:02	8:18	9:35	7:43	10:13
Median	8:57	9:29	10:39	9:08	10:38
Q_3	9:49	10:23	11:39	10:09	11:38
Maximum	12:17	12:53	14:31	12:20	13:37

ity. Since there is no evidence that there is a difference between these three classes, they will be grouped together and referred to as Class TC, for Turban Cycles.

The subclasses of Class 7 are compared in Figure 6. Here there appears to be a difference in the data based on whether Rift erupts just before or just after a Grand eruption. Again, however, Rift tends to erupt after Grand has erupted, so there is actually very little data in sub-class 7b, only 12 data points. The median of Class 7b is 9h54m versus 9h08m as the median of Class 7a, so it appears to be associated with longer intervals. The regions of Grand's eruption cycle that are used in the definition of Class 7b and Class 6 are contiguous with an ill-defined boundary between them. However, the median of Class 7b is 9h54m which is much shorter than the median value of 10h35m for Class 6. The boundary between these two classes needs to be more clearly defined and more data from this class analyzed before any conclusions could be drawn about the effect of a Rift eruption during this time. Because of the small amount of data in Class 7b, it will not be included in any further analysis. Class 7a has 64 intervals in it and will be included in further analysis. Class 7a has an interesting structure to it and will be discussed later in this paper.

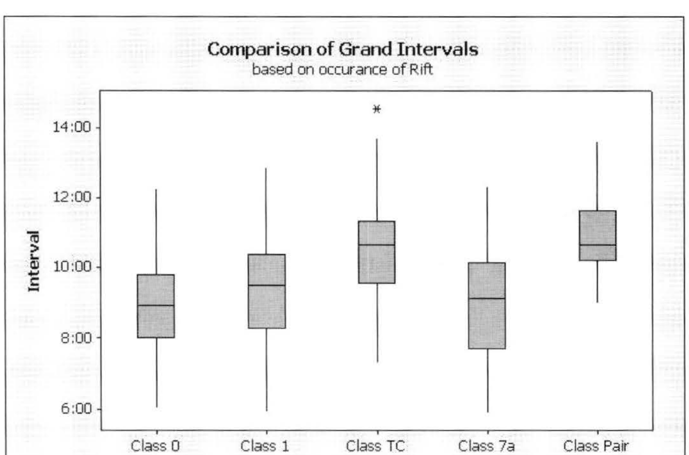

Figure 7. Comparison of Grand intervals based on classification after initial analysis.

The statistics for the classes that are still of interest are reported in Table 4 and boxplots representing the data are displayed in Figure 7. Remember that Class 1 is a combination of subclasses 1b and 1a and Class TC is a combination of Classes 4, 5, and 6. Notice that with these restrictions on the classes of interest, there is no longer a need to be concerned about the subjectivity of the method of classification. There are now clear differences in the definitions of the remaining classes and the categorization of a particular Grand interval into one of these classes is unambiguous.

Upon inspection of Figure 7, it appears that the boxplots for Classes 0, 1 and 7a are similar and that these are different from the boxplots of Class TC and Pair. Of the classes that appear similar (Classes 0, 1 and 7a), Class 0 and 7a have virtually identical means (8h57m and 8h58m respectively). However, the difference between the means of Classes 0 and Class 1 is a bit larger. The mean of Class 1 is a half hour longer than the mean of Class 0 (9h27m and 8h57m respectively). However, when considering all the statistics of the classes, there appears to be little difference overall. Typically in ambiguous situations, a two-sample t-test is used to determine if there is evidence that the means of two populations that the samples came from are different. This test assumes that the samples

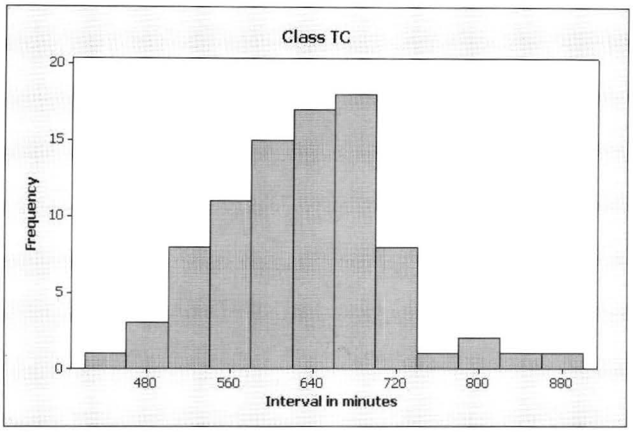

Figure 8. Histogram of Grand intervals in Class TC. Interval times are in minutes.

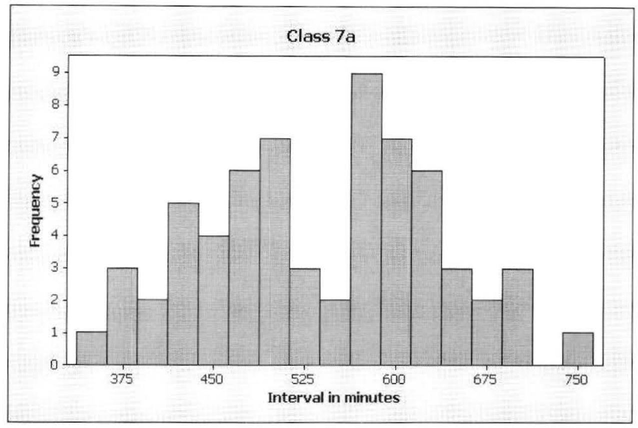

Figure 9. Histogram of Grand intervals in Class 7a. Interval times are in minutes.

were chosen randomly and that the samples are independent, which is not the case here. With these caveats in mind, the p-value of the test was 0.081. This means that there is no evidence from these samples, at a 5% level of significance, that the difference that we see in the means of the two classes reflects a true difference in the actual means of all the Grand eruptions that would fall into these two class types. However, this p-value is sufficiently low to provoke a great deal of interest. It is possible that the difference that is seen in these samples reflects a true difference in the behavior of Grand. This sample is insufficient to answer the question, so more study will be required.

Class TC and Class Pair appear to have statistics that are different from Class 0. The two classes have similar medians, 10h39m for Class TC and 10h38m for Class Pair, which is very different from the median of 8h57m for Class 0. If this sample is representative of the overall behavior, then based on the medians, one could say that intervals that have a Rift eruption occurring during the Turban Cycles period have intervals that are approximately 1h40m longer than those that have no Rift eruption associated with them. It is important to remember that the above statement is a statistical statement. There is quite a lot of variability in the intervals of these two classes, so individual eruptions may not appear to follow the pattern. An individual Grand eruption that has a Rift occurring during the Turban Cycles period may have a fairly short interval, while one with no Rift activity associated with it may have a long interval.

Boxplots are good for comparing different distributions but do not reveal details like the shape of a distribution. The distributions for Classes 0 and 1 are both reasonably normal, meaning that the distributions each had a single peak and were roughly symmetrical. The distribution for Class Pair was also unimodal but was skewed right, meaning that the right tail of the distribution is longer and contains more data points than the left tail. Both Class TC and Class 7a had unusually shaped distributions that merit further comment. The histogram for Class TC is given in Figure 8. This distribution is definitely not normal and has a very sharp drop off in the number of intervals longer than 700 minutes, even though the tallest bar is the one from 660 to 700 minutes.

The histogram for the data in Class 7a is displayed in Figure 9. This distribution is distinctly bimodal. While the overall statistics for this class are very similar to the statistics for Class 0, the

Table 5 — Statistics of Grand Intervals based on Classification

Class:	7a "Short"	7a "Long"
Number	31	33
Mean	7:34	10:16
Standard Deviation	0:48	0:48
Minimum	5:54	9:06
Q_1	7:03	9:39
Median	7:43	10:16
Q_3	8:11	10:52
Maximum	8:49	12:20

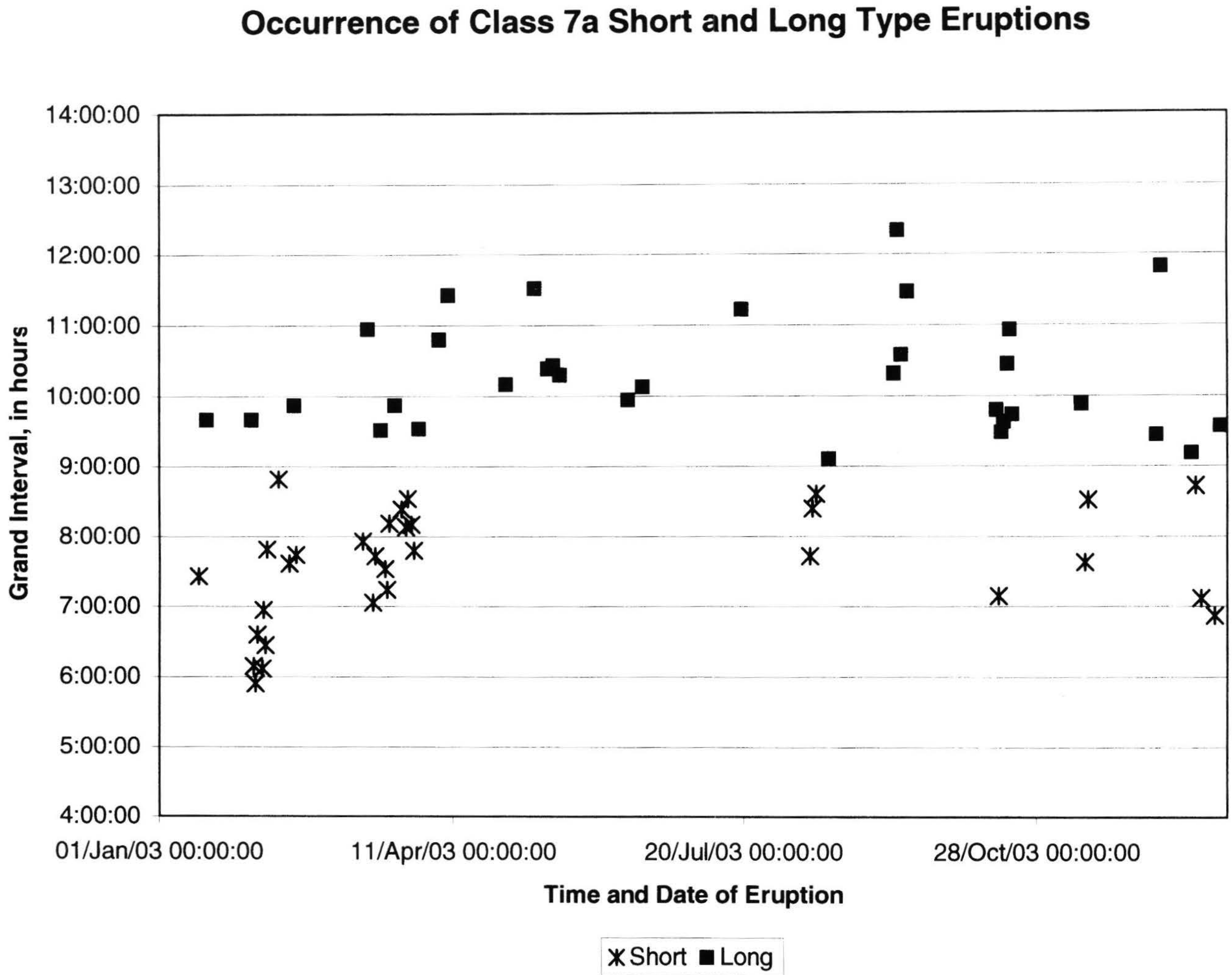

Figure 10. Seasonality of the short and long type intervals of Class 7a.

distribution of the individual eruptions that compose this class is very different. The first mode peaks in the bar centered on 500 minutes (8h20m) and the second mode peaks in the bar centered on 575 minutes (9h35m). The bar centered at 550 minutes appears to be a natural place to divide the two modes. To define a more specific value, a more detailed inspection of the data values was done and this showed that a natural dividing point between the two modes is at approximately 9 hours (540 minutes). Dividing class 7a into two subclasses ("7a short" and "7a long") at 9 hours produces two subclasses of almost equal size. Table 5 displays the statistics of these two subclasses. In an attempt to find an explanation for this bimodal behavior, plots were constructed with the subclasses plotted with different symbols. In four separate graphs, the time difference between Grand's start and Rift's start, Rift's duration, Rift's Interval and the Time and Date of Grand's start were plotted versus Grand's Interval. The only graph that showed a difference between the "7a short" and "7a long" classes was the Time and Date of Grand's start versus Grand's Interval, see Figure 10. No "7a short" type eruptions occurred between March 28 and August 11. There was then a smaller gap from August 13 to October 14. None of the other graphs showed noticeable differences in distributions of the data between the two sub-classes. Further investigation of this class is warranted.

Table 6 — Classification of Intervals for February 1–7, 2003

Date and Time	Interval	Classification
01/Feb/03 11:34	9:40	7a
01/Feb/03 18:32	6:58	1a
02/Feb/03 00:41	6:09	7a
02/Feb/03 06:50	6:09	2
02/Feb/03 12:51	6:01	0
02/Feb/03 18:45	5:54	7a
03/Feb/03 00:40	5:55	1a
03/Feb/03 07:16	6:36	7a
03/Feb/03 13:34	6:18	2
03/Feb/03 20:35	7:01	0
04/Feb/03 03:05	6:30	7b
04/Feb/03 09:27	6:22	1b
04/Feb/03 16:18	6:51	0
04/Feb/03 22:25	6:07	7a
05/Feb/03 04:30	6:05	1a
05/Feb/03 11:27	6:57	7a
05/Feb/03 18:59	7:32	1a
06/Feb/03 01:26	6:27	7a
06/Feb/03 08:29	7:03	1a
06/Feb/03 16:18	7:49	7a
07/Feb/03 00:53	8:35	1a
07/Feb/03 12:03	11:10	5
07/Feb/03 22:39	10:36	5

Comments about a week of very short Grand Intervals

In February 2003, there was a period of 6 days (February 1 to 6) in which Grand had 18 consecutive eruptions whose longest interval was 7h32m (the next longest interval was only 7h03m). Rift showed a strong preference in the location of its eruptions during this period. Table 6 shows the data and classifications for all of the eruptions during the week of February 1 to February 7, 2003. Most of the eruptions of Rift occurred very close to an eruption of Grand and erupted with every other Grand eruption during the time of shorter intervals. The only exceptions to this were that two times the Rift eruption occurred a little farther away from the eruption of Grand but still during Turban and Vent afterplay. In both of these cases the next eruption of Grand had no Rift associated with it. There was only one other Grand eruption during this time that had no Rift eruption associated with it. The longer intervals that broke this pattern at the end of the week had Rift eruptions that occurred during the Turban Cycles period. Because the amount of data is limited, it is unclear if this pattern of eruptions is significant in relation to the short length of the Grand intervals. In the sample of 310 intervals that was analyzed, no sequence of eruptions of this length had a pattern of eruption like this, although shorter periods of Rift erupting in connection with alternate eruptions of Grand did occur.

Conclusions and Future Work

Based on this sample there was evidence of a statistical relationship between the location of a Rift eruption start and the length of the interval of Grand in 2003. This relationship was most apparent when comparing intervals that had no Rift eruption associated with them and those that had a Rift eruption occur during the Turban Cycles period. The median interval length of the latter group was 1h40m longer than the median interval length of the former group.

From this sample, there is no conclusive evidence that eruptions of Rift occurring close to a prior Grand eruption produced subsequent Grand intervals that were any different from Grand intervals that were associated with no Rift activity. However, this does not mean that there is no difference. Further study is required.

Several classes studied in this analysis lacked sufficient sample size to draw conclusions from. Larger samples would be needed to study the properties of Class 2, Class 3 and Class 7b intervals. However, the small sample size of Class 3 is of interest in itself, since it indicates that Rift rarely erupts during the time of lowest activity of Grand, Turban and Vent Geysers. In addition, criteria will have to be established to better define the boundaries of these particular classes.

The bimodality of Class 7a is interesting and needs to be investigated further. The effect of West Triplet eruptions, which were not analyzed relative to Grand's intervals, should be investigated to see if they play a role. Since almost all Rift eruptions are preceded by an eruption of West Triplet, the effect of this geyser is likely to be important.

Acknowledgements

I would like to thank and acknowledge the agencies and people who participated in or supported the collection, analysis, and dissemination of the data used in this article. Clearly the National Park Service deserves acknowledgement and, within the NPS, the Yellowstone Center for Resources, The Geology Group under Supervisory Geologist Henry Heasler, and the Interpretative Rangers who entered the electronic times for Grand Geyser into the Old Faithful Visitor Center Logbook are the groups that are known to me. I would also like to acknowledge GOSA for maintaining an electronic copy of the OFVC logbook on the web. Specifically, I would like to acknowledge Ralph Taylor, for analyzing the data and answering many questions, Mary Beth Schwartz, for answering questions and Lynn Stephens, for transcribing the OFVC logbook.

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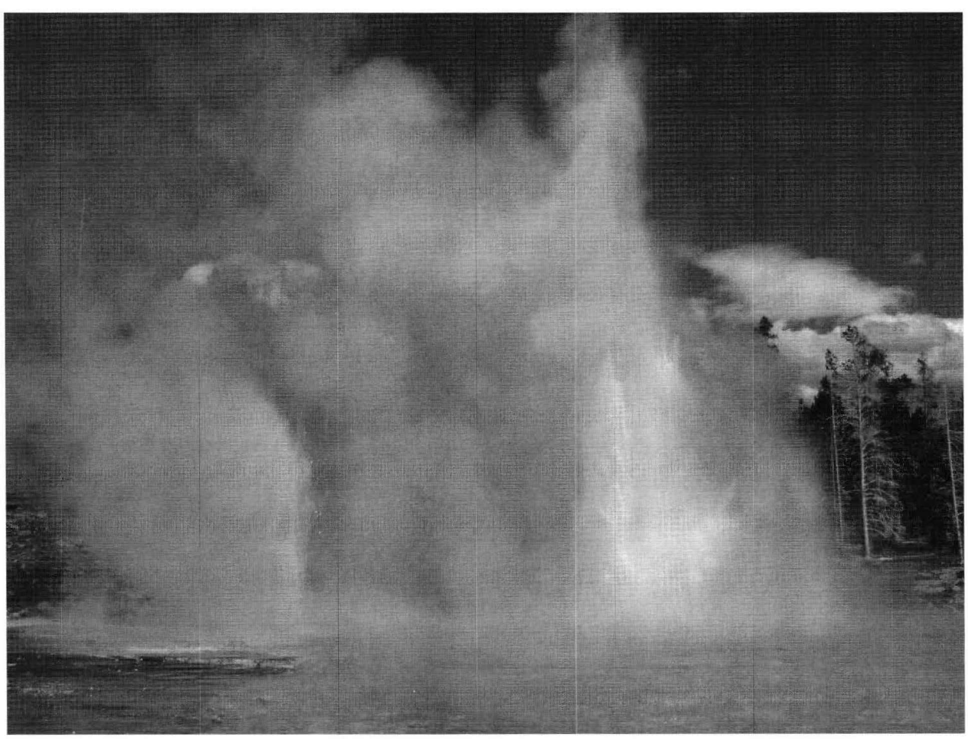

Grand Geyser, accompanied by Vent Geyser (left) and Turban Geyser (nearly invisible, center) in eruption on May 30, 2002. Rift Geyser is just outside the right edge of this picture. [Photo by Scott Bryan]

Fan and Mortar Geysers in 2003

by Tara Cross

Abstract

Fan and Mortar Geysers continued activity during 2003, but as compared to 2002 their eruptions took place on more erratic intervals. This change was accompanied by significant changes in the activity of the minor vents during "event cycles."

Introduction

Fan and Mortar Geysers had one of their strongest periods of activity from May 2002 to March 2003. During this time, no interval exceeded 8 days and there were several stretches of a month or more with regular, 3 to 5 day intervals. Starting in April, 2003, Fan and Mortar became erratic. While their longest intervals were in April, May, and June, Fan and Mortar never truly settled into a regular pattern during 2003. Intervals after June ranged from 4 to 12 days. This article discusses some of the changes observed in the minor activity of Fan and Mortar during 2003.

The vents of Fan and Mortar

- The vents of Fan: In order south to north: River, High, Gold, Angle, Main, and East.
- The vents of Mortar: Upper Mortar, Lower Mortar, Bottom Vent, Frying Pan.
- River, High, Gold, and Angle comprise the "minor vents."
- Main Vent, East Vent, and Lower Mortar comprise the "main system." Activity by Main Vent is the best indication of high energy levels in the complex.
- Other vents within the complex are Back Vent, Crack Vent, Beach Springs, Tile Vent, Spiteful Geyser, Norris Pool, and Backwater Spring.

All of these vents are identified on the map published in *The GOSA Transactions*, Volume VII [Figure 1 *in* Cross, 2002].

Definition of terms

Minor cycles have typically been timed from the start of River Vent's minor eruption to the start of the next River Vent.

A *pause* occurs when the minor vents of Fan shut off before Angle begins its minor eruption. If only River comes on and then shuts off, this is referred to as a *River pause*. If River, High, and Gold come on and then all three shut off, this is referred to as a *Gold pause*. If Angle comes on, the cycle is complete and there cannot be a pause. When two pauses occur consecutively without a full minor cycle being completed, this is referred to as a *double pause*. When three pauses occur consecutively without a full minor cycle being completed, this is a *triple pause*.

During 2001, 2002, and 2003, River Vent occasionally sputtered on weakly and then shut off within a few minutes. This activity was referred to as a *cough*. Coughs could include weak activity by High, Gold, and even Angle. While coughs were not considered to be the same as a pause, they could sometimes have the same result: a shift of energy to the Main system.

The difference between periodic splashing in Bottom Vent and true eruptions of Bottom Vent continued to blur during 2003. As in 2002, episodes of cyclic splashing were commonly seen in the minutes before River Vent started or during pauses. However, a dramatic change in the behavior of Bottom Vent was observed in September 2003. Rather than having series of 1 to 11 distinct eruptions, Bottom Vent began having longer series of eruptions. These series included anywhere from 5 to 22 eruptions with brief pauses of a few seconds between one eruption and the next. Durations varied from as short as 10 seconds to as long as 15 minutes. Every eruption cycle observed after September 7 included extended activity by Bottom Vent. However, the longest observed series

Table I. Fan & Mortar eruptions in 2003

Date and Time *	Interval
January 4 @ 1029	I~4d1h49m
January 8 @ 1100	I=4d0h31m
January 11 @ 2237E	I~3d11h37m
January 14 @ 1516E	I~2d16h39m
January 18 @ 1223E	I~3d21h07m
January 20 @ 1503	I~2d2h40m
January 24 @ 0740E	I~3d16h37m
January 29-30 @ est. 1800-0000	I~5½d
February 12 @ 0803E	unknown
February 17 @ 1301E	I~5d4h58m
February 21 @ 0637E	I~3d17h36m
February 25 @ 2056E	I~4d14h19m
March 1 @ 0608E	I~3d9h12m
March 5 @ 0558E	I~4d23h50m
March 8 @ 1110E	I~3d5h12m
March 11 @ 0349E	I~2d16h39m
March 16 @ 1315E	I~5d9h26m
March 19 @ 2241E	I~3d9h26m
March 23 @ 0422E	I~3d5h41m
March 29 @ 0349E	I~5d23h27m
April 4 @ 0553E	I~6d2h04m
April 8 @ 1701	I~4d11h08m
April 18 @ 0556E	I~9d12h55m
April 26 @ 1757	I~8d12h01m
June 8 @ 1322	I=42d19h25m
June 25-26 @ overnight	I~17½d
July 7-8 @ overnight	I~12d
July 15 @ 1549	I~7½d
July 22 @ 1116	I=6d19h33m
July 31 @ 0645	I=8d20h29m
August 9 @ 1007	I=9d3h22m
August 15 @ 1304	I=6d2h57m
August 21 @ 1832ns	I~6d5h28m
August 26 @ 0020	I~4d5h48m
September 1 @ 0927	I=6d9h07m
September 7 @ 0423	I=5d18h56m
September 18 @ 1226	I=11d8h03m
September 26 @ 0343E	I~7d15h17m
October 3 @ 1354	I~7d10h11m
October 10 @ 1051	I=6d20h57m
October 18 @ 0116	I=7d14h25m
October 24 @ 2046	I=6d19h30m
October 30 @ 1402	I=5d18h16m
November 4 @ 2215E	I~5d8h13m
November 9 @ 1838E	I~4d20h23m
November 19 @ 0815E	I~9d13h37m
November 24 @ 0225E	I~4d18h10m
December 3 @ 1644E	I~9d14h19m
December 11 @ 2117E	I~8d4h33m
December 20 @ 1057E	I~8d13h40m

* "E" represents electronically recorded times.

of Bottom Vent eruptions occurred between September 11 and October 10.

In 2001 and 2002, *Lower Mortar minors* were commonly seen during event cycles. They usually occurred when Lower Mortar's periodic splashing built into a sustained eruption and the water level in the vent rose to overflow. In 2003, Lower Mortar minors were once again seen during event cycles in July, August, and early September, but were very infrequent during the rest of September and October.

Main Vent splashing, pauses, Bottom Vent eruptions, or Lower Mortar minors have been referred to by observers as "events." Cycles that include any of these behaviors are referred to in this article as *event cycles*.

Until 2001, major eruptions of Fan and Mortar typically started from a behavior referred to as *classic lock*, when High, Gold, and sometimes Angle had strong, continuous jetting activity to 3-10 feet. In a significant change from previous activity, the most common start type in 2001 was the *Upper Mortar initiated* eruption. During 2002 and 2003, a little more than half of the observed starts began this way, while the remainder started from a classic lock. On three occasions in 2001, eruptions were observed to start during a long Lower Mortar minor. This behavior was not seen in 2002 or 2003.

Changes in the Fan and Mortar Complex

Fan and Mortar's formation continued to erode in 2003. The most noticeable physical change in Fan Geyser's formation occurred during a powerful major eruption on April 8, 2003. A large piece of layered geyserite situated on the edge of Main Vent's opening was completely blown away. This made a considerable change in the appearance of Main Vent as seen from the trail. Another eruption on July 31 blew out a piece of geyserite that had split the vertical portion of Main Vent's column, turning it into a solid sheet of water.

Bottom Vent continued to enlarge itself and have larger, more powerful eruptions during 2003. These eruptions also caused heavy erosion on the east side of Mortar's formation.

Changes in related features

Observers have speculated that there may be a connection between the Fan and Mortar complex and Link Geyser, located to the south across the Firehole River. In 2002, Link Geyser had its best year of activity since 1983, with 12 recorded major eruptions. None of the observations made during 2002 that indicated an underground connection between Link and Fan and Mortar. It may be merely coincidence that both geysers experienced a decline in activity between 2002 and 2003.

During 2001, the water level in Norris Pool rose a few inches and it had strong boiling during Fan and Mortar's major eruptions. In 2002, the water level rose during some eruptions but not as much. In 2003, there were no reports of behavior changes in Norris Pool during Fan and Mortar's major eruptions.

No noticeable changes were observed in Spiteful Geyser or Backwater Spring.

Summary of 2003 activity

In most active years, Fan and Mortar have experienced a seasonal "spring slowdown" during April, May, and June during which intervals became irregular and sometimes extended to several weeks in length. Before Fan and Mortar's eruption on April 26, minor activity was consistent with the "spring mode" behavior observed in 2001 and 2002, with cycle lengths ranging from 20 to 80 minutes. Main Vent frequently puffed steam or even roared gently between cycles, but actual splashing was not seen. This behavior continued for about two weeks after the April 26 eruption. No events were seen at Fan and Mortar during this time.

The interval following this eruption was nearly 43 days, the longest recorded since Fan and Mortar's reactivation from a 19-month dormancy in 2000. During this interval, the minor activity of Fan and Mortar declined until no sign of an impending eruption could be seen. In early May, cycle lengths were typically 50 to 90 minutes. When River Vent was off, Main Vent would usually have some puffs of steam and maybe a roar or two in tandem with a few huffs from Upper Mortar, but this activity did not lead to Main Vent splashing. Typically, water levels were mediocre, neither low nor encouraging. Frying Pan was observed to steam a few times but did not have true eruptions. The only departure from this was the occasional "cough" and a few weak pauses. Gradually, the cycles stabilized to 50 to 60 minutes long, with the time River Vent was on exceeding the time it was off by a ratio of about 2 to 1. There was no evidence of an energy shift to "Main system."

Because of their dormancy, few observations were made of Fan and Mortar's behavior during May. Scattered observations made in early June indicated that cycle lengths were getting longer and water levels were higher than those observed in May. These observations may have been an early indication of more energy in the system, as they were followed by a major eruption on June 8. An observant visitor was able to confirm that the eruption started from classic lock, but no other details are known.

The following two eruptions occurred overnight and were not seen. By early July, Fan and Mortar were showing signs of returning to the behavior seen during the summers of 2001 and 2002, with event cycles observed periodically. The first known strong event cycle occurred on July 6 and indicated to observers that there was sufficient energy for a major eruption. The next major eruption was overnight, July 7-8.

Beginning on July 15, Fan and Mortar became more consistent. More regular intervals of 6 to 9 days allowed observers to see most of the eruptions for the remainder of the summer season. Throughout July and August, eruption cycles resembled those seen during the majority of 2002. Strong, consistent Main Vent splashing continued to be the key component of any strong cycle. Eruption cycles also included single and double pauses, series of 2 to 4 eruptions by Bottom Vent, and 1 to 3 Lower Mortar minors.

After a major eruption on September 7, there was an abrupt change in Fan and Mortar's minor activity. Beginning on September 11, Bottom Vent was observed to have long series of eruptions. The previous known maximum number of Bottom Vent eruptions during a single cycle was 11, seen in May 2002. In contrast, Bottom Vent series in September 2003 included anywhere from 5 to 21 eruptions. Lower Mortar minors that had been common during July and August, as they were in the summer of 2002, no longer occurred. Main Vent splashing rarely lasted beyond the fifth Bottom Vent eruption in the series. This dramatic shift can be seen in the eruption cycle chart.

Possibly because of this change in behavior, Fan and Mortar followed with their longest interval since June, 11 days. The September 18 eruption was preceded by a series of 12 Bottom Vent eruptions. This behavior continued until October 17, when a Lower Mortar minor was observed. After this, Bottom Vent series tended to have fewer eruptions. In spite of inconsistent minor behavior, Fan and Mortar were remarkably regular between September 18 and November 4 at 5½-7½-day intervals. Nothing is known about Fan and Mortar's minor activity after the major eruption on October 30. However, electronic monitor results indicate that Fan and Mortar continued to have intervals ranging from 4¾ days to 9½ days.

Strong cycle events

During most of 2001 and 2002, the most reliable sign of energy in the Fan and Mortar complex was visible splashing in Main Vent. This continued to be the case in 2003. Main Vent splashing was seen during every observed eruption cycle. Main Vent splashing could occur during a pause, after one or more coughs, or during the off time between cycles.

Lower Mortar minors were commonly seen during strong cycles before September 11. After that date, Lower Mortar minors were not commonly seen, and no observed eruption cycle included a Lower Mortar minor. A few Lower Mortar minors were witnessed in October, typically during cycles when Bottom Vent had 2-5 longer eruptions rather than a long series of short eruptions.

During the spring slowdown, Bottom Vent eruptions were not commonly seen. As Fan and Mortar began to have shorter intervals in July and August, Bottom Vent eruptions were seen during most strong event cycles, with 1 to 6 eruptions being typical. As noted earlier, Bottom Vent eruptions became the indicator of strong cycles starting on September 10.

Pauses

During 2002, eruptions of Fan and Mortar could be preceded by single or double pauses. Single or double River pauses were most typical, but six eruption cycles included Gold pauses. This changed dramatically in 2003, when only one observed eruption cycle included a Gold pause. There were 6 eruption cycles with single River pauses, 2 with double River pauses, and one with a double pause consisting of one Gold and one River pause. It is important to note that only 9 complete eruption cycles were observed during 2003, compared with 25 in 2002. Triple pause cycles were observed in 2003, but none that were observed led to an eruption. Since 2000, only one observed triple pause cycle has led to an eruption.

Eruption cycles

Due to erratic intervals in 2003, only 19 eruptions were seen from the start, compared to 32 in 2002. Furthermore, only nine complete eruption cycles were witnessed; data is incomplete for the other ten. Still, some patterns emerged in eruption cycles, as shown on the eruption cycle chart.

Start types

Between April 26 and August 15, 8 eruptions were seen from the start and only one eruption was initiated by Upper Mortar surging. The rest started from classic lock. Starting with the August 26 eruption, 7 of 8 observed starts were initiated by Upper Mortar surging, while only one began from a "classic lock." This change occurred about two weeks before the shift in activity to Bottom Vent on September 11. For 2003, 10 observed eruptions were Upper Mortar initiated, and 9 started from a "classic lock." As in 2002, no eruptions were triggered by Lower Mortar minors.

In 2003 the time from the start of River to the start of a major eruption was highly variable, ranging from 19 minutes to greater than 46 minutes. While the range for Upper Mortar initiated eruptions (19 to greater than 35 minutes) was similar to the range for classic lock initiated eruptions (19 to greater than 46 minutes), the average time was longer for Upper Mortar initiated eruptions. In 2002, the longer River-to-start times occurred dur-

Table II. Fan and Mortar Eruption Cycle Chart, January – October, 2003*

Date	Time	Pause? (time on-off)	Bottom?	Lower Mortar minor?	Start Type	River to start	Observer
1/4	1029	?	possibly	at least one	UM	?	T. Cross
1/8	1100	?	?	?	UM	?	M. Lang
1/10	1503	?	?	?	lock	>18m	M. Lang
4/8	1701	?	at least 2	yes (d=1m16s)	lock	21m	M. Keller
4/26	1757	probably	no	no	lock	>46m	T. Cross
6/8	1322	?	?	?	lock	?	visitor report
7/15	1549	River (14-10)	yes – 2	yes (d=1m15s, 1m40s)	lock	19m	A. Bunning
7/22	1116	River (17-36)	yes – 3	yes (d=1m20s, 1m36s)	lock	22m	A. Bunning
7/31	0645	River (11-22)	yes – 4	yes (d=30s, 1m55s)	lock	19m	A. Bunning
8/9	1007	Gold (8-19), River (8-15)	yes (d=1m49s)	no	UM	27m	L. Stephens
8/15	1304	River (4-12)	yes – 4	yes (d=1m22s, ~45s)	lock	30m	L. Stephens
8/26	0020	River (>4-20), River (14-11)	yes – 2	yes (d=37s, 30s)	UM	31m	A. Bunning
9/1	0927	River (10-12)	yes – 3	yes (d=30s, 1m, 20s)	UM	27m	L. Stephens
9/7	0423	River (13-5)	yes – 4	no	UM	30m	A. Bunning
9/18	1226	?	yes – 12	no	UM	~21m	Bob Leib
10/3	1354	?	yes – 13	no	UM	27m	Steve Eide
10/10	1051	?	yes – 10	no	UM	19m	S. Robinson
10/18	0116	?	at least 4	no	UM	>35m	A. Bunning
10/24	2046	River (15-6), River (9-25)	yes – 3	no	lock	22m	A. Bunning

*Chart includes only eruptions where information about the eruption cycle was available. Thank you to Michael Lang, Mike Keller, Andrew Bunning, Lynn Stephens, Bob Leib, Steve Eide, and Steve Robinson for providing information.

ing spring mode; however, in 2003, a range of 19 to greater than 34 minutes was seen even after the geysers had become more regular during July and August.

Conclusion

In 2003, Fan and Mortar's eruption cycles continued to have many of the same characteristics as those seen during 2001 and 2002. After continuing to have regular intervals through March, longer intervals of 8 to 10 days led to the longest interval recorded since 2000. Fan and Mortar continued to have irregular intervals until July, when shorter, 6 to 9 day intervals began to occur. However, intervals were never truly regular, and several major changes occurred in the minor activity observed in the complex. While observers continued to monitor the minor and major activity of Fan and Mortar, it was more difficult than it had been in 2001 and 2002 because of the longer and more irregular intervals.

Acknowledgments

I am indebted to a number of other observers for observations made while I was not able to watch Fan and Mortar. Thank you to all those contributed data and observations used in this article: Michael Lang, Mary Beth Schwarz, Dick Powell, Bob Leib, Steve Eide, Steve Robinson, Graham Meech, T. Scott Bryan, Mike Keller, Jens Day, David Goldberg, Paul Strasser, Suzanne Strasser, and above all Andrew Bunning and Lynn Stephens. Special thanks also go to all those who offered helpful suggestions in the writing of this article: Andrew Bunning, Paul Strasser, Suzanne Strasser, Stacey Glasser, and especially Nancy Cross.

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Geyser gazer Ralph Friz enjoying Fan and Mortar on September 1, 2003. Note the rainbow, which was incredibly intensly colored during this mid–morning eruption. [Photo by Scott Bryan]

The Eruptive Patterns of Atomizer Geyser — an historical and quantitative examination

by Lynn Stephens

Abstract

Atomizer Geyser has an interesting pattern of activity—a series of minor eruptions leading up to the major eruption. During August 2003, detailed observations about the characteristics of Atomizer's series of minor eruptions were made. This report describes the results of these observations and compares the conclusions with other reports about Atomizer's behavior.

LOCATION AND INTRODUCTION

Atomizer Geyser is located in the Cascade Group of hot springs in the Upper Geyser Basin of Yellowstone National Park. Atomizer consists of two small cones, located to the west of Artemisia Geyser near the brink of the embankment on which Artemisia is located. Almost all of Atomizer's eruptive activity comes from the southwestern cone. Generally, the northeastern cone only participates during the major eruptions when an atomizer–like spray of steam and water occurs during the early minutes of the major eruption and a steam plume is ejected during the steam–phase of the eruption. On rare occasions, independent eruptions of the northeastern cone have been observed between the concluding minor and the major eruption.

George Marler [1958] indicated that he could find no records that Atomizer had been systematically observed prior to 1958. Based on his 1958 observations, Marler developed the following description of Atomizer's eruptive cycle:

> ...there are two distinct types of eruptions: a steam–phase type of over thirty minutes duration, and one that lasts for less than a minute and is unaccompanied by a steam period. This latter type of activity is of much more frequent occurrence.
>
> ...The steam–accompanied eruptions so completely exhaust the geyser's resources that many hours are required for the build up of a new eruptive potential. The nature of this buildup, and the sequence of events leading up to the next steam–phase eruption, are very interesting and seem to have no counterpart in any other geyser.
>
> It is several hours following the steam–phase activity before Atomizer's depleted water system is sufficiently replenished so water will again flow from its crater. This flow is brief before an ebb takes place, but from then until the eruption the flow occurs about every twenty to thirty minutes....After several overflow and ebb periods one of the overflow periods results in an eruption. The eruption takes place within a minute or less of the beginning of the overflow. This eruption seems to be a precursor to several succeeding ones of similar character whose intervals are about an hour and a half. These eruptions are but seconds in duration.
>
> After a number of short–period eruptions, steam–phase activity results; this activity apparently is the climax of an eruptive build–up.

Since that time, other descriptions of the phases of Atomizer's eruptive pattern have been substantially the same as Marler's description. The term "major eruption" has generally replaced the phrase steam phase type of eruption and the term "minor eruption" has been applied to the precursor eruptions unaccompanied by a steam period. Thus, Atomizer's eruptive pattern consists of a major eruption, a quiet period during which no aboveground activity is visible, a period during which periodic overflow occurs, a series of minor eruptions, and the subsequent major eruption.

In 1993, Dave Leeking noted that "the sequence of events leading up to these steam–phase eruptions had been well known and remains substantially unchanged from Marler's [1973] account." Although the sequence of events may be well known, detailed observations about some of the characteristics of the series of minor eruptions have not been reported. In August 2003 data about the series of minor eruptions was collected. This article presents and analyzes data from the August

2003 observations, and compares these results with information available from previous observations and reports.

DATA COLLECTION

During August 2003 a concerted effort was made to collect information about Atomizer's series of minor eruptions. For some sections of this paper the August 2003 observations were supplemented by observations made during the summers of 1988, 1989, and 1990. Most observations were made from the hillside east of Artemisia, looking west toward Atomizer. A few observations were made from the west side of the Firehole River, looking east toward Atomizer.

In August, 2003, data was collected on minor eruptions preceding 33 major eruptions of Atomizer. Data about the complete series of minors was collected for 18 series. In 12 of the other 15 cases, the start of the minor series was not determined. In one case, data about the first four minors was collected, but the major was not observed. In two cases, the time (and duration) of one of the "middle" minors was not observed. Additional observations included two major eruptions where no preceding minor was recorded, and one initial minor in a series where the preceding major had been observed.

Data collected included start times and durations for minor eruptions, and relationship of the minor to the preceding and/or succeeding major if that information was known. Many minors start from a period of occasional overflow. Sometimes Atomizer will bubble up from the overflow, then the bubbling will stop without lifting into a minor eruption. Start times were based upon when the column lifted rather than overflow or bubbling. This method is consistent with the method used by Leeking [1993]. Data about height was not collected because a point of reference or baseline for making accurate height estimates was not available.

The data was then used to describe characteristics of Atomizer's series of minor eruptions such as number of minors in the series, durations of the minors, intervals between minors, interval between the next–to–last (penultimate) and concluding minor, and interval between the concluding minor and the subsequent major. Although the major focus of the observations was to obtain information about characteristics of the series of minor eruptions, data about intervals between major eruptions was also obtained.

INTERVALS BETWEEN MAJOR ERUPTIONS

A. Total Interval between Major Eruptions

Quantitative information about the interval between Atomizer's major eruptions apparently was not obtained until sometime in the 1970's and did not become generally available in published sources until the 1980's.

Marler [1958] stated that prior to his 1958 observations there was "a belief on the part of all who have spent considerable time in the Old Faithful area that Atomizer played infrequently, days and possibly weeks transpiring between eruptions." As a result of his 1958 observations, he concluded "Atomizer was active at least once and sometimes several times daily. The frequency of its play seemed to be governed by the nature of its activity." He did not draw any conclusion about the length of the major–major interval. Fifteen years later Marler noted in the *Inventory of Thermal Features* [1973], that intervals between major eruptions still hadn't been determined.

Sam Martinez, a Volunteer in the Park, started filing reports about geyser activity during the 1970's. In his June 1974 report, he reported "one major interval of Atomizer which was found to be 14 3/4 hours." This is the first observation of a major to major interval that the author was able to locate.

In the first edition of T. Scott Bryan's *The Geysers of Yellowstone* [1979], Atomizer's interval is listed as "1 per day".

In his 1982 *Annual Report*, Roderick Hutchinson noted:

> Seasonal Naturalist T. Scott Bryan and others worked hard to obtain sufficient data from Atomizer this summer so to better understand its eruptive cycles...A complete eruptive cycle at the time of Marler's tenure occurred one or more

> times daily....At the time the description of Atomizer was written, the intervals between steam phase eruptions had not been determined. Even today, no accurate measure of the average interval has been able to be satisfactorily made. Irregularity may be cause of this problem.

Although "no accurate measure of the *average* interval" [emphasis added] had been obtained, Hutchinson did cite some estimates of the interval. Hutchison quoted from a July 23, 1982, memo from Bryan, "...observations on July 21 and 22 showed the complete cycle from major to major to probably be on the order of 14 hours, again in accord with observations from the past 4 years or so but contrary to those of earlier years (18 hours)." Hutchison's next sentence expanded the possible range from major to major when he wrote "While not definite, there may have been a 20 hour interval on May 20–21, and a short interval on July 26."

Dave Leeking [1993] made an effort in 1985 to obtain "the first–ever, accurate determination as to its [Atomizer's] true eruptive nature." With respect to the interval between major eruptions, he wrote:

> For many years the Park Service Naturalists and geyser gazers had only vague ideas about the interval between these major eruptions. I heard estimates everywhere from 14 to 22 hours, and at times Atomizer was said to erupt "once per day." It was because of this great lack of knowledge that, during July and August, 1985, I obtained nine exact and four approximate major intervals....They were surprisingly consistent, varying between approximately 13½ hours and 15¾ hours....The average of the 13 intervals was 14h 47m. One additional major interval of 14h 52m was obtained on June 25–26, 1984 by Rocco Paperiello. Using truncation, the average interval remains 14h 47m when this interval is added to the 1985 data.

The 1986 edition of Bryan's *The Geysers of Yellowstone* was changed to state that "major eruptions recur about every 15 hours" and the table entry for Atomizer showed an interval of 13½ to 15½ hours.

When he wrote the article about his 1985 observations, Leeking [1993] updated his observations to include information that had become available through the early 1990's. He expanded the range of precise intervals to include his 1986 observation of a minimum of 12h48m and his 1988 observation of a maximum of 16h34m. The approximate range was expanded in 1992, as reported by Leeking [1993]: "Scott Bryan used markers to confirm one interval longer than 19½ hours."

The 1995 edition of *The Geysers of Yellowstone* reflected these expansions in the range by including a statement that: "The known range is from 12½ to 19 hours between successive major eruptions, but almost all fall within a much tighter 14 to 16 hours." The table entry for Atomizer's intervals was changed to read 12½ to 16 hours.

Other reports quantifying intervals between major eruptions of Atomizer have periodically appeared in *The Geyser Gazer Sput*. A review of the reports about Atomizer showed that reported maximum and minimum precise intervals did not change until the early 2000's. An interval of <12h32m reported in October 2002 was the shortest known major–major interval as of that time. In August 2003, the author observed a double interval of 24h45m, which meant that at least one of the two intervals had to be less than 12h23m. Leeking's 1988 observed maximum of 16h34m was expanded slightly by a closed interval of 16h37m that the author observed in August 2003. As of the end of 2003, Bryan's 1992 interval of >19 1/2 hours through markers remains the longest reported interval.

Start times were observed for at least every other major eruption during August, 2003, beginning with a major eruption at 13:51 on August 2 and ending with a major eruption at 15:55 on August 31. These observations resulted in 18 closed major to major intervals and 15 double major to major intervals. These intervals are shown in Table 1.

The average for the 18 closed intervals in 2003 is 14h21m, with a median of 13h58m, a minimum of 12h39m, a maximum of 16h37m, and a standard deviation of 1h16m. When the 15 double intervals are included, the average interval increases by 11 minutes to 14h32m. This 11 minute increase is only a 1.3% increase over the 14h21m average for the 18 closed intervals.

Table 1: Atomizer Major to Major Interval, August 2003, Arranged Chronologically

Date	Double Interval	Average for Double Interval	Closed Interval
8/3/03	31:45	15:52/15:53	
8/4/03			13:55
8/5/03	29:34	14:47/14:47	
8/6/03			13:16
8/6/03			12:55
8/7/03			16:37
8/8/03	30:07	15:04/15:03	
8/9/03			13:40
8/9/03			13:30
8/10/03			16:13
8/11/03	28:56	14:28/14:28	
8/12/03			15:18
8/13/03	30:21	15:10/15:11	
8/14/03			15:04
8/14/03			13:10
8/15/03			14:57
8/16/03	30:50	15:25/15:25	
8/17/03			16:18
8/18/03	27:43	13:52/13:53	
819/03	24:45	12:22/12:23	
8/20/03	27:24	13:42/13:42	
8/21/03			13:58
8/22/03	31:44	15:52/15:52	
8/23/03			14:56
8/23/03			12:39
8/24/03			13:35
8/25/03	28:50	14:25/14:25	
8/26/03	27:25	13:42/13:43	
8/27/03			15:39
8/28/03	27:59	13:59/14:00	
8/29/03	30:25	15:12/15:13	
8/30/03			12:44
8/31/03	31:56	15:58/15:58	

Table 2: Comparison of 1985 (Leeking), 1990 (Stephens), and 2003 (Stephens) Observations

Time Period	Average Interval	Minimum Interval	Maximum Interval	Number of Intervals
1985	14h47m	~13h30m	~15h45m	13 closed
1990	14h33m	13h50m	16h25m	8 closed
1990	14h45m			8 closed + 8 double
August 2003	14h21m	12h39m	16h37m	18 closed
August 2003	14h32m	<12h23m		18 closed + 15 double

A comparison of Leeking's 1985 observations, the author's 1990 observations (previously unpublished), and the August 2003 observations is shown in Table 2. (Leeking's approximate major intervals were determined by estimating the start time based on how long Atomizer had already been erupting when he arrived, so the author treated them as closed intervals.)

The average for the 1990 closed and double intervals is 14h45m, very close to Leeking's average of 14h47m average for 1985. Both the 1990 minimum and maximum are longer than Leeking's 1985 minimum and maximum, but are within limits he had reported for 1986 and 1988.

The 2003 observations for the closed intervals show a broader range of intervals than had been observed in 1985, with both a larger maximum and a smaller minimum. An F test of variance indicated that the variances of the 1985 and 2003 closed interval data sets were not equal ($F=3.07$, $df= 17/12$; $p < .03$). This confirmed that Atomizer's major–major intervals were more variable in 2003 than they had been in 1985.

The average interval for the 2003 observations is less than the average for the 1985 observations. The difference between the 1985 average and the 2003 closed interval average of 26 minutes is only 3% of the 2003 average. A t–test for differences between sample means assuming unequal variances shows this difference is not statistically significant ($t = 1.26$, $df= 29$, $p <.109$).

When the 2003 double intervals are included in the computation of the average, the difference of 15 minutes between the 1985 and 2003 average is only 1.7% of the 2003 average of 14h32.

The interval between majors can be divided into two segments: (1) time from the preceding major to the first minor, and (2) time from the first minor to the succeeding major. Although the average major–major intervals for 1985, 1990, and 2003 are not significantly different, the lengths of each of the two components within the major–major interval do appear to have changed, as will be discussed in the next two sections. These changes appear to have offset each other so that the average major–major interval for 2003 was about the same as that for 1985.

Table 3 shows the 18 closed intervals for 2003 arranged in ascending order. Three (16.7%) intervals were less than 13 hours; seven (38.9%) intervals were 13–14 hours; two (11.1%) intervals were 14–15 hours; three (16.7%) intervals were 15–16 hours; and three (16.7%) intervals were 16–17 hours.

Examination of the data shows a break of approximately one hour. There were no intervals between 13h55m and 14h56m. The reason for this break appears to be related to a particular pattern

Table 3: 2003 Closed Intervals Arranged in Ascending Order

12h39m (3)*	13h10m (4)*	14h56m unk	15h04m	16h13m
12h44m*	13h16m unk	14h57m (5)	15h18m	16h18m
12h55m (3)*	13h30m (4)		15h39m	16h37m
	13h35m			
	13h40m*			
	13h54m			
	13h55m*			
N = 3 (16.7%)	N = 7 (38.9%)	N = 2 (11.1%)	N = 3 (16.7%)	N = 3 (16.7%)

The number of minors in the preceding series is shown in ( ) where that number is known. Intervals involving a 10–12 minute interval between the concluding minor and the major are marked with an *. If the interval between the concluding minor and the major was not determined, the interval is marked with "unk".

of minor activity that was observed in 2003, and will be discussed in the section "Interval Following Each Minor."

It would seem that the length of the major-to-major interval would be shorter when there are fewer minors in the series. Examination of the data in Table 3 shows that both series of three minor eruptions were associated with major-to-major intervals of less than 12h55m (12h39m and 12h55m). The shortest observed major-to-major interval associated with a series of four minor eruptions was 13h10m. There is no overlap between the length of the longest major-to-major interval (12h55m) associated with a series of three minors and the length of the shortest major-to-major interval (13h10m) associated with a series of four minors in the 2003 data. However, there were only four observations of the length of the major-to-major interval where the number of minors was also determined (two observations for major-to-major intervals encompassing three minors and two observations for major-to-major intervals encompassing four minors) in 2003. Due to the limited number of observations, the possibility that the length of a major-to-major interval encompassing a series of three minor eruptions could be longer than the length of a major-to-major interval encompassing four minors cannot be excluded.

Examination of the data shows that a 10–12 minute interval between the concluding minor and the major does not always result in a shorter major–major interval. (Dave Leeking [2002] applied the term "quick comeback" to the situations where the major eruption occurred "about 10 minutes after the last minor.") Major to major intervals that included a "quick comeback" between the concluding minor and the major were observed in the 12½ to 14 hour range and were not observed in the 15 to 16½ hour range. However, two major–major intervals that did not involve a "quick comeback" also appeared in the 13 to 14 hour range, and were shorter than two major–major intervals that included a "quick comeback".

The dangers of using small sample sizes can be demonstrated using the 2003 data (Table 1). Moving averages for three intervals were calculated using either three consecutive closed intervals or one closed interval plus the preceding or succeeding double interval. These moving averages have almost a two hour range. If someone had witnessed only the three consecutive intervals on August 23–24, the average would be 13h43m. This average is 49 minutes, or 5.6%, less than the average for all the closed and double intervals observed in August. On the other hand, if someone witnessed the double interval on August 15–16 followed by the closed interval on August 17, the average for these three intervals would be 15h42m. This average is 70 minutes, or 8.0%, more than the average for the closed and double intervals. The range between these two averages is just one minute short of two hours.

Because the shortest double interval observed in August was both preceded and succeeded by double interval observations rather than a closed interval on either side, it does not enter into the calculations of the moving average for three consecutive intervals. Using moving averages for 5 consecutive intervals does include the shortest double interval. This results in a 5 interval moving average of 13h13m. This "average" is 79 minutes (9.1%) less than the 14h32m average for all the closed and double intervals observed in August.

If the data for August 2003 is representative of Atomizer's activity in other years, statements about Atomizer Geyser's average interval based on sample sizes of 3–5 observations should probably include the disclaimer that the population average could be as much as 20% larger or smaller than the sample average. For example, using the three consecutive closed intervals for August 22–24 (14h56m, 12h39m, and 13h35m) the sample mean is 13h43m (823 minutes) and the 95% confidence interval estimate of the population mean is 13h43m +/- 2h51m (823 minutes +/- 171 minutes), or 13h43m +/- 20.7%.

B. Interval Between Preceding Major and First Minor in a Series

The interval between Atomizer's major eruptions can be divided into two pieces—(1) the time from the start of one major eruption to the start of the first minor in the series leading up to the next major eruption and (2) the time from the first minor to that next major eruption.

In August, 2003, six observations of the time between the preceding major and the first minor were collected, as shown in Table 4. The six observations average 9h25m, range from a minimum of 8h31m to a maximum of 10h19m, and have a median of 9h31m.

Bryan [1986] indicated it would be "about 8 hours" between the major and the first minor, and in 1995 stated that it "will usually be 6 to 8 hours after the major" before the first minor. In 1988 the author observed one interval between the major and the first minor of the succeeding series. That interval was 9h22m. In 1990 the author recorded two

Table 4: Interval Between Preceding Major and First Minor

Interval	Date
8h31m	8/09/03
8h32m	8/15/03
9h02m	8/14/03
10h01m	8/23/03
10h06m	8/06/03
10h19m	8/24/03

observations for the time from the major to the first minor—one of 8h58m and one of 9h01m. Because the sample size was very small, I did not draw any conclusions about whether the time between the major and first minor was changing. However, the minimum for the 2003 observations is about 8½ hours based on six observations, half an hour longer than previous reports had indicated. Although the sample size is still small, there is no reason to believe there was any bias in the author's data collection procedures. Apparently it is now taking longer for Atomizer's water system to regenerate sufficiently to support a minor eruption that it had in earlier years.

C. Interval From First Minor to the Subsequent Major

Possibly because the interval from the first minor to the subsequent major, or total duration of the series of minor activity, is quite variable, no references attempting to quantify it were located by the author. I observed 21 such intervals in August 2003. The results of these observations are shown in Table 5. The number of minors in the interval is indicated in parenthesis next to the inter-

Table 5: Distribution of Duration of the Series of Minors

Interval (Number of Minors)	Interval (Number of Minors)	Interval (Number of Minors)	Interval (Number of Minors)	Interval (Number of Minors)	Interval (Number of Minors)
< 3 hours	3:00 – 3:59	4:00 – 4:59s	5:00 – 5:59	6:00 – 6:59	> 7 hours
2:38 (3)*	3:46 (4)*	4:01 (4)*	5:23 (4)	6:11 (5)	7:04 (5)
2:49 (3)*	3:59 (4)*	4:08 (4)*	5:25 (4)	6:15 (5)	
		4:13 (4)*	5:29 (4)	6:23 (5)	
		4:16 (4)*		6:34 (5)	
		4:59 (4)		6:49 (5)	
		4:59 (4)		6:51 (5)	
				6:54 (5)	
N = 2 (9.5%)	N = 2 (9.5%)	N = 6 (28.6%)	N = 3 (14.3)	N = 7 (33.3%)	N = 1 (4.8%)

*Indicates the interval was associated with an 10–12 minute interval between the final minor and the major.

val. Those intervals associated with a "quick comeback" interval are marked with an *. The number of minors in the series and the interval between the concluding minor and the major were determined for all 21 of the intervals reported here.

The overall average for the 21 durations is 5h11m, with a minimum of 2h38m and a maximum of 7h04m. The median is 5h23m, indicating that the data is slightly skewed to the left. The standard deviation is 1h22m, for a coefficient of variation of .2635.

Examination of the data shows that the number of minors in a series was related to the duration of the series, as would be expected. The divisions between the number of minors and length of the total interval are "clean" with no overlap. Both intervals under three hours contained only three minors, and conversely, both series of three minors resulted in short intervals. The 11 intervals between 3h0m and 5h59m were all associated with series of four minor eruptions. Finally, all intervals exceeding six hours were associated with series of five minors.

Examination of the data also shows that the eight shortest durations were associated with "quick comeback" intervals between the concluding minor and the subsequent major. Both series of three minors resulted in a "quick comeback" interval to the major. None of the series of five minors resulted in a "quick comeback" interval to the major. Results for the series of four minors were mixed—some resulted in a "quick comeback" interval; some did not.

The interval from the first minor to the succeeding major is impacted by the number of minors in the series, the intervals between the minors, and the interval between the concluding minor and the major. Given that the average major to major interval is not statistically different between 1985 and 2003, but one piece of that interval—the length of time from the preceding major to the start of the minor series—has lengthened, then it would appear that the length of the other piece—the interval between the first minor and the succeeding major—must have shortened. In 2003 it appears that at least some of the change may be associated with a decrease in the number of minors in the series.

IV. CHARACTERISTICS OF THE SERIES OF MINOR ERUPTIONS

A. Descriptions and Quantification of Components of Atomizer's Series of Minor Eruptions

Based on his 1958 observations, George Marler reported:

> It is several hours following the steam–phase activity before Atomizer's depleted water system is sufficiently replenished so that water will again flow from its crater. This flow is brief before an ebb takes place, but from then until the eruption the flow occurs about every twenty to thirty minutes....After several overflow and ebb periods one of the overflow periods results in an eruption....This eruption seems to be a precursor to several succeeding ones of similar character whose intervals are about an hour and a half. These eruptions are but seconds in duration.

A decade later, Marler [1968] observed that "The series [of minor eruptions] is characterized by eruptions of 40 to 50 seconds duration which play to a height of about 20 feet. Four or more such eruptions occur to be followed by the councluding [*sic*] performance."

In his 1970 report, Marler did not specify the number of minor eruptions in the series preceding a major. However, he did change his statement about frequency of the minors from the "about an hour and a half" used in his 1958 report to "about hourly" in the 1970 report. He also changed his quantification of the duration from the "40 to 50 seconds" in the 1968 report to "about a minute's duration" in the 1970 report. In his *Inventory of Thermal Features* [1973], he went back to "several" as his quantification of the number of minors preceding the major, used the phrase "a minute or less" to describe the durations, and stated that intervals "are about an hour and a half."

Sam Martinez's 1972 report is the earliest report located by the author that noted the bimodal nature of the length of time between the concluding minor and the subsequent major. He reported that he observed a 14 minute interval between the concluding minor and the subsequent major. He also stated: "Before this the preliminaries have always preceeded [sic] the eruption by at least 1 hour and 45 minutes this year."

In 1973, Martinez reported "The interval between minor eruptions is about one hour 45 minutes." His September 1974 report stated that during July 1974 he observed several eruptions. He provided a detailed description of the complete pattern of activity.

> 1. End of the steam phase from a major eruption.
> 2. Dormant period of about 6 hours during which there is no overflow and no water visible but distant growling is heard far below for a few hours.
> 3. Water becomes visible in the main cone, slowly rising (a little over 6 hours after the last eruption or can be as long as 8 hours afterward).
> 4. The main crater enters a period of cyclic overflowings. The water rises from a point near the top of the throat.
> 5. Four of five cycles before the first minor eruption, bubbles begin to appear just before the rocking starts. Two or three cycles before the first eruption the bubbles are interrupted by a splash or two. The cycle terminating in the first minor eruption is much the same as the two before it. The splashes were a little larger and there are more of them. They become more frequent toward the end of the 4½ minute overflow period. Just when you would expect the water level to drop, the center of the bowl explodes into a violent fountain, growing quickly to a maximum height of 15 to 25 feet. This first eruption lasts around 30 seconds but it can be as long as 1 minute...
> 6. The next eruption occurs in about 1½ to 1¾ hours...
> 7. Minor eruptions following the first 2 to 4 are usually not preceeded [*sic*] by any overflow cycles. These typically overflow, splash, and go into eruption directly. The heights of these later minor eruptions are greater but the durations are all just less than a minute long.
> 8. The major eruption begins in exactly the same way a minor does.

In timing duration of Atomizer's minor eruptions, the author starts timing when "the center of the bowl explodes." In essence, the overflow period is treated as preplay, much the same as Old Faithful preliminary splashes are considered preplay rather than part of the duration of the eruption. As previously noted, this method of timing is consistent with the method used by Dave Leeking [1993].

The author's observations indicate that the major eruption may "begin in exactly the same way a minor does" as noted by Martinez. However the "quick comeback" major eruptions start from an extended period of gurgling inside the tube and splashing above the top of the cone, rather than from a period of overflow and splash. Sometimes this period of gurgling and/or splashing does not result in the major. The impact of this post eruptive activity following a minor on the interval between minors is discussed in the sections "Intervals Between Minors" and "Events Following Each Minor."

In the first edition of *The Geysers of Yellowstone*, Bryan [1979] stated that Atomizer has "a series of minor eruptions that occur several times at intervals of 60 to 90 minutes. The larger cone spouts to about 20 feet for less than a minute."

R. Hutchinson's 1982 report contained several statements about Atomizer. There was no statement about the number of minors in a series. However, he did note that durations recorded in the logbook ranged from 15 to 51 seconds. T.S. Bryan had apparently stated in a July 23, 1982 memo that "intervals are usually very regular, at about 1h10m..." Hutchinson stated that: "Such an observation apparently was made during a short period of exceptional stability." Hutchinson supported this assertion by citing a few of the intervals recorded in the logbook with the statement: "Entries in the thermal logbook showed a great range in intervals between Atomizer's minor eruptions: 13 minutes (May 10); 63 minutes (June 24); 5 minutes (July 3); 12, 63, and 11 minutes (July 6); 101 minutes (July 21); 57 minutes (July 22); etc. just to cite a few."

The intervals cited by Hutchinson fall into three groups—one of 5, 11, 12, and 13 minutes; one of 57, 63, and 63 minutes; and one of 101 minutes. While the intervals in the second two groups are representative of intervals between minors that have been reported by other observers, the intervals in the first group are instead representative of intervals between the concluding minor and the major eruption. One explanation for this difference may be that observers did not always place the notation "major" next to entries in the logbook and Hutchinson assumed that the eruptions were always minor eruptions, when in fact the second eruption may have been a major eruption.

In the 1986 edition of *The Geysers of Yellowstone*, the description of Atomizer's pattern of activity had been expanded to read:

> Following one major eruption, it will apparently be about 8 hours before anything of note happens. By then there have been a number of brief overflows from the main vent, these recurring every few minutes...One of these overflows leads into an eruption. Once started, these minor eruptions normally recur every hour. Lasting a minute or less, they may reach 25 feet high. There are probably six such minor eruptions during a typical cycle. Finally, following a normal minor interval, an eruption merges into the major activity.

This is the earliest statement about the number of minors in a series ("probably six") that the author located.

Bryan noted that "it was only in 1985 that we finally obtained accurate information about what Atomizer really does." Much of the information probably came from Leeking's 1985 observations, although they were not published until 1993.

Leeking [1993] wrote:

> After several hours of inactivity following the ...steam phase, Atomizer's western cone begins to have periodic overflows. There are a half dozen or more minor eruptions during the interval leading to the major.
>
> The durations of the minor eruptions vary between about 25 and 75 seconds, those of the first few minors being shorter than those of the last few before the major....
>
> Atomizer's eruption intervals show an interesting pattern. Once begun, the minor eruptions tend to recur on intervals of about 1 hour until the final two intervals. The span between the penultimate and the final minor is most often between 1½ and 2 hours long. The interval between the final minor and the major is bimodal, being either 10 to 16 minutes long *or* about 1 hour long.

Leeking's description of the eruption intervals within the minor series was the first published description that noted the interval between minors was a function of where the interval occurred within the series of minors.

Landis [1988] also provided quantification for some of the elements of Atomizer's minor cycle.

> Minor eruption durations averaged 50 seconds....A series of minor eruptions occurred which led up to a major eruption....Durations of these minor eruptions were about 20 – 40

> seconds. Intervals between minors averaged about 1 – 2 hours. Durations of minor eruptions continued to increase as a major eruption neared, with minor durations of about 70–80 seconds occurring just prior to a major eruption....Intervals between eruptions within a series of minors averaged 80 minutes..., and tended to shorten 1 – 2 intervals prior to a major eruption...Major eruptions occurred 60–80 minutes after a minor eruption...

It is interesting to note that Landis did not report the possibility of a "come–back" major approximately 10–12 minutes after a minor. Apparently he was unaware of some of the observations made by the author during 1988. It is also interesting to note that neither Leeking [1993] nor Landis [1988] commented on the possibility of an interval between the concluding minor and the major as long as 1¾ hours, such as those reported by Martinez in the 1970's and Hutchinson in 1982.

Bryan's 1995 edition of *The Geysers of Yellowstone* contained revised and expanded information about Atomizer's series of minor eruptions as follows:

> It will usually be 6 to 8 hours after the major, and 2 to 4 hour after the first overflow, until the first of a series of minor eruptions takes place. Minors then recur about every hour, with six to eight usually occurring prior to the next major eruption. It is possible to tell approximately where Atomizer is within its minor series based on observing the duration and the height of a single minor. The first eruption of the series lasts less than 30 seconds and is only 20 to 25 feet high. Each subsequent minor is somewhat longer and stronger than the one before, and the last of the series often lasts over 1 minute and reaches up to 35 feet high. In addition, whereas the minor intervals are about 1 hour, sometimes (not always) the *next to the last* minor interval will approach 2 hours instead. The final interval, from the last minor to the major, is usually 1 hour, too. Infrequent final intervals as short as 12 minutes are known, as are a very few as long as 1 ¾ hours.

This same information appears in the 2001 edition of *The Geysers of Yellowstone*. Bryan [personal communication, 2004] confirmed that his phrase "next to the last minor interval" refers to the interval between the last two minors. This last minor to minor interval is the one that Leeking referred to as the interval between the penultimate and ultimate minor.

The observations of August 2003 generally corroborate this pattern and most of the ranges, with some exceptions:

1. time from preceding major to the first minor, as already discussed in the section "Interval Between Preceding Major and First Minor in a Series",
2. the number of minors in the series, as will be discussed in the section "Number of Minors in a Series",
3. the (in)frequency of final intervals as long (or longer) than 1¾ hours, and
4. the (in)frequency of the 12 minute intervals between the final minor and the major, as will be discussed in the section "Interval Between the Concluding Minor and the Major".

The August 2003 observations also revealed more variability in the intervals between minors than had been previously reported.

Table 6: Number of Minors in a Series

Reporter and Year	Number of Minors
Marler, 1958	"several"
Marler, 1968	"four or more"
Marler, 1973	"several"
Bryan,1979	"a series"
Bryan, 1986	"probably six"
Leeking, 1993	"half a dozen or more"
Bryan, 1995/2001	"six to eight usually"
Stephens, 2003	Average 4.3; range 3-5

B. Number of Minors in a Series

Reports from earlier publications and the results of the 2003 observations about the number of minors in a series are summarized in Table 6.

Prior to 2003, the author had recorded data on a complete series of minors only three times. In 1990 the author recorded two series of four minors and one series of five minors. These observations are consistent with Marler's 1958 "four or more", but less than

Table 7: Number of Minors in the Series				
Number of Minors	3	4	5	Total
Number of Observations	2	10	8	20
Percent of Observations	10%	50%	40%	100%

Leeking and Bryan's "six to eight usually".

In 2003, the author recorded the number of minors for 21 series. The results are shown in Table 7. There were three minors in two (10%) of the series, four minors in 10 (50%) of the series, and five minors in eight (40%) of the series. The average number of minors in the observed series was 4.3.

During the summer of 2003, when the author first mentioned that she had observed series of three minors, she was asked if she was certain that she hadn't missed an earlier minor. For the series of three minors observed on August 6, she had been at the Artemisia-Atomizer viewing area for 3 ¾ hours before the first minor occurred. On August 23, she had been there for slightly over 3 hours before the first minor occurred. In both cases she had been there long enough to ensure that she had not missed a minor eruption. The 2003 observations of series of three minors was not unprecedented. Series consisting of three minors were reported in the August 2000 issues of The Geyser Gazer Sput, where it was noted that T.S. Bryan had reported on June 04, 2004 that "Atomizer is having only 3 or 4 minor eruptions before the major."

None of the series observed in 2003 had six minors. However, the possibility that some of the minor series that were not observed in their totality included six minors cannot be excluded. The longest closed interval in 2003 for which the complete series of minors in that interval was recorded was only 14h57m, and there were five minors in the series. Thus, in the three closed intervals exceeding 16 hours, there would be room for another interval of 60 to 90 minutes, which would have been sufficient to accommodate a sixth minor. However, it is also possible that those intervals included only five minors—9½ hours to first minor, 1½ from minor #1 to #2, 1 hour from #2 to #3, 1 hours from #3 to #4, 2 hours from #4 to #5, and 1½ hours from #5 to the major.

Since the proportion of series with three minors was only 10% of the series for which the total

Table 8: Duration of Minor (shown as minutes:seconds)					
	First Minor	Second Minor	Third Minor	Fourth Minor	Fifth Minor
Minimum	0:13	0:26	0:36	0:41	0:55
Maximum	0:33	0:43	1:02	1:14	1:24
Mean	0:26	0:35	0:46	1:02	1:08
Median	0:28	0:36	0:46	1:02	1:05
Standard Deviation	0:05	0:04	0:06	0:10	0:09
Coefficient of Variation	0.19	0.11	0.13	0.16	0.13
Count	22	21	20	18	8

Table 9: Analysis of Variance—Durations of Minors						
Source	df	SS	MS	F	P value	Significant
Position of Minor in series	3	13861.7	4620.6	98.34	.000	Yes
Error	75	3523.9	47.0			
Total	78	17385.6				

number of minors was observed, series with three minors could still be considered to be "infrequent". However, statements about the range of the number of minors in Atomizer's series of minors should be changed to reflect a lower boundary of three minors. And, series consisting of four or five minors must now be considered frequent.

As previously noted, it appears that although it took longer for Atomizer's system to regenerate sufficiently for minor eruptions to start in 2003, on average, it took fewer minors before the major eruption was able to occur, so the total interval did not significantly shorten when the average interval for 2003 is compared with the average interval in 1985.

C. Duration of Minor Eruptions

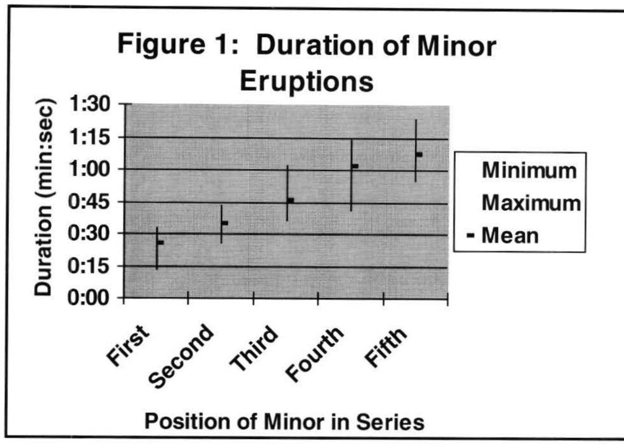
As reported by Landis [1988], Leeking [1993] and Bryan [1995 and 2001], the average duration of each minor increases as the minors progress through the series. Summary statistics for durations of minor eruptions observed in August 2003 are shown in Table 8. The measures of central tendency—minimum, maximum, mean, and median—all increased as the position of the minor in the series increased. The standard deviation also increased, but the increase was not linear. The standard deviations for minor #1, #2, and #3 were similar, while the standard deviations for minors #4 and #5 increased. When the standard deviation is expressed as a percentage of the mean (the coefficient of variation), minor #1 had the highest variability, followed by minor #4.

Bryan [1995 and 2001] noted that: "It is possible to tell approximately where Atomizer is within its minor series based on observing the duration and the height of a single minor. The first eruption of the series lasts less than 30 seconds and is only 20 to 25 feet high." The 2003 data generally supports these observations.

With respect to the duration of the first eruption of the series, four (18%) of the 22 durations recorded for the initial minor exceeded 30 seconds, but only by 2 or 3 seconds.

Tests of variance indicated that the assumption that the variances for the durations of the minors were equal had to be rejected. (Bartlett's Test—assuming normal distribution: Test statistic 17.531; $p = 0.002$; Levene's Test—any continuous distribution: Test statistic 4.278, $p=0.003$.) Visual examination of the standard deviations indicated that minors #1, 2, and 3, with standard deviations of 5.722, 4.127, and 6.611 seconds, respectively, had much less variance than minors #4 and 5, with standard deviations of 10.335 and 9.798 seconds, respectively.

Analysis of variance (ANOVA) is generally used when more than two population means need to be tested. ANOVA assumes that although different samples may come from populations with different means, they have the same variance. The effect of unequal variances upon ANOVA results depends in part upon whether the model includes fixed or random effects and whether the sample sizes are approximately equal or unequal. The ANOVA F-test is only slightly affected by inequality of variance if the model contains fixed factors only and has equal or nearly equal sample sizes. The data on Atomizer minors is a model with fixed factors. The order number of the minor is determined by where it occurs in the series rather than being randomly chosen or assigned. Also, the results are applicable only to the minors studied. No attempt will be made to generalize from these results to a greater number of minors. This satisfies the first requirement. Unfortunately, while the sample sizes for Minors #1, 2, 3, and 4 were approximately equal (22, 21, 20, and 18, respectively), the sample size for Minor #5 was less than half the sample size of the others (8 observations). The only observed cases of a fifth minor in 2003 occurred when there was post-minor splashing/gurgling, or a failed attempt at a major eruption, immediately after Minor #4, as discussed in the section "Events Following Each Minor." For these reasons, ANOVA was used to test whether the durations of Minors #1, 2, 3, and 4, were different, but Minor #5 was not included in the analysis.



Results of the overall ANOVA test (Table 9) showed that at least one of the average durations was different from the others.

To test whether the durations increased as the minors progressed through the series, student t tests for differences were performed to determine whether the differences in the mean intervals are statistically significant at the .05 level of confidence. Therefore, the pair-wise comparisons of interest were Minor #1 versus Minor #2, Minor #2 versus Minor #3, and Minor #3 versus Minor #4. Because the overall test of indicated there was at least one mean significantly different from the other means, protected t test of pair-wise comparisons was used for pair-wise comparisons. As shown in Table 10, all differences in durations were statistically significant.

As a check on the validity of the results, Fisher's pair-wise comparisons were also performed with an overall significance level of .05 and an individual test significance level of .01. The null hypothesis of no difference can be rejected when the Fisher's confidence interval does not include zero. As shown in Table 10, none of the confidence intervals included zero. The Fisher's pair-wise comparison also indicated that the null hypothesis of no difference between the means of the different minors could be rejected.

The ranges and average for durations for each of the minors are shown in Figure 1. This figure demonstrates the overlap of the ranges of the minors. The range for Minor #1 overlaps only one other Minor—Minor #2. The range for Minor #5 overlaps two other Minors—Minors #3 and #4. But the ranges for Minors #2, #3, and #4 overlap three other Minors. In 2003 it was still possible to tell *approximately* where Atomizer was within its minor series, particularly with respect to whether the

Table 10: Results of Follow-up Tests for Pair-wise Comparisons of Durations

	Protected t test Comparisons			Fisher's Follow-Up	
Minor Numbers	F	F_c	Significant	Fisher's confidence interval	Significant
Minor #1 vs 2	10.74	4.00	Yes	-14.739 to -3.685	Yes
Minor #2 vs 3	9.98	4.00	Yes	-16.596 to -5.123	Yes
Minor #3 vs 4	8.97	4.00	Yes	-22.287 to -10.190	Yes

Table 11: Durations (shown as minutes:seconds) of Minors Depending Upon Number of Minors in the Series

	In Series of 3	In Series of 4	In Series of 5
Minor #1			
Mean	0:31	0:28	0:24
Count	2	10	8
Minor #2			
Mean	0:39	0:35	0:35
Count	2	10	8
Minor #3			
Mean	0:59	0:46	0:44
Count	2	9	8
Minor #4			
Mean		1:06	0:59
Count		10	7

minor was early in the series (Minor #1 or Minor #2) or whether it was very late in the series. Unfortunately, since the minor series could be as short as three eruptions, knowing where the minor was in the series did not necessarily translate into being able to make an estimate of how much time remained before the major eruption. For example, in 2003, knowing that an eruption had a duration of 26 seconds (the mean duration for the initial minor) and placing the minor eruption "early in the series" only meant that the major eruption could be as close as 2¾ hours or as long as 7 hours away.

There is some preliminary evidence that the duration of a minor may be a function of the number of minors in the series, at least for minors #1, #3, and #4. Average durations for the minors categorized by the number of minors in the series are shown in Table 11. As a general statement, the smaller the number of minors in a series, the longer the duration of the minor. The average duration of the first minor in a series of three is 0:31 (seconds); in a series of 4 it is 0:28; and in a series of 5 it is 0:24. The average duration of Minor #2 in a series of 3 is 0:39, and the average duration drops to 0:35 for Minor #2 both in series of 4 and 5 minors. The average duration of Minor #3 is longest when it is the concluding minor in a series of 3 (0:59) and shortest when it is the middle minor in a series of 5 minors (0.44). And, the average duration of Minor #4 is longer when it is the concluding minor in a series of 4 (1:06) than when it is the next to last minor in a series of 5 (0:59)

This visual examination suggests that longer durations indicate more energy in the system, which would imply that the major could occur after fewer minors. Because of the limited sample sizes, especially for series consisting of three minors, potential problems with violation of homogeneity of variance assumptions, and unequal number of observations for the different minors in each type of series, statistical tests were not performed to determine whether the differences were statistically significant. This will be investigated in a future research project.

The data was also examined to determine whether the duration of the final minor varied depending on whether or not the final minor was followed by a "quick comeback" major. The results of that analysis are shown in Table 12. Examination of the results shows that short duration minors preceded both "quick comeback" concluding minor to major intervals and longer concluding minor to major intervals. There is no evidence supporting a conclusion that a shorter duration concluding minor requires less time for the system to regenerate sufficiently to support a "quick comeback" major eruption.

The three concluding minors with the longest durations (1:20, 1:24, and 1:30) were not followed by a "quick comeback" major eruption. It is possible that a concluding minor eruption of "a sufficiently long" duration may exhaust the system such that a "quick comeback" major eruption is not possible. More observations will have to be gathered to test this hypothesis.

D. Intervals Between Minors

Table 13 contains a summary of statements made by other reporters about intervals between minors in Atomizer's series of minors. A review of these statements shows a general range of intervals from 1 to 1¾ hours, except the interval between the next to last and the last minor, which can be up to two hours. It also indicates an evolution of the understanding about the complex nature of intervals within Atomizer's series of minor eruptions.

In August, 2003, 69 intervals between minor eruptions were recorded. The intervals range from a minimum of 51m to a maximum of 2h30m, with an average of 1h20m, a median of 1h12, and a standard deviation of 23m. Table 14 shows the distribution of the intervals in 15 minute categories. Almost half the intervals are between 1 and 1¼ hours. Sixty–five percent of the intervals are between 1 and 1½ hours. Seven of the intervals (10%) exceed 2 hours. These results indicate that statements about the range of Atomizer's intervals need to be expanded to allow for an upper boundary of 2½ hours.

These overall statistics mask differences in the intervals based on where the interval occurred in the series. For example, the first minor to minor interval was the longest interval in six of the 18 series for which the intervals between every minor in the series was observed. The second minor to minor interval was shorter than the first minor to minor interval in 11 of the 19 series where the two intervals were observed, or more than 50% of the cases. This decrease gives support to statements such as Landis made that intervals between minors sometimes tend "to shorten 1–2 intervals prior to a major eruption."

Descriptive statistics for intervals between specific minors determined by position of the minor in the series are shown in Table 15. The range and average for intervals between each of the minors are compared in Figure 2.

Table 12: Duration (minutes:seconds) of Concluding Minor and Whether It Was Followed by "Quick Comeback" Major

No	Yes
0:49 (4)	0:51 (4)
0:55 (5)	
0:57 (unk)	
1:00 (unk)	1:00 (unk)
1:01 (5)	1:02 (3)
1:03 (5)	1:02 (4)
1:03 (5)	
1:07 (unk)	
1:08 (5)	1:08 (unk)
1:08 (4)	
1:08 (unk)	
1:10 (5)	1:10 (4)
1:11 (unk)	
1:12 (unk)	
1:14 (4)	1:13 (4)
1:14 (4)	1:14 (4)
1:15 (unk)	1:14 (4)
1:20 (5)	
1:24 (5)	
1:30 (unk)	

Number in ( ) indicates number of minors in the series, if known.

Figure 2: Intervals Between Minor Eruptions

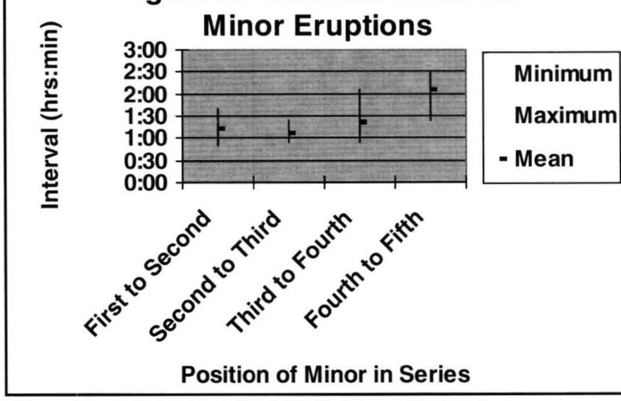


Table 13: Intervals between minors	
Reporter and Year	Minor Intervals Cited
Marler 1958	about an hour and a half
Marler 1970	about hourly
Marler 1973	about an hour and a half
Martinez 1973	one hour 45 minutes
Martinez 1974	Between first and second minor is 1½ to 1¾ hours
Bryan 1979	60 to 90 minutes
Bryan 1982	About 1h10m
Hutchinson 1982	Cited intervals 5-13 minutes [probably minor to major], and intervals from 57 to 101 minutes
Bryan 1986	normally recur every hour
Leeking 1993 (1985 observations)	about 1 hour, except for the interval between the penultimate and the final minor, which was "most often between 1½ and 2 hours long
Landis 1988	averaged 80 minutes, and tended to shorten 1-2 intervals prior to a major eruption
Bryan 1995/2001	about 1 hour; sometimes (not always) the next to the last minor interval will approach 2 hours instead

Table 14: Frequency of Intervals Between Minors						
	< 1:00	1:00–1:14	1:15-1:29	1:30-1:44	1:45-1:59	>1:59
Number	8	32	13	6	3	7
Percent	11.6%	46.4%	18.8%	8.7%	4.3%	10.1%

Table 15: Intervals Between Minors						
	Interval Between Minors # and #					
	#1 and #2	#2 and #3	#3 and #4	#4 and #5	Unknown	overall
Minimum	0:51	0:54	1:05	1:23	0:53	0:51
Maximum	1:41	1:24	2:05	2:30	2:01	2:30
Range	0:50	0:34	1:00	1:07	1:08	1:39
Mean	1:14	1:07	1:21	2:05	1:31	1:20
Median	1:12	1:07	1:12	2:15	1:36	1:12
St. Dev.	0:14	0:08	0:20	0:24	0:28	0:23
Coefficient of Variation	.189	.119	.247	.192	.308	.288

The minimum interval between eruptions shows a consistent increase as the minor series progressed, rising from 51m to 54m to 1h05m to 1h23m. This is the only descriptive statistic that does show a consistent increase.

The other descriptive measures — maximum, mean, median, standard deviation, and coefficient of variation — all decrease for the second minor-to-minor interval (the interval between minors #2 and #3) when compared to the corresponding measures for the first minor–to–minor interval (the interval between minors #1 and #2). The measures also all increase for subsequent minor-to-minor intervals. For example, the maximum for the second minor–to–minor interval is 17 minutes less than the maximum for the first minor–to– minor interval. The maximum for the third minor–to–minor interval is 41 minutes larger than the maximum for the second minor-to-minor interval, and the maximum for the fourth minor-to-minor interval increases another 25 minutes. On average, the second minor–to–minor interval was both shorter and less variable than the first minor–to–minor interval; the third minor–to–minor interval was both longer and more variable than the second minor–to–minor interval, and the fourth minor–to–minor interval was both longer and more variable than the third minor–to–minor interval.

Statistical tests were performed to determine (1) whether the assumption could be made that the samples came from populations with equal variances and (2) whether the differences between the average intervals as the minors progressed through the series are statistically significant at the .05 level of significance.

Bartlett's test resulted in rejection of the hypothesis that the intervals between minors came from populations with similar variances (Bartlett's test statistics = 15.37; p-value = .002.). Although the model is a fixed effects model, as previously discussed, sample sizes were not equal and I did want to include the interval between Minors #4 and #5 in this analysis. The nonparametic Kruskal-Wallis test, which does not require that the populations have equal variance, was used to test whether the differences between the average intervals are statistically significant at the .05 level of significance.

The overall test indicated that the null hypothesis that the populations had equal means could be rejected at the .05 level of significance (Kruskal-Wallis test statistic $H = 21.2$, $df = 3$, $H_c = 7.81473$, $p=.000$). Follow-up tests (Table 16) indicated that the differences in the average intervals are statistically significant for all of the comparisons as the minors progressed through the sequence. The second interval was significantly shorter than the first interval, supporting Landis' statement that intervals tend to shorten one to two intervals before the major, especially when the series contains only three or four minors. Following the second minor interval, intervals between the minors increased as the minors progressed through the minor series, with each interval significantly longer than the preceding interval.

To determine whether the early intervals in a series could be used to predict the number of minors in the series, the data on intervals was subdivided according the number of minors in the series. Since there were only two series consisting of three minors, the analysis was limited to series with four or five minors. The results are shown in Table 17.

Visual examination of the data indicated preliminary evidence that there is a difference in the average minor to minor intervals depending on whether the series contains four or five minors. The means and medians are consistently larger when the series contains four minors than when the series contains five minors. Visual examination indicates that the variability of the minor

Table 16: Test of Differences Between Minor to Minor Intervals

Difference Between Minor to Minor Intervals	D	C_{kw}	Significant
First vs Second Minor Intervals	10.99	7.0687	Yes
Second vs Third Minor Intervals	14.15	7.4634	Yes
Third vs Fourth Minor Intervals	23.50	10.16	Yes

to minor intervals for the first and second minor intervals is relatively the same regardless of whether the series contains four or five minors. Visual examination also shows that the variability in the third minor interval was much different depending on whether the series has four or five minors. F tests of Variance (see Table 18) confirmed the visual examination.

As previously noted, ANOVA is affected by unequal variance when the sample sizes are also unequal. Sample sizes ranged from 7 to 10—a large percentage difference. Each of the series was numbered and random numbers were used to reduce the number of sample observations to seven. A two-factor ANOVA with the number of minors as one factor and the position of the minor to minor interval as the second factor was used to test whether the difference in the length of the minor to minor intervals was statistically significant. The results (shown in Table 19) confirm the visual analysis. The null hypothesis that the interval is the same regardless of whether the series contains four or five minors can be rejected ($p = .003$). The null hypothesis that the minor to minor intervals are the same regardless of whether it is the first, second, or third minor interval can also be rejected ($p = .045$). The interaction between the number of minors in the series and the position of the minor to minor interval is not statistically significant.

Examination of the intervals between the third and fourth minor (Table 20) showed that the longer it took between the third and fourth minors, the more likely it was that the series would consist of only four minors. This could be interpreted to mean that the longer build–up time prior to the fourth minor allowed the system to generate enough energy for the major to occur without a fifth minor. In 2003, if the fourth minor started less than 70 minutes after the third minor, a fifth minor was required before the major eruption occurred. Once the interval extended beyond 80 minutes, the next event was the major eruption. In 2003, intervals between 70 and 80 minutes could result in either another minor or the major as the next eruptive event. It is possible that the area of overlap will enlarge as more observations are collected in future years.

Another factor that influences the interval between minors is whether or not there is gurgling inside the tube and/or splashing from the tube in

Table 17: Intervals Between Minors Categorized by Number of Minors in the Series

Interval between Minors	Minimum	Maximum	Mean	Median	Standard Deviation	Number of Observations
First Minor Interval (Minor #1 to Minor #2)						
Series of 4	0:52	1:41	1:18	1:22	0:15	10
Series of 5	0:51	1:31	1:11	1:08	0:13	8
Difference	0:01	0:10	0:07	0:14	0:02	
Second Minor Interval (Minor #2 to Minor #3)						
Series of 4	1:01	1:23	1:10	1:09	0:07	9
Series of 5	0:54	1:13	1:02	1:01	0:06	8
Difference	0:07	0:10	0:08	0:08	0:01	
Third Minor Interval (Minor #3 to Minor #4)						
Series of 4	1:12	2:05	1:32	1:21	0:23	9
Series of 5	1:05	1:15	1:09	1:08	0:03	7
Difference	0:07	0:50	0:23	1:13	0:20	

Table 18: F Tests of Variance for Interval Differences Between Series of 4 and Series of 5 Minors					
Minor to Minor Interval	F	F_c	df	P value	Significant
First	1.22	3.68	9/7	.404	No
Second	1.44	3.73	8/7	.323	No
Third	38.87	4.15	8/6	.000	Yes

the 15 minutes immediately following the minor. Sometimes the minor ends with no audible or visible activity immediately after the minor. Sometimes the minor ends, audible gurgling and visible splashing continues or begins a few minutes later and then this activity results in a "quick comeback" major. Alternatively, sometimes the minor ends, audible gurgling and visible splashing begins and continues for up to 20 minutes after the minor, but this activity does not result in a "quick comeback" major.

Although no references to this post–minor activity were located in the reports reviewed by the author, she has heard comments from various observers that when the post–minor gurgling/splashing occurs and the major does not happen within 15 minutes of the minor, then it will be about 1½ hours before the next event occurs. That event could be either another minor, or it could be the major. For example, on August 7, Atomizer continued to gurgle and bubble following the minor at 07:21, resulting in a 2h01m interval before the next minor at 09:22. This minor was followed by another minor at 10:15, which in turn was followed by the major at 11:53. Alternatively, on August 16, a minor at 16:09 was followed by audible gurgling and splashing until 16:21. In this case, the next event was a major at 17:59.

Not all minor to minor intervals between 1½ to 2 hours were preceded by post–eruptive activity following the minor. Whether or not a long minor–to–minor interval was preceded by post–eruptive gurgling/bubbling depended upon where the long interval occurred in the series of minors. For example, there were five 1½ to 2 hour minor to minor intervals between the first and second minor eruptions. None of these involved post minor gurgling/bubbling following the first minor. (As a side note, there were no intervals exceeding 90 minutes between the second and third minor eruptions.) There were three cases of long intervals (1h59m, 2h02m, and 2h05m) between the Minors #3 and #4. Two of these were associated with post eruptive gurgling/bubbling; one was not. All long intervals between the fourth and fifth minor were associated with post–eruptive activity and will be discussed in the section on "Events Following Each Minor."

Table 19: Two-Way ANOVA—Interval (minutes) versus Number of Minors, Position of Minor to Minor Interval					
Source	dF	SS	MS	F	P
Number of Minors	1	1787.52	1787.52	9.95	.003
Position	2	1214.90	607.45	3.38	.045
Interaction	2	222.90	111.45	.62	.543
Error	36	6465.14	179.59		
Total	41	9690.48			

Table 20: Intervals Between Third and Fourth Minor Categorized by Number of Minors in the Series

4 minors	5 minors
	1:05
	1:06
	1:07
	1:10
1:12	1:12
1:12	1:12
1:14	1:15
1:16	
1:21	
1:28	
1:59	
2:02	
2:05	

Finally, all the intervals exceeding 1h45m except one occurred as the final minor interval in the series of minor eruptions. Four of the six intervals between 1h30m and 1h45m occurred between Minors #1 and #2. The other two intervals in this range occurred as the final minor interval. As a generalization, in 2003, "super long" intervals occurred at the end of the series, but "long" intervals could occur either at the beginning or the end of a series.

E. Interval Between Next to Last (Penultimate) Minor and Concluding Minor

Dave Leeking [1993] first indicated recognition that the interval between the next to last and concluding minor could be longer than the intervals between other minors in the series. Leeking reported that the interval between the penultimate and final minor "...is *most* often between 1½ and 2 hours long." [emphasis added.] Bryan's 1995 and 2001 editions of *The Geysers of Yellowstone* include the statement that "...whereas the minor intervals are about 1 hour, sometimes (not always) the *next to the last* minor interval will approach 2 hours instead."

In 2003, the interval between the last two minors in the series was determined for 21 series. These intervals are shown in Table 21 with the number of minors, where known, shown in ( ). Overall, the intervals ranged from a minimum of 0h53m to a maximum of 2h30m, with a median of 1h31m and a mean of 1h40m.

In 2003, about 25% of the intervals were between 1½ and 2 hours, and almost 30% exceeded 2 hours. It appears that there were fewer intervals in the 1½ to 2 hour range in 2003 than there had been in 1985. The reason for this is probably not a migration toward shorter intervals, but rather an increase in intervals longer than Leeking's upper boundary of 2 hours. If 1h45m is chosen as the lower boundary for "approaching 2 hours", then 43% of these intervals approached or exceeded 2 hours. Intervals in 2003 exceeding 2 hours were frequent enough to justify expanding the upper boundary to 2½ hours instead of 2 hours.

When the last minor to minor intervals are subdivided according to the number of minors in the series, the values for the minimum, maximum, mean, and median are all higher when the series contained five minors than when the series had four minors, as shown in Table 22. An F test of variance indicated that the samples could be assumed to come from populations with equal variances ($F = 1.13$, $F_c = 3.58$, df 6/8, $p = .424$). A test of means indicated that the hypothesis that the samples came from populations with equal means could be rejected at the .05 level of significance ($t = 2.81$, $t_c = 1.76$, df 14, $p = .007$). The concluding interval in a series of five minors was significantly longer than the concluding interval in a series of four minors. The reason for this difference is discussed in the next section "Events Following Each Minor."

F. Events Following Each Minor

In 2003, the first minor was always followed by a second minor, with no post eruptive gurgling/bubbling observed following the first minor. The second minor was always followed by a third minor, with no post eruptive gurgling/bubbling observed following the second minor. Events following the third, fourth, and fifth minors varied, as shown in Table 23. Regular intervals were defined as 1 to 1¼ hours. Long intervals were defined as 1h20m to 2½ hours.

Table 21: Interval Between Penultimate and Concluding Minor

< 1:00	1:10 – 1:14	1:15 – 1:29	1:30 – 1:44	1:45 – 1:59	> 1:59
0:53 (unk)	1:12 (4)	1:16 (4)	1:31 (unk)	1:47 (5)	2:02 (4)
	1:12 (4)	1:19 (3)	1:42 (unk)	1:57 (5)	2:05 (4)
	1:14 (4)	1:21 (4)		1:59 (4)	2:15 (5)
		1:23 (5)			2:20 (5)
		1:24 (3)			2:27 (5)
		1:28 (4)			2:30 (5)
N = 1 (4.8%)	N = 3 (14.3%)	N = 6 (28.6%)	N = 2 (9.5%)	N = 3 (14.3%)	N = 6 (28.6%)

Minor #3 was followed by post–eruptive gurgling/splashing in only four (22%) cases. Of these four cases, two (50%) were followed by a quick comeback major and two (50%) were followed by a long interval before the next minor occurred. The proportion of the time Minor #4 was followed by post eruptive gurgling/splashing increased to 76% (13 out of 17). But the proportion of the time that this activity resulted in a quick comeback minor stayed about the same. The 13 minors followed by post eruptive gurgling/splashing split almost evenly between quick comeback majors (6/13 = 46%) and long intervals before the next minor (7/13 = 54%). Minor #5 was followed by post eruptive gurgling/splashing only one time in the seven cases that were observed. This was in turn followed by a long interval between Minor #5 and the major. Both the proportion of cases where the minor was followed by post eruptive gurgling/splashing (14%) and the percentage of time this activity resulted in a quick comeback major (0%) decreased.

Table 24 shows the frequency of occurrence of post minor gurgling/splashing for the 33 cases where at least one minor was observed prior to the major eruption. In those series where at least two minors were observed prior to the major, only 2 of the 24 cases (8.3%) did not involve post-minor gurgling/splashing. Conversely, 22 of the 24 cases (91.7%) did involve post-minor gurgling/splashing.

There were nine cases where only the concluding minor and the major were observed. In two of these cases, the minor was followed by post-minor gurgling/splashing leading to a "quick comeback" major. In the other seven cases, the minor was followed by an interval of approximately one hour. Post-minor eruptive gurgling/splashing could have occurred following one of the minors preceding the single pre-major minor that was observed. However, there is a possibility that post-minor eruptive gurgling/splashing did not following any of the un-

Table 22 Descriptive Statistics—Interval Between Penultimate and Concluding Minor (hours:minutes)

	Overall	Series of 4 Minors	Series of 5 Minors
Count	21	9	7
Minimum	0:53	1:12	1:23
Maximum	2:30	2:05	2:30
Mean	1:40	1:32	2:05
Median	1:31	1:21	2:15
Standard Deviation	0:28	0:23	0:24

observed minors preceding the one minor that was observed. Treating all of the unknown, or missing data, cases as "no" yields the most conservative estimate of the proportion of series that did not involve post-minor gurgling/splashing. This would result in nine "no" cases out of the 33 observations, or 27.3%. In other words, at a minimum 73% (and possibly more) of the cases did involve post-minor splashing/gurgling.

The one hour gap between the length of major to major intervals between 13h55m and 14h56m was probably related to post-minor gurgling/splashing that did not result in a "quick comeback" major. When the post-minor activity was not followed by a "quick comeback" interval, it resulted in a long interval between the minor with post-minor activity and the succeeding minor. This long interval was often in excess of two hours. When post-minor gurgling/splashing did not occur, the interval between minors was generally about an hour. Intervals less than 13 hours probably had only 3 minors in the series and included a "quick comeback" major. Intervals between 13 hours and 14 hours probably had either four minors followed by a "quick comeback" major, or no post-minor gurgling/splashing after either the third or the fourth minor. Intervals with a minimum length of just under fifteen hours probably had post-minor gurgling/splashing after either the third or fourth minor and did not include a "quick comeback" major after the concluding minor.

Table 23: Frequency of Events Following Selected Minors

	Interval to Next Event		
	Next Event = Minor	Next Event = Major	Frequency
	Minor #3		
Post Eruptive Activity			
Yes		Quick Comeback	2 (11.1%)
Yes	Long		2 (11.1%)
No	Long		1 (5.6%)
No	Regular		13 (72.2%)
Unknown			1
Total			18
	Minor #4		
Post Eruptive Activity			
Yes		Quick Comeback	6 (35.3%)
Yes	Long		7 (41.2%)
No		Regular	4 (23.5%)
Total			17
	Minor #5		
Post Eruptive Activity			
Yes		Long	1 (14.3%)
No		Regular	6 (85.7%)
Total			7

Table 24: Frequency of Post-Minor Gurgling/Splashing			
	Post-Minor Gurgling/Splashing		
	Yes	No	Unknown
Series where at least two minors were observed prior to the major eruption	22	2	
Concluding minor and major observed	2		7
Total	24	2	7

G. Interval Between the Concluding Minor and the Major

As noted in the most recent edition [2001] of *The Geysers of Yellowstone,* "The final interval, from the last minor to the major, is usually 1 hour, too. Infrequent final intervals as short as 12 minutes are known, as are a very few as long as 1¾ hours."

Observations during August 2003 of the interval between the concluding minor and the major are shown in Table 25. Where the number of minors in the series is known, it is indicated in ( ) next to the interval. Intervals were determined for 31 cases. Examination of the data shows that "quick comeback" intervals appear as a distinct group, separate from the remaining intervals.

The distinction between intervals of "about an hour" and intervals of "about 1¾ hours" is less clear. There is a five minute break between 1:14 and 1:19 and a six minute break between 1:19 and 1:25. Since there was a 13 minute break between 1:25 and 1:38, the 2003 data appears to fall into a set of intervals of about 60–80 minutes, and two "long" intervals that could be characterized as "about 1¾ hours". When the intervals are segregated into these three groups, the "quick comeback" intervals account for 35.5% of the observations, the "about 60–80 minute" intervals account for 58.1% of the cases, and the "about 1 ¾ hour (long)" intervals occurred in 6.5% of the cases. These proportions indicate that although intervals between 1½ and 1¾ hours are still infrequent, "final intervals as short as 12 minutes" were not infrequent in 2003. If intervals of 70 to 85 minutes are not considered "about an hour" long, then a third category should be added to earlier statements that intervals between the final minor and the major are either 10 to 15 minutes or about 1 hour long.

Dave Leeking [2002] noted the disappearance and subsequent reappearance of the "quick comeback" intervals.

> ...it was in late May of 1997 that David Monteith reported seeing the first known (at least to me) 'quick comeback'—that is, short, about 10 minutes after the last minor—last minor to major interval seen since the early 1990's or earlier. These 'quick comeback' intervals have been common once again in 1998–2002 as they were when I first observed the geyser consistently in July and early August of 1985. As stated in Scott Bryan's Geysers of Yellowstone [*sic*], these 'quick comeback' intervals were rare in the early to mid–1990's.

Possibly because the focus of his 1993 article was Atomizer's major intervals, Leeking did not provide any indication of the proportion of the intervals between the final minor and the major that were "quick comeback" intervals in 1985.

The author recorded 31 observations of the interval between the final minor and the major eruption during the three years 1988, 1989, and 1990. The results of these observations are shown in Table 26. The data appears to show a decline in the proportion of "quick comeback intervals", with a decrease from 55.6% to 25.0% in 1990. However, the sample sizes are small and the difference in the proportions between 1989 and 1990 is not statistically significant at the .05 confidence level. The proportion of "quick comeback" intervals in 2003 (35.5%) is higher than the 25% proportion in 1990, but has not reached the 50% level of 1988 and 1989.

Although the sample sizes are small, the number of minors in a series does appear to have some

Table 25: Distribution of Intervals Between Concluding Minor and Major--2003

"Comeback" Interval	Interval 0:55 – 1:09	Interval 1:10 – 1:25	Interval 1:26 – 1:35	Interval > 1:35
0:11	0:58	1:10 (5)		1:38
0:12 (4)	1:00 (5)	1:10 (5)		1:50 (5)
0:12 (3)	1:03 (5)	1:12		
0:12	1:04	1:14 (4)		
0:12 (4)	1:05 (4)	1:19 (4)		
0:12 (4)	1:05 (5)	1:19		
0:12 (4)	1:05 (5)	1:25		
0:12 (4)	1:07 (4)			
0:12 (3)	1:07 (5)			
0:12 (4)	1:07			
0:12	1:08			
N = 11 (35.5%)	N = 11 (35.5%)	N = 7 (22.6%)	N = 0	N = 2 (6.5%)

relationship to the nature of the interval between the concluding minor and the subsequent major, as shown in Table 27. Both series of 3 minors resulted in "quick comeback" intervals. None of the series of 5 minors resulted in a "quick comeback" interval. Series of 4 minors were split between "quick comeback" intervals (60%) and other intervals (40%).

One further comment about the "quick comeback" intervals. During August, 2003, all the "quick comeback" intervals I recorded were 11–12 minutes. However, the author has seen "quick comeback" intervals as short as 5 minutes after the major. On July 2, 1990, she observed a major that started 5 minutes after the minor. Usually, when a "quick comeback" major occurs, there is a period following the end of the preceding minor during which Atomizer gurgles and periodically sends marble size droplets of water above the level of the cone but standing water is not visible at the top of the cone. This activity usually starts 3 to 5 minutes after the end of the minor and continues for several minutes until at about the 10–12 minute mark the column of water lifts inside the tube and results in an eruption. On July 2, 1990, the column lifted suddenly at the time the preliminary activity usually starts instead of going through the customary several minutes of preliminary activity. This resulted in an interval of five minutes between the concluding minor and the major. On September 5, 2003, I witnessed a "quick comeback" interval of 8 minutes between the start of the concluding minor and the start of the major. In this case, the gurgling and bubbling started about five minutes after the major ended and continued for only three additional minutes before the column lifted into the major eruption.

Table 26: Intervals Between Final Minor and Major – 1988 - 1990

Year	Comeback Intervals Number (Percent for Year)	Non-Comeback Intervals Number (Percent for Year)	Total Number Of Cases
1988	3 (50.0%)	3 (50.0%)	6
1989	5 (55.6%)	4 (44.4%)	9
1990	4 (25.0%)	12 (75.0%)	16
Total	12 (38.7%)	19 (62.3%)	31

Table 27: Comparison of Number of Minors in the Series and Interval between the Concluding Minor and the Subsequent Major

Number of Minors in Series	Comeback Interval	55 – 85 Minute Interval	> 90 Minute Interval	Total
3	2	0	0	2
4	6	4	0	10
5	0	7	1	8
Unknown	3	7	1	11
Total	11	18	2	31

In 2003, the average interval between the concluding minor and the major was 1h12m and the median was 1h07m for the 20 intervals between concluding minor and the major that did not include a "quick comeback". These 20 intervals range from a minimum of 0h58m to a maximum of 1h50m, with a standard deviation of 0h12m. A review of the data indicated that the mean is skewed by the two longest intervals—the maximum interval of 1h50m and the next longest interval of 1h38m. In each of these two cases, there is one standard deviation between that interval and the next shortest interval. If these two intervals are considered outliers, the mean for the remaining 18 cases drops to 1h08m, only one minute greater than the median of 1h07m, and the standard deviation drops to six minutes. A review of other events that occurred during these two minor cycles indicates that in the case of the 1h50m interval, there was unusual eruptive activity that occurred between the final minor and the major. This unusual eruptive activity consisted of independent activity from the northeastern cone, and is discussed in the following section "Unusual Minor Activity". This activity would justify excluding the interval. However, nothing unusual was noted in the cycle that included the 1h39m interval between the final minor and the major, which would argue against excluding that interval from the calculations.

H. Unusual Minor Activity

Leeking [1993] reported two known cases of a "bizarre minor eruption by Atomizer" during which "[T]he normally inactive [north]eastern cone erupted large drops of water, about the size of standard marbles, up to 3 feet high for 2m 35s without any accompanying steam…This strange eruption was followed by an entirely major eruption of Atomizer at 09:53 [16 minutes after the "bizarre minor"]. He reported that Paul and Suzanne Strasser had seen one like that in about 1979. Leeking concluded that "This shows, however, that such activity is not unique; in fact, that it has been seen twice in a geyser only infrequently observed might imply a fair degree of frequency for this action."

The author recorded one such episode of independent activity from the northeastern cone during August 2003. On August 17, she arrived after Atomizer's minor series had started. A 76 second minor was recorded at 07:06 and a 90 second minor was recorded at 08:58. Following that minor, there was audible post–minor gurgling from Atomizer but no above ground splashing until about 09:15. At 10:00 there was audible eruptive activity in the vicinity of Atomizer. Water was erupting several inches to a foot above the top of the northeastern cone. This eruptive activity continued for about 2½ minutes and was succeeded by a major eruption at 10:17, 17 minutes after the "bizarre minor." The total interval between the last minor and the major was only 1h19m.

During August 2003 the author arrived at Atomizer in time to witness the events between the final minor eruption and the major eruption—the time frame during which the three reported cases of independent activity from the northeastern cone have occurred—30 times. If her experience in 2003 is indicative of the frequency with which this activity happens, it happens during less than 4% (1/30 = 3.3%) of Atomizer's major to major cycles. Although the activity is not unique, the 2003 observations of less than a 4% rate of occurrence, do not indicate a "fair degree of frequency", at least for 2003.

CONCLUSION

The basic nature of Atomizer's pattern of activity remains unchanged since it was first described by Marler in 1958. Based on the August, 2003 observations though, the boundaries on some generalizations about the components of the pattern need to be revised and or modified.

In August, 2003, the average major–to–major interval was approximately 14½ hours with a range from under 12½ hours to over 16½ hours. The first minor in the series leading up to the major occurred about 8½ to 10½ hours after the preceding major. This minor was followed by two to four additional minors before the succeeding major eruption. The interval between the first minor and that succeeding major varied from just over 2½ hours to slightly over 7 hours.

Durations of the minors increased as the minors progressed through the series, but intervals between the minors did not show a steady increase. Instead, in many cases, the first minor interval was longer than the second minor interval. Intervals between the minors ranged from under 1 hour to 2½ hours. Although the majority of the intervals over 1½ hours occurred as the final minor to minor interval, these long intervals could also occur as the first or third minor interval.

The final minor to minor interval (next to last using Bryan's terminology, or interval between the penultimate and final minor using Leeking's terminology) ranged from slightly under 1 hour to 2½ hours. Over 50% of the final minor to minor intervals exceed 1½ hours and almost 30% exceeded 2 hours.

The interval between the concluding minor and the major ranged from 11 minutes to almost 2 hours. In 2003, 35% of the series of minors ended with a quick comeback major where the major occurred 10–12 minutes after the concluding minor. Statements about the nature of the interval between the concluding minor and the major should probably include three groups—intervals of 10–15 minutes, intervals about 1 to 1½ hours, and infrequent intervals between 1½ and 2 hours.

There was some evidence that the length of the second and third minor intervals and the duration of the fourth minor could be used to predict whether the series would include four or five minors.

These observations provide some baseline data that can be used for comparison purposes in future studies to determine whether changes in Atomizer's pattern of behavior occur.

Acknowldegements

Thank you to Dean Lorenz and Jake Young and Leslie Phillips who provided me with data that supplemented my August 2003 observations. Thank you also to Professor Holly Zullo for her comments and suggestions for changes that greatly improved the paper.

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Atomizer Geyser on August 3, 2003. [Photo by Lynn Stephens]

The birth of "Aftershock Geyser"
Upper Geyser Basin

By Mike Keller

Abstract

The summer of 1997 there was an increase in activity in Seismic Geyser that included the formation of a new vent, later named "Aftershock." This paper will discuss the history of Seismic Geyser and detail the formation, growth, and activity of "Aftershock," which was first noted in May 1999 and continued activity into March 2004.

History prior to 1999

Before discussing the outbreak of "Aftershock" lets revisit the birth of its neighbors, Seismic and Seismic's Satellite.

Following the August 17, 1959 Hebgen Lake earthquake, an area of hot ground formed in the area of today's Seismic Geyser. George Marler and Donald White wrote the following in their 1975 report [Marler and White, 1975]:

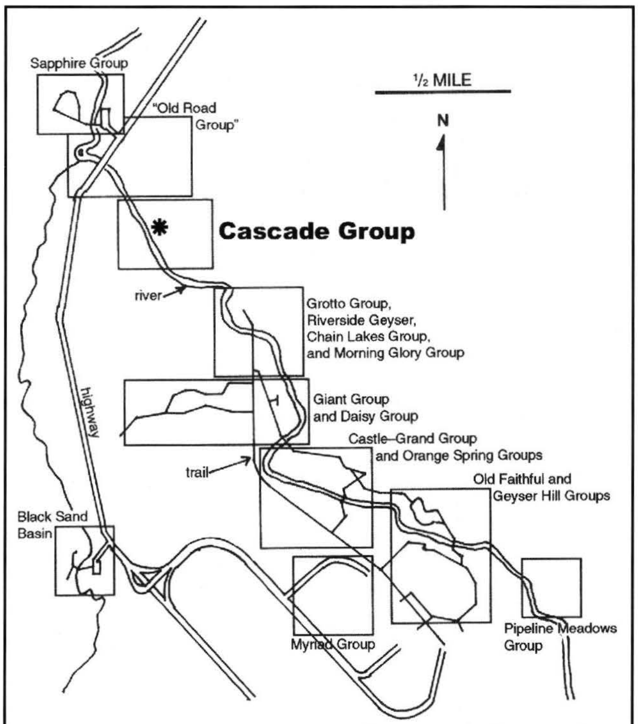


Figure 1. The location of "Aftershock Geyser" is shown by the star within the Cascade Group of the Upper Geyser Basin, Yellowstone National Park. [Map © 2001 T. Scott Bryan]

> Within several days after the earthquake, two new fractures were observed in an embankment of old sinter that borders the east bank of the Firehole River in the Upper Geyser Basin about 550m south of the Biscuit Basin parking area... The break nearest the river was the most conspicuous, being about 20m long. The eastern fracture was about 15m east of the edge of the steep declivity to the river and was about 10m long. Steam was issuing near the central part of each break... Recorded temperatures of both the upper and lower fumaroles were about 95ºC"...
>
> During the remainder of 1959, the discharge of steam under slight pressure continued unabated from both fumaroles.

This activity remained unchanged until the winter of 1962–1963, when Marler observed the following [*ibid.*]:

> Sometime during the previous winter, explosive activity had occurred at the site of the upper fumarole. Where steam previously had been hissing through a narrow rift, there was now a large crater. Numerous large blocks of sinter from 0.3 to 1m in diameter were strewn about randomly, bearing evidence the crater had formed explosively... The crater was 1.5 to 2m deep and was elongated perpendicular to the river, measuring about 2.7 to 4.9m.
>
> During all of 1963, water jets about 1m high played into the crater every few seconds; the jets shot at an angle of about 45 degrees from the west end of the crater. The water drained from the bottom of the crater immediately after each jetting. Thus, the former fumarole had evolved into a small geyser.

For the remainder of 1963 and through 1964, the activity slowly increased in size with eruptions reaching up to 4 meters. By the end of 1964, the activity in the other fumarole had ceased. Further changes took place in the winter of 1964–1965 [*ibid.*]:


Seismic Geyser shortly after its major development. [NPS photo, electronic slide file #04840]

> Sometime prior to April 1965, a new explosion or series of explosions occurred near the west end of the crater. Sudden release of energy had not only greatly enlarged the earlier orifice but had also torn out obstructions. The water, now discharged in much greater volume, erupted vertically instead of at an angle.
>
> Yellowstone evidently now had a new geyser of no mean proportions. Because of the nature of its origin, Marler... suggested that it be named 'Seismic'. During 1965, little change occurred in the nature of its activity. Massive bursts of water rocketed from the crater every 1 to 3 minutes. Most of the bursts were from about 2 to 6m high, but occasionally, water jetted to a height of nearly 15m.

Over the next few years, the activity from Seismic continued to increase. By the late 1960's, Seismic was the largest erupting geyser in this portion of the Upper Geyser Basin [*ibid.*]:

> During the years of 1967 through 1969, the pattern of Seismic's eruptive activity underwent progressive changes. The length of the quiet phase between eruptions slowly increased to about 40 to 50 min. Each eruption was complex, with a duration of about 15 to 20 min, during which 30 or more separate bursts occurred... The first burst of each sequence explosively broke the surface of the pool...
>
> On several occasions during 1970, Marler spent 2 hours or more at a time at Seismic to determine the nature of its eruptive pattern, which seemed to have changed somewhat from that of the three previous seasons. Each complex eruption consisted of at least three separate periods of activity, of which the second was always the longest, on one occasion lasting for 19 min. The duration of a complex eruption was variable, with extremes from about 19 to 31 min. An unfailing sign of the termination of each complex eruption was a drop in the water level of about 0.35m in the crater... The quiet and eruptive phases were about equal in duration, with each ranging from about 20 to 30 min. The heights of the 1970 eruptions were similar to those observed during the 1967–1969 period. The maximum height was about 12m or slightly less than the estimated maximum bursts of the 1965–1966 period.

During the spring of 1971, there was another explosion and another new geyser was formed [*ibid.*]:

> Sometime between late February and April of 1971, a vent (now called 'Satellite') developed on the east shoulder of the crater. Satellite's vent, like Seismic, resulted from one or more explosions... When first observed in 1971, the water was boiling vigorously in Satellite's crater, welling up from 0.6 to 1m. Steady boiling was generally characteristic of its pattern throughout the remainder of the season, but periodically Satellite erupted with massive bursts to a height of about 3 to 3.7m and occasionally to 6m. Its eruptions were synchronized with those of Seismic, with both vents erupting simultaneously. The new geyser's activity decreased the vigor of Seismic's eruptions. However, at times, Seismic erupted to heights as much as 7½ to 9m.

Further changes in the activity of Seismic and Satellite continued in 1972 [*ibid.*]:

> During the previous winter of 1971–1972, Satellite's vent had enlarged about to 3.7 by 3.7m, compared to the 1.8 by 2.4m vent of 1971. No further changes took place in Seismic's crater during the 1971–1972 winter, probably because it had ceased eruptive activity... Geyser activity was confined wholly to Satellite's vent, while Seismic had become an intermittently overflowing spring.
>
> Intervals between eruptions of the new vent during 1972 ranged from 15 to 37 minutes; each eruption lasted 21 to 31 minutes and consisted of either two or three separate periods of spouting. Each eruption was initiated by a rise in

> water level of about 20cm in both craters. During each period of activity Seismic discharged without boiling... Boiling in Satellite was continuous from eruption to eruption, with surges of 0.6 to 1m between eruptions. As each eruption progressed, massive surges rose from 2 to 3m high, with an occasional burst to 6m.

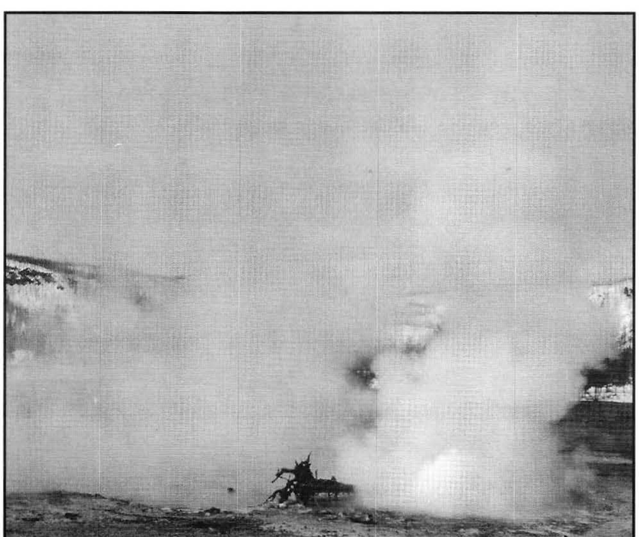
This activity appears to remain unchanged in 1973, but more changes were noted in 1974 [*ibid.*]:

> In June 1974, all eruptive activity was confined to Satellite, most commonly surging to heights of about 1m but with some spurts to 3m or a little higher... The duration of observed eruptions of Satellite ranged from 31 to 47 min, and the eruption intervals ranged from 49 to 66 min.

While the exact year of dormancy in Seismic's Satellite is unknown, this feature was definitely inactive by 1987. From this year until 1997, Seismic was in a steady state of overflow.

The birth of "Aftershock"

The first reported activity from Seismic Geyser since the early 1970's took place in June of 1997. A visitor reported seeing it erupt to a height of about 20 feet while walking on the bicycle path between Biscuit Basin and Daisy Geyser [Paperiello, 1997]. In July, Ralph Taylor, Rocco Paperiello, and I spent about 5 hours watching Seismic from this same bicycle path. Every 21 to 23 minutes Seismic would begin to have voluminous overflows that would last from 3 to 5 minutes. During two of these, Seismic was seen to erupt. The first eruption reached about 6 feet and the other reached about 12 feet, separated by an interval of about 44 minutes. After the second eruption, no further eruptions were seen during the next 3½ hours. From July through early November, I always found Seismic to be active and having periods of heavy overflow. While occasional eruptions were seen in July and August, I am not aware of any in September, October or November of 1997.



"Aftershock" (right) and Seismic Geysers in February 2000. [Photo by Mike Keller]

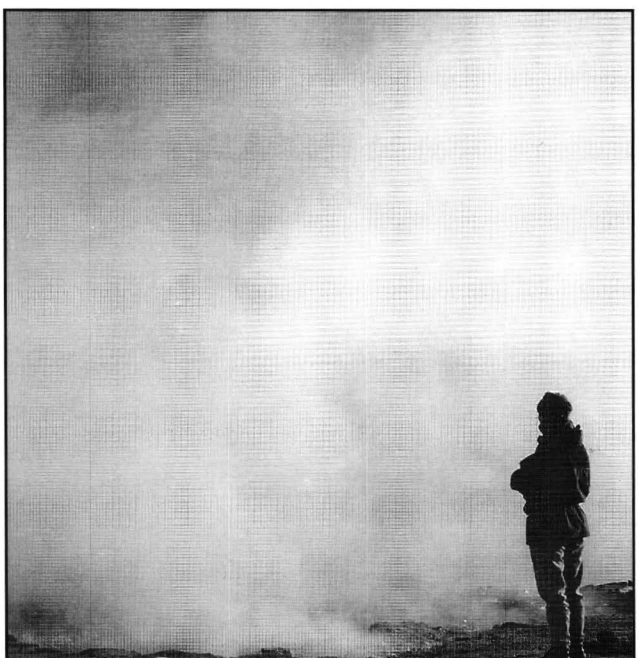
In January, March, and May of 1998 Seismic was still overflowing heavily at frequent intervals, but by September of that year the overflow had stopped. On September 20, 1998, I found Seismic to be in steady overflow. This continued throughout the winter months of 1998–1999.

In May of 1999, I found Seismic to again be having periodic overflows. Seismic's Satellite was also active. This was the first time I saw activity from this vent. It would start to erupt at the very end of Seismic's overflow and boil up to about a foot. In June, while helping with GPS mapping of this area, a new crater was found about 10 feet to the north of Seismic. This crater would later become "Aftershock" Geyser. On the day it was found, it measured about 1.5 feet by 3 feet and was about 2 feet deep. Within it were several large slabs of sinter and no vent was visible at its bottom. Water would slosh into this vent from the south (in the direction of Seismic) during the heavy overflows of Seismic. Along with this, several thumps would come from the ground between this feature and Seismic. Just when this feature would fill to the brink of overflow it would begin to act like a blowhole and forcefully push water into the air. The play would vary from eruption to eruption but could reach up to 15 feet. While the size of the crater gradually increased over the year (it measured 2 feet by 3 feet in August) the play grew weaker so that by September it would only overflow with its neighbor. In my 1999 "Thermal Highlights" report I commented the following on Seismic and its new vent [Keller, 1999]:

> **Seismic Geyser** — This geyser reactivated in 1997, but by the end of 1998 it had returned to a near dormant state. In May of 1999, it was found to be active again. The eruptions were

> small, usually consisting of heavy overflow with strong wave action and boiling to about a foot. At the end of the eruption, Seismic's Satellite would have an eruption which could reach up to 3 or 4 feet. Intervals between the eruptions were 14 to 23 minutes apart [*sic*]. In June, a new vent began to break out about 9 feet to the northwest of Seismic. During Seismic's eruptions, water would slosh into the bottom of this vent, causing it to fill. Just when this vent would begin to reach overflow, it would begin to have strong bursts which would reach from 6 to 15 feet in height. This vent would only erupt with Seismic. Both this vent and Seismic were still active in October.

When I first returned to the area in December of 1999 I found none of these three geysers to be active, but Seismic was still having periodic overflows at 17 to 32 minute intervals. The vent of "Aftershock" had grown since October. On December 09 the vent measured 5 feet by 9 feet at its widest points. Wash from previous activity extended both north and west. The most noticeable change in the vent was that the source of water was no longer coming in from the side but from a deep vent in the crater. It appeared that enough subsurface erosion had finally taken place for the main source of water to evolve within the crater. At weekly intervals through early January I kept checking to see if these geysers were active, but each time I found only Seismic to be having its periodic overflows.



To provide some sense of scale, this picture shows Cynthia Keller standing next to **"Aftershock."** [Photo by Mike Keller]

In early February of 2000, I was pleasantly surprised to find all three of the geysers active once again. While I do not know the exact day they reactivated, it occurred sometime between January 14 and February 04, 2000. An e-mail I sent to the geyser list–serve on February 10 included the following:

> **Seismic:** The new geyser which broke out to the northeast of Seismic in June is active again. This summer this vent would erupt with Seismic's overflows, and would reach about 2 to 8 feet. By October, the vent was no longer erupting, but was having strong overflows with Seismic.
>
> Sometime between early January and February 04, this vent began erupting again. Intervals are running from 22–36 minutes. Durations are near 8 minutes. Eruptions are reaching from 6 to 25 feet in height. The vent, which was roughly 2 feet by 3 feet in August, is now a jagged crater some 12 feet by 8 feet (or as Cynthia says, "an entire redwood hot tub would fit in it"). The geyser erupts with Seismic's overflows. At the end of the eruption, Seismic's Satellite will begin to erupt up to 4 feet, and the main vent of Seismic can roil up about a foot.

Another email I sent on February 20, 2000 read:

> Seismic's new vent is still active. Intervals are still running from 22–36 minutes with 26 minutes being the average. Most durations are 5 to 7 minutes, and the bursts are from 6 to 15 feet high, and 4 to 12 feet wide.

With the increase in activity from the new vent it needed a name better than "Seismic's new vent". Given the nature of its neighbor's creation and that this new geyser seemed to be a late–stage continuation of that process, the name "Aftershock" seemed logical. Shortly after I started using this name, Scott Bryan independently began using it as well in email and dialog with other geyser observers.

Between February 20 and March 05 there was a marked increase in the size and power of "Aftershock's" eruptions. During this time its vent increased in size again and during many of its eruptions there would be rocks larger than a football being thrown from it. On March 05 I submitted the following via another email:

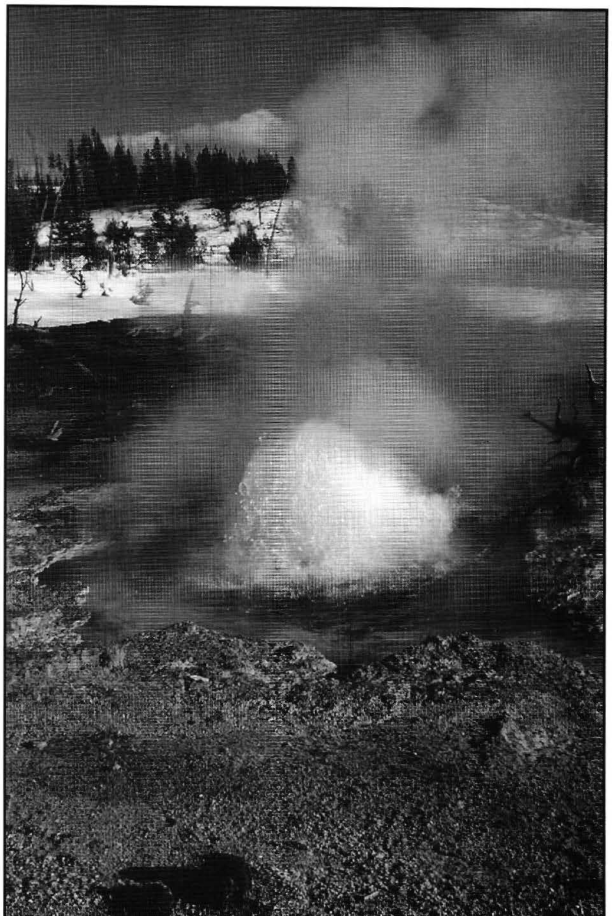
> With the much appreciated assistance of the NPS, I have spent a considerable amount of time watching the new vent at Seismic.
>
> In short, it is getting bigger and stronger. The eruptive activity observed for today is the best yet. Over the past two weeks the vent has enlarged itself by about 40% mostly to the east and south. There is still a large chunk of sinter covering the vent, and part of the eruption is deflected off this ledge. Standing nearby, I get the impression of a chamber as big as a two car garage under the ledge. From two to three minutes preceding this vent's eruption one can feel the ground swell upward and very strong thumps can be felt as much as 40 feet away. The eruptions consist of massive surges of water. Most bursts today were from 6 to 20 feet high and 4 to 35 feet wide! At its best, the entire surface area of the pool is being thrown into the air!
>
> At the conclusion of its eruptions today, both Seismic and Seismic's Satellite were erupting up to as much as 3 feet. The amount of eruptive activity in these two geysers is dependant on the strength of eruption from the new vent. The bigger the eruption, the bigger the eruption from Seismic and Seismic's Satellite.

Over the next 10 days there was a gradual decline in the activity from "Aftershock". While the intervals and durations remained the same, there were fewer large bursts from the geyser. In the two weeks prior to March 05 about 70% of the eruptions had at least three or four bursts that would send the entire surface of its pool into the air. With these bursts there would be a number of broken sinter slabs being tossed to the north. By March 15, maybe 20% of the eruptions would have one or two bursts of this caliber. I measured the crater on March 07 and found it to be 10 feet by 21 feet at its widest points. The following is from an email I sent on March 15, 2000:

> Seismic's new side vent is still active. Intervals have been 19–29 minutes. The crater continues to slowly grow to the west. The activity in the past week hasn't been as good as it was in early March, but most of the eruptions are still reaching 6 to 12 feet, 8 to 20 feet wide.

When I returned to the Park in April I found the three geysers were still active. The wash extending from "Aftershock" was the largest I had seen yet, reaching almost 80 feet to the north and 60 feet to the west. Despite spending many hours in the area over the next two weeks, I never witnessed an eruption that came close to reaching the edges of this wash area. The largest eruption I ever witnessed from "Aftershock" was on April 18, 2000, when it sent two bursts in one eruption to a height of about 40 feet. The second of these bursts was easily 60 feet wide, and this burst filled about 70% of the wash area! These ever increasing eruptions of "Aftershock" were soon to end, however.

"Aftershock" Geyser and vicinity showing the intensely washed and scoured surroundings during the major–scale activity of April 2000. [Photo by Mike Keller]



"Aftershock" Geyser on March 29, 2003, showing the minor activity that continued into 2004. [Photo by Mike Keller]

On April 25 only two eruptions reached 15 feet in height. By May 11 the biggest bursts were at best about 8 feet in height. As the heights became smaller, the intervals became shorter, eventually to the point that by the end of May the only activity was a constant roiling in the vent that would occasionally be punctuated by boiling up to about 3 feet. Despite reports of activity in August of 2000 [Keller, 2000] (I investigated the geyser a few hours after a report of an eruption on August 15 and found no signs of fresh wash and flowers growing within a few inches of the crater), "Aftershock" remained dormant until the spring of 2001. During this dormancy Seismic was in a steady state of overflow.

In late May of 2001 I found "Aftershock" once again to be active. As with all previous eruptive cycles, it would erupt during the overflows from Seismic. A major difference this time, however, was that Seismic's Satellite was not erupting during or after the overflow of Seismic. The strength of play from "Aftershock" was also much weaker than it had been in 2000. I reported the following in the August, 2001 *Geyser Gazer Sput*:

> "Aftershock" Geyser is active again. It started having small eruptions about 3 weeks ago. The largest eruptions I have seen have been to about 5 feet. It is erupting every 25–40 minutes, with overflow from Seismic.

From May of 2001 to March 2004 (this writing), "Aftershock" continued to have small eruptions every 20 to 40 minutes. None of them have approached the volume or power of those seen in 1999–2000. The largest reached about 6 feet and most were only 1 to 3 feet high. These eruptions continued to occur at the same time Seismic began to overflow heavily. No activity has been seen from Seismic's Satellite since April 2000.

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Keller, Mike, 2000, *In* Monteith, David, "Late Summer Geyser Geyser Activity": *The Geyser Gazer Sput*, v. 14, no. 5 (October 2000), p 25; *to wit*: **"Aftershock"** LS (8/15) Rocco reported that he saw an eruption of "Aftershock" yesterday. NOTE-On follow up with Rocco he just observed steam from the road — when I checked the crater it was evident that it had not erupted recently."

Marler, George and White, Donald, 1975, "Seismic Geyser and its Bearing on the Origin and Evolution of Geysers and Hot Springs of Yellowstone National Park": Geological Society of America *Bulletin*, v. 86, no. 6 (June 1975), p 751–752.

Rocco Paperiello, 1997, personal communication.

Eruption Data
Seismic and "Aftershock" Geysers

Date	Time	Interval	Duration	Height (feet)
Seismic Geyser				
7/9/97	1724			
	1747:22	~23m	4m 08s	
	1809:10		3m 48s	6
	1831:47		3m 44s	
	1855:10		4m 50s	12
	1918:19		3m 27s	
	1939:47		5m 03s	
	2001:16		5m 30s	
	2022:53		5m 32s	
	2044:15		4m 54s	
	2106:39		4m 50s	
	2129:31		3m 52s	
	2150:38		4m 08s	
	2212:10		4m 30s	
	2233:59		3m 17s	
"Aftershock" Geyser				
2/10/00:	1544		7m	15
	1608	24m	8m	8
	1632	24m	7m	12
2/19/00				
	1536:06		5m 24s	6
	1600:58	24m 52s	5m 57s	10
	1626:12	25m 14s	5m 06s	6
	1650:58	24m 46s	5m 52s	8
2/21/00	0837		5m	12
	0906	29m	6m	7
	0929	23m	5m	15
	0953	24m	6m	6
	1017	24m	7m	8
	1041	24m	7m	8
2/23/00	1544		7m	6
	1608	24m	6m	8
	1635	27m	6m	20
	1702	27m	6m	12
	1729	27m	6m	6
3/05/00	1410		6m	12
	1433	23m	7m	18
	1456	23m	7m	15
	1519	23m	7m	10
	1544	25m	7m	20

3/07/00	0926ie		>5m	8
	0950	>24m	7m	12
	1017	27m	7m	15
	1042	25m	7m	10
	1107	25m	6m	8
	Crater measured 10 X 21 feet at widest points on this day			
3/10/00	1600ie		>4m	8
	1625	>25m	5m	6
	1651	26m	7m	5
	1718	27m	6m	7
4/16/00	1645		6m	10
	1712	27m	5½m	4
4/18/00	1804		7m	20
	1832	28m	6m	40
	1901	29m	8m	18
	1938	37m	6m	20
4/22/00	1148ie			
	1216	>28m	6m	25
	1245	29m	7m	8
	1315	30m	7m	15
	Crater measured 21 X 17 feet at its widest points			
11/30/01	active			
12/07/01	active			
3/29/03	1311		6m	1
	1344	33m	7m	2
	1419	35m	6m	1
4/05/03	active			
4/16/03	active			
5/01/03	active			
5/18/03	active			

Recent Activity of "Secluded Geyser"
(UNNG-PMG-4), Upper Geyser Basin

by Stephen Michael Gryc

Abstract

Secluded Geyser, also known as UNNG-PMG-4, is a little-studied spring in the Pipeline Meadows Group of the Upper Geyser Basin. During June of 2004 it erupted in series. Data on the geyser is scant, but observations are given in the hope that others may become interested in adding to the information about this small but intriguing feature.

Location

The Pipeline Meadows Group is part of what George Marler called Pipeline Springs, a part of the Upper Geyser Basin that lies southeast of Geyser Hill and which includes both the Pipeline Meadows Group and the Pipeline Creek Group. Many springs of the Pipeline Meadows Group lie close to the Firehole River (north and east of the river) and can be viewed from the Old Faithful Lodge Cabin area on the opposite bank. Both the designation UNNG-PMG-4 and the informal name "Secluded Geyser" were given by T. Scott Bryan, who appears to be the first person to discover that the spring was a geyser. His observations of Secluded Geyser date back to 1985.

Secluded Geyser is the most northerly spring in the group, situated well up the hillside above the Firehole River. It is a few hundred feet east and slightly north of PMG-1 (also known as "Dilapidated Geyser").

Secluded Geyser's Crater

Secluded Geyser's crater is roughly rectangular with dimensions of approximately 6 feet by 4 feet, 10 inches. It is only an inch or two deep near its perimeter. A circular depression in the center of the crater descends to the main vent which is off center to the northeast. The depression is about 3 feet in diameter, and the main vent is about 18 inches below the pool level. The water shows a pale blue color around the vent. Eruptions occur from the main vent, but there is a second vent, again off center, to the southwest. Tiny bubbles can often be seen rising from this second vent, but it does not appear to play a significant part in eruptions.

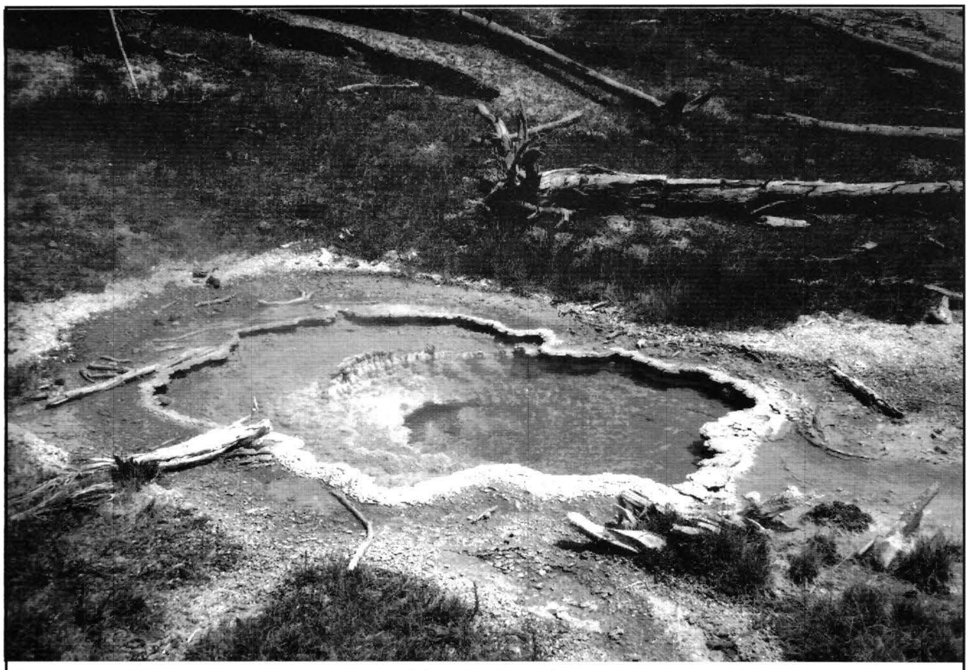

Figure 1. The crater and setting of **Secluded Geyser**, viewed from about the southwest. [Photo by Stephen Gryc]

The two "ends" of the rectangular crater have different appearances. The southwestern end (the end opposite the main vent) is no more than 3 inches deep, and its bottom is smooth with the look of grey mud. The northeast end is a little shallower (no more than 2 inches deep) and features globular

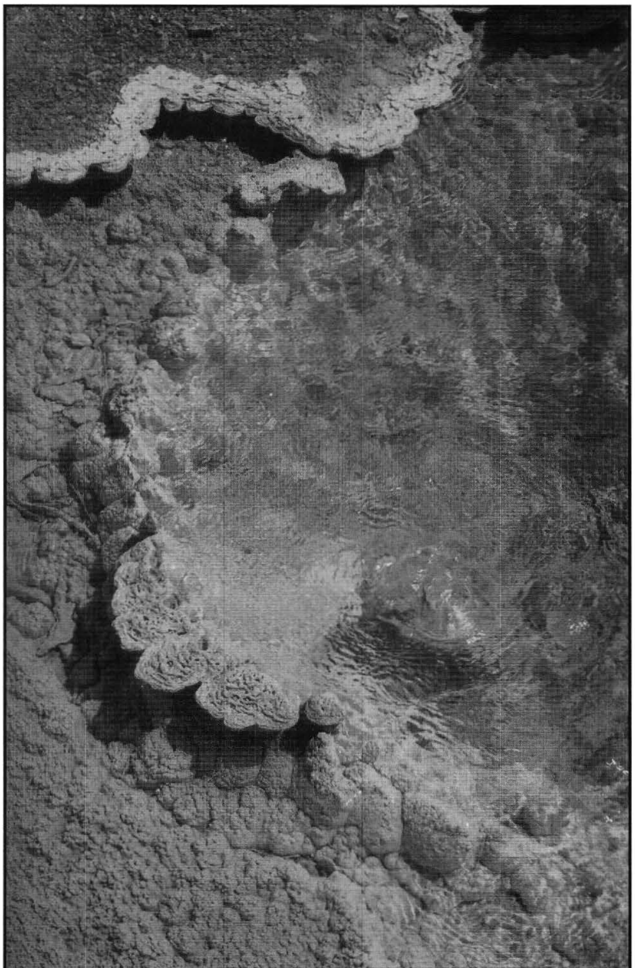

Figure 2. Detail of the inner wall of geyserite "mushrooms" above the vent of Secluded Geyser. Part of the scalloped rim of the crater is visible at the top of the photo. A bubble can be seen breaking the surface of the pool. [Photo by Stephen Gryc]

deposits of grey sinter. In the northeast end there is a wall of geyserite "mushrooms" (small columns with enlarged, flat tops) that curves around the edge of the central depression. The entire crater is rimmed with scalloped sinter deposits.

Eruptions from Full Pool

Secluded Geyser's pool fills gradually between eruptions. Although eruptions can occur from a low or partially filled pool, I will first describe the eruptions from a full pool such as those I saw in June of 2004. The southwest end of the crater usually has water to its edge, but there will often be exposed sinter in the northeast end. One can easily perceive how the pool is filling by watching the water gradually cover the globular sinter that slopes up to the rim of the crater. The pool will periodically rise and fall, the rise occurring with increased bubbling from the main vent. Gradually the pool gets higher with many successive periodic rises and falls. After the water has covered all of the sinter, the pool will remain at an elevated level and may overflow. Before an eruption the bubbling turbulence that characterizes the periodic rises in pool level will intensify and become steady. The entire surface of the pool will pulse before the first splash of the eruption.

The eruption consists of distinct bursts that attain a maximum height of about 3 feet and is often accompanied by thumping sounds. (Thumping sounds are also heard occasionally as the pool fills.) Secluded Geyser has been known to erupt as high as 10 feet, so 3–foot eruptions have been termed "minor eruptions." According to Bryan, only minor eruptions are seen in most years, and I saw only minor eruptions in my three days of observation. The full–pool eruptions I witnessed varied in duration between 1 minute 3 seconds and 1 minute 21 seconds. The pool may overflow slightly before an eruption, and an eruption from a full pool will send water into the runoff channels. Water may also overflow the entire perimeter of the pool. After an eruption the pool level drops quickly, exposing most of the sinter in the northeast end of the crater but never completely draining. Almost immediately, the pool begins to again fill slowly.

Eruptions from Low or Partially Filled Pools

Pool level is not a good indicator of imminent eruption. Even with a high pool, it may be hours before an eruption takes place. On June 18, 2004, I saw the pool rise and hold level for about 2 hours before an eruption occurred. The pool began to overflow slightly 18 minutes before the first eruption I witnessed that day.

In the case of eruptions from low or partially filled pools, the water level will rise quite suddenly before an eruption. The pool may overflow during the eruption, but I witnessed eruptions from low pools where there was no overflow and no water

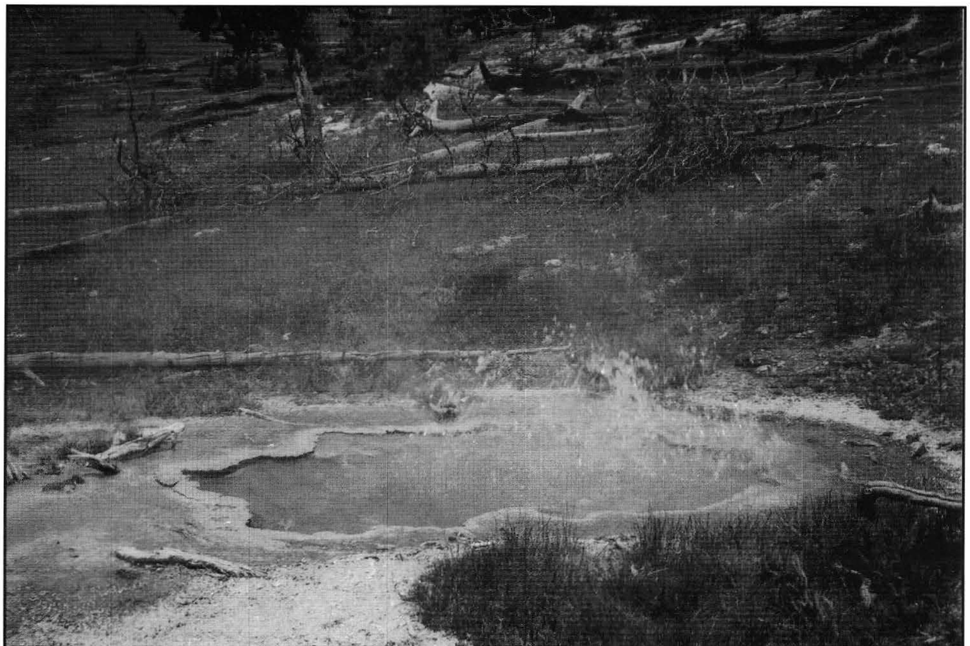

Figure 3. Secluded Geyser in eruption, as photographed from the east. Shown is a typical burst about 2 feet high. [Photo by Stephen Gryc]

sent into the runoff channels. Eruptions from low pools are weaker and briefer than eruptions from full pools. Durations of the low-pool eruptions that I saw varied between 27 and 59 seconds.

Patterns of Eruption

Secluded Geyser is cyclic, with series of eruptions alternating with periods of quiet. The small amount of data that I collected is insufficient to suggest specific durations for active and inactive periods. During my three–hour observations on three successive days, I saw only active periods on two days and witnessed the initial two eruptions after a quiet period on the other day. My observations suggest that active periods are fairly frequent — one or more a day — and that series of eruptions and inactive periods are both hours long.

Calculating an average interval between eruptions during active periods is also difficult due to the small amount of data. From my observations and from the comments of other recent observers (especially Mike Frazier), it seems that approximate half-hour intervals followed by a short interval of 4 to 7 minutes may be common. There seems to be a tendency for eruptions to occur in pairs. I observed one such half-hour interval/short interval pair on each day of my observations. Short interval eruptions were weaker and shorter in duration than the preceding eruptions. On June 19, I also observed what I would call "aborted eruptions." These aborted eruptions seemed to be the beginnings of short-interval eruptions, but after a couple weak splashes the pool would drop and eruptive activity would cease.

The patterns I observed in 2004 were similar to ones observed in the two previous years. Jeff Cross writes about his observations in 2002:

> On 15 September PMG-4 was active. Eruptions occurred singly or in pairs separated by about 3-5 minutes. [Intervals] between single eruptions or pairs of eruptions were 14-34 minutes. Height was 1-2 feet with the first eruption of a pair being larger. Durations were 26-67 seconds with the first eruption of a pair being longer.

On June 8, 2003 Mike Frazier waited 7 hours and 15 minutes for the initial eruption of a series. The second eruption came after an interval of 46 minutes. Then there was an interval of 26 minutes with a following short interval 5 minutes later. After an interval of 33 minutes another pair of eruptions occurred, the short-interval eruption occurring 6 minutes after the first of the pair. On the basis of his direct observations and on observation of markers left in the run-off channels, Frazier estimated the duration of one quiet period (interval between initial eruptions of successive series) to be between 12 and 20 hours.

I have no record of an observed duration for an eruptive series or interval between initial eruptions of successive series. It is hoped that an increased awareness of Secluded Geyser will lead to a greater interest in this geyser and a larger amount of data gathered.

Table 1. "Secluded Geyser," Eruption Observations from June 17-19, 2004

Start Time	End Time	Interval	Duration
June 17, 2004. Observation begins at 1330; run-off channels wet.			
1337:08	1338:11	>7 minutes	1m 03s
1341:30	1341:57	4m 22s	0m 27s
1506:36	1507:40	1h 24m 39s	1m 04s
1536:32	1537:14	29m 56s	0m 42s
Observation ends at 1620.			
June 18, 2004. Observation begins at 0830; run-off channels wet.			
1140:31	1141:51	>3 hours (initial)	1m 20s
1146:55	1147:30	6m 24s	0m 35s
Observation ends at 1200.			
June 19, 2004. Observation begins at 0840; pool full and slightly overflowing.			
(Aborted eruption start times and intervals are shown in parentheses.)			
0916:15	0917:36	>36 minutes	1m 21s
0923:14	0923:49	6m 59s	0m 35s
0955:50	0956:49	32m 36s	0m 59s
(1001:37)		(5m 47s)	
1029:22	1030:15	33m 32s	0m 53s
(1033:58)		(4m 36s)	
Observation ends at 1110.			

Dormancy

T. Scott Bryan reported in July 2004 that Secluded Geyser had entered a period of dormancy. He wrote:

> Secluded (PMG-4) is dormant, and has been for some time. Orange cyanobacteria is completely gone, water cycling but at least 3 inches below overflow at the high point.

Other periods of dormancy (e.g. 1993) are known. It is hoped that Secluded Geyser will become active again in the near future.

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Hot Spring and Geyser Activity in the Pine Springs Group, Upper Geyser Basin

by T. Scott Bryan

Abstract
The hot springs within the Pine Springs Group have seldom been documented, perhaps because no geyser activity of major scale has been observed there and because it historically has mostly been obscured from view by dense surrounding forest. During 2003–2004, the largest geyser eruptions known to have occurred within the group's "North Annex" were observed. Those eruptions and other aspects of the Pine Springs' activity are summarized here.

Location and Introduction

The Pine Springs Group of hot springs is practically centered within Yellowstone's Upper Geyser Basin, lying east of Black Sand Basin, southwest over a small hill from the Daisy Group and north of the "freeway interchange" of the access road into the Old Faithful area. However, no maintained trail enters the area (historically, the Howard Easton Trail passed between The Old Ruin and the North Annex) and, prior to the wildfires of 1988, these springs were mostly surrounded by dense lodgepole pine forest and could not be easily seen from afar.

Overall, then, the historic nature of geyser and other hot spring activity in the group is largely unknown. Certainly the springs were visited during the 1800s and their locations (at least in general) were shown on the various geological survey maps drafted since then. Written descriptions of the springs are lacking, though. Mud Geyser is hardly more than shown on an 1890 map, and Allen and Day [1935] as well as Marler [1973] entirely fail to even mention the existence of the group. Even I in my book [Bryan, 2001] give the group the briefest of mentions while entirely failing to show its location on the index map.

By far the most detailed descriptions ever produced are those of Wolf [1984], and information from that report is used in this article.

The most detailed map of the area is that drafted by the U. S. Geological Survey during the post–1959 earthquake studies. The entire Pine Springs area is included on Map V.D.1. "Black Sand," a portion of which is reproduced at full scale on the following page (Figure 2).

The Hot Springs of the Pine Springs Group

The single most dominant feature of the Pine Springs Group is a large siliceous sinter formation that often is referred to as an old, deeply

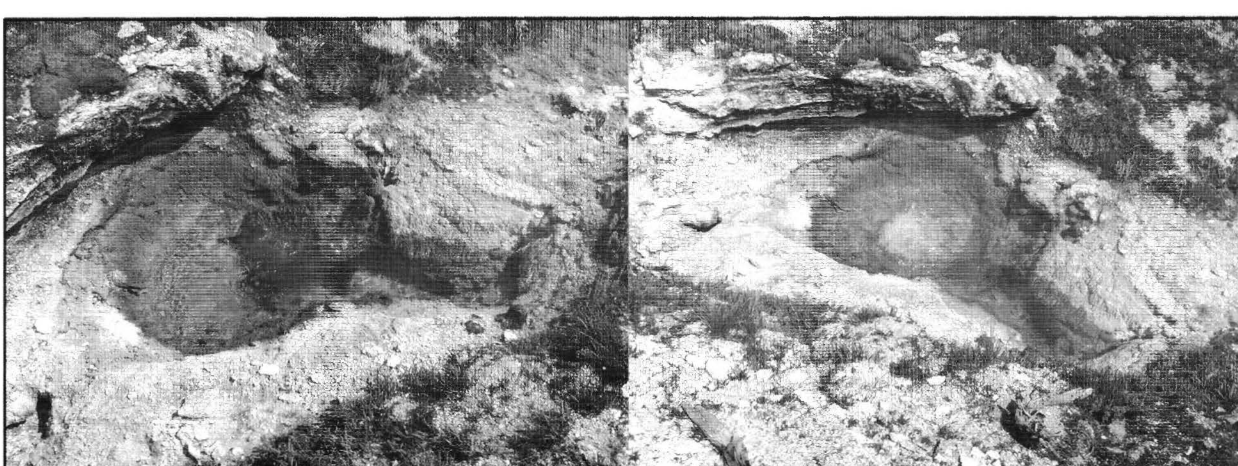

Figure 1. The **"Fracture Geyser"** of this report, shown quiet (left) and in eruption (right) on June 04, 2003. [Photos by Scott Bryan]

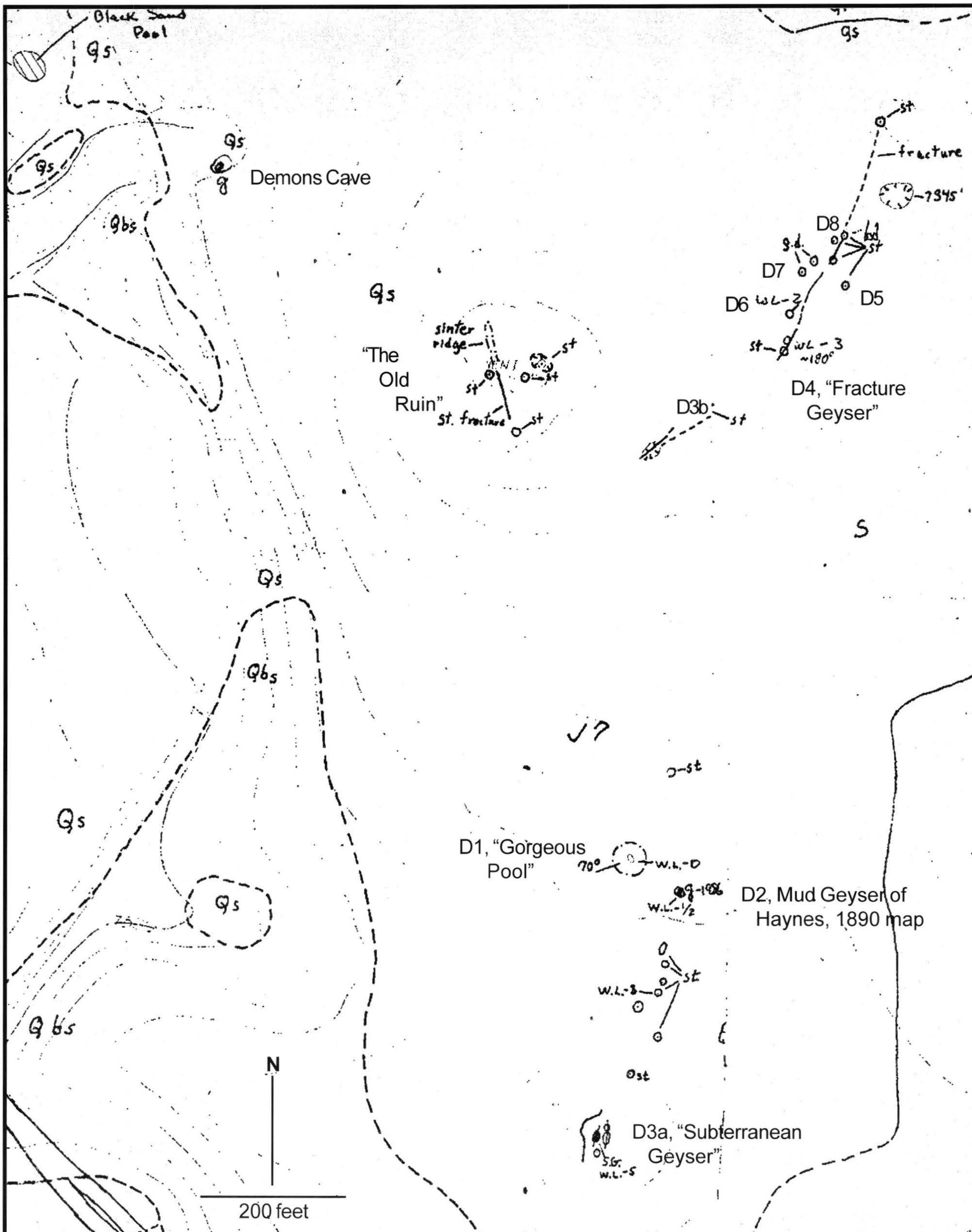

Figure 2. **Map of the Pine Springs Group, Upper Geyser Basin**, scanned from U. S. Geological Survey, Yellowstone Thermal Map V.D.1. "Black Sand." Note the location of Black Sand Pool at the upper left (northwest) corner of the scan; other names have been added for the purpose of this report. Letter–number combinations (such as "D1") are from the map in Wolf [1984]; note that "D3" appeared two times, so here is expressed as D3a and D3b. Black Sand Basin is a short distance west of this area, and the highway interchange bridge and cloverleaf is just out of the lower right portion of the scan. Scale: 1 inch = 200 feet.

weathered and eroded cone. In fact, it more likely is a dissected remnant of a broad geyserite mound that was originally punctured by numerous hot spring plumbing tubes and vents. Some of these openings still steam a little, something readily visible only in cool weather. The feature is old enough that much of the sinter is chalcedonic; that is, the original amorphous opaline silica has crystallized into a microgranular quartz, a process that requires many hundreds if not thousands of years to accomplish. In her mapping and description, Marie Wolf [1984] informally named this as "The Old Ruin."

Radiating outward from The Old Ruin is a series of fracture zones. One that extends with intermittent surface expression at least 1,000 feet to the south ultimately controls the locations of the springs of the "South Annex" of the Pine Springs Group. Another curves away to the east and then northeast, reaching as far as 600 feet and hosting the hot springs of the "North Annex." Both of these fractures contain a few weak steam vents, especially at spots close to The Old Ruin. Another fracture may extend to the northwest to include Demons Cave (generally considered a part of Black Sand Basin), and still another with no obvious features delves northward.

In Wolf [1984], most of the larger, more distinct springs of the Pine Springs Group were given letter–number designations (such as "D1"). These numbers are shown on the map of Figure 2 and are used as available in the following brief descriptions.

Four of the springs have also been given names. One of these, Mud Geyser, can be taken as formal in nature as it was first applied on a map in 1890

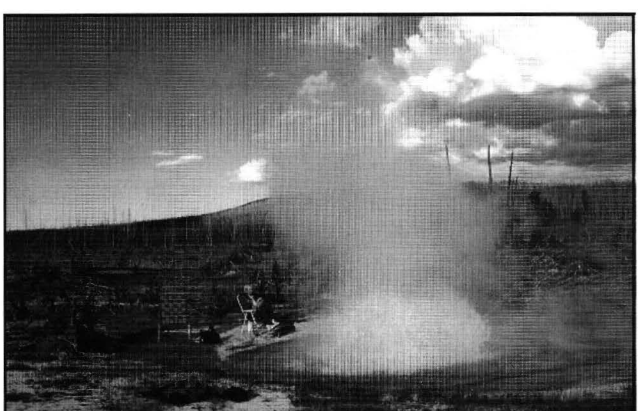

Figure 3. Marie Wolf at **Mud Geyser**. [Photo by Mike Keller, 1989]

[Haynes, *in* Guptill, 1890]. The other names are informal. "Gorgeous Pool" and "Subterranean Geyser," were given by Marie Wolf and/or Rocco Paperiello and used in Wolf [1984], and "Fracture Geyser" by myself for this report.

Springs of the "South Annex" or "Fracture Group"

D1. "Gorgeous Pool" is a very shallow spring surrounded by a substantial sinter rim. The crater, whose depth might actually be considerable, is nearly filled with orange cyanobacteria topped by only a few inches of clear water. Usually standing a few inches below overflow, on infrequent occasions this spring has been seen with seeping discharge.

D2. Mud Geyser was apparently named by F. Jay Haynes on a map produced in 1890, when eruptions up to 30 feet high were reported. More recently it usually stands as a lukewarm pool with seeping discharge. A few modern eruptive episodes are known, as in 1986 and 1989 (Figure 3; this same photo, mislabeled as "Mud Spring," appeared on page 12 of *The GOSA Transactions*, Volume VIII). Some of those rather infrequent bursts reached perhaps 6 feet high.

Unnumbered. Marking the alignment of the south fracture, between springs D2 and D3a, is a series of old craters that visibly steam on chilly days. One of these occasionally holds a bit of tepid water in its bottom.

D3a. "Subterranean Geyser" is the most significant geyser of the Pine Springs Group as a whole. Although the crater is readily visible from the Old Faithful access road, the eruptions are only rarely seen from afar. This is because the geyser occupies a deep, jagged crater elongated along the fracture zone. Subterranean is cyclic in its activity. Series of frequent minor eruptions, weak and with durations of only a few seconds, are occasionally interrupted by major eruptions. These majors reach as high as 10 feet above the pool level and may have durations as long as 4 minutes. The intervals between the majors can be as short as 8 minutes or so, but I also recall once watching the geyser for well over an hour without a major taking place.

Springs of the "North Annex" or "Mud Geyser Group"

D3b. is nothing more than a small, gently steaming opening within a wide spot along the east–northeast fracture zone.

D4. "Fracture Geyser" proved itself during 2003 to be the largest definitely–known geyser in the North Annex (Figure 1). The USGS thermal mapping of the 1960s noted three other springs in this complex (but interestingly, *not* this one) as geysers, but written descriptions of those eruptions are unknown (see D5, D7 and D8, below). Fracture Geyser is located within an eroded crater complex of at least three vents directly astride the east–northeast fracture zone. Since at least the early 1970s, 180°F water has stood in these vents about 3 feet below the surface, but no eruptions were witnessed until May 2003 [personal observation]. The activity observed then continued without notable variation at least into the following September. Both the quiet intervals between the eruptions and the durations were 15 to 30 seconds long. Most play reached about 2 feet above the pool level, but splashed areas beyond the crater implied unseen bursts of much larger size. In May 2004, one eruption at least 4 feet high was witnessed after an interval of about 2 minutes.All other observed action was similar to that of 2003.

D6. is a shallow, mud–lined crater a few feet north of Fracture Geyser. It, too, contains visible water at about 180°F. Although not known to ever have erupted, during 2003 its water level did vary a bit in synchrony with Fracture Geyser, rising perhaps 1 inch at the onset of those eruptions.

D5, D7 and D8 are the three among a whole series of vents and collapse depressions scattered along the fracture zone. Because many of these are not identified on Thermal Map V.D.1. "Black Sand," it is difficult to associate these spring numbers with individual features.

D5 appears to be simply a depression that steams from a cavern–like opening at one side.

D7 seems to indicate two springs indicated by the map as dormant geysers, a small handwritten "g.d." appearing next to each vent. These openings bear badly weathered but still–beaded geyserite around and within their openings.

D8 is probably a jagged vent whose surface geyserite is deeply weathered but whose vent interior contains beaded, fresh–appearing geyserite. Water can be heard intermittently gurgling at depth, making it clear that this spring remains active as a weak, subterranean geyser. However, it certainly has not had suficial activity in a very long time.

Unnumbered but denoted by a depression hachures on the Thermal Map is a large, circular crater. Largely filled with soil and sparse vegetation, it clearly once was a pool of significant size but now appears to be thoroughly extinct.

Also **unlabelled** except as a steam vent is a final opening at the northeastern extremity of the fracture zone. Like many others in this area, the vapor is visible only on cold days.

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Great Fountain Geyser, August 2002. [Photo by Mike Newcomb]

The Lower White Creek Group Since 1996

Lower Geyser Basin, Yellowstone National Park

by Gordon R. Bower

Abstract

Dramatic changes in geyser activity occurred in the White Creek Group in summer of 1996, around the same time as a series of earthquakes west of the Lower Geyser Basin. Some of the new activity ended quickly, but other changes appear to have been permanent. Increases in Botryoidal Spring's and A-0 Geyser's intervals since 1997 have been accompanied by increases in durations, so that the overall energy flux has remained nearly constant. Some evidence of previously undocumented underground connections from Botryoidal Spring to A-0 Geyser and Great Fountain Geyser has been found.

Introduction

The White Creek Group of hot springs lies at the southeastern corner of the Lower Geyser Basin. White Creek follows the contact between the 150,000 to 160,000-year-old Mallard Lake and Elephant Back rhyolite flows. The creek descends from the Central Plateau through a narrow ravine that opens onto the glacial fill of the Firehole River valley [Christiansen, 2001; Muffler et al., 1982]. There are warm springs along the length of the White Creek valley, but geysers are confined to a stretch 600 meters long at the mouth of the valley. The area is reached via Firehole Lake Drive, which roughly follows the lava–till contact along the east edge of the Lower Geyser Basin and passes through the northwest corner of the White Creek Group. A hiking trail leads southeast from the Great Fountain Geyser parking area up the north side of White Creek and provides closer access to the thermal area.

Marler [1973] labels the portion of the White Creek Group north and west of the roadway as a separate "Great Fountain Group." This is a bookkeeping convenience, as there is no obvious geologic reason to treat the northwestern most springs as a separate hydrothermal system.

This paper is concerned primarily with a cluster of thermal features packed into a level area about 100 meters square, bounded by White Creek on the south, the Firehole Lake Drive to the northwest, and the hillside to the east. This area includes five named thermal features (A-0, A-1, and A-2 geysers; Botryoidal Spring; and Logbridge Geyser), one sizable unnamed quiet spring, and countless small spouters, springs and dry holes in the sinter platform. Figure 1 is a photographic overview and Figure 2 is a map of the study area.

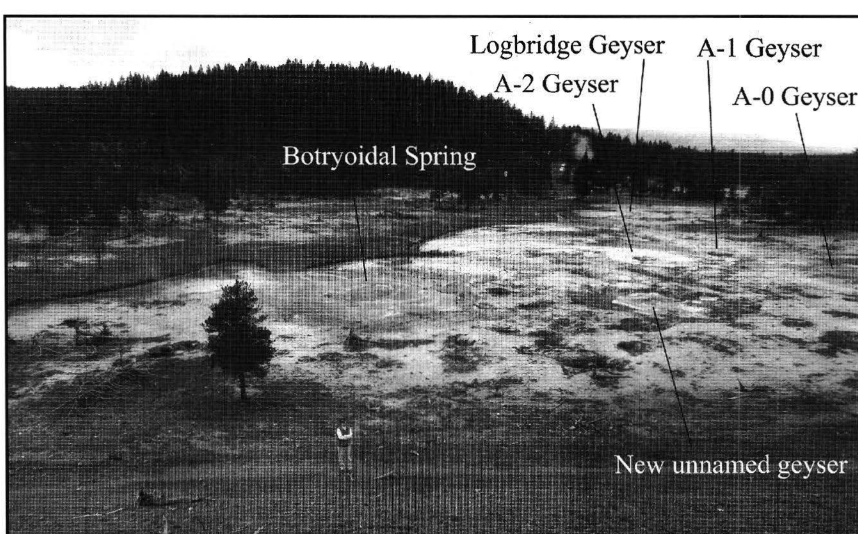

Figure 1. The lower White Creek Group, as viewed looking west from the nearby hill. Name labels indicate some of the individual features; compare with the map of Figure 2. [Photo by Robert Bower]

Individual thermal features and historical activity

By far the most important geyser near White Creek is Great Fountain Geyser, about 125 meters north of the main study area. Great Fountain's general pattern of activity has remained essentially unchanged since its discovery in 1869: eruptions consist of a series of bursts over the course of an hour, the largest reaching 30 to 60 meters high. They recur about twice a day. The average interval between eruption series varies over time, but has stayed between 9 and 13 hours for many years. Eruptions were more frequent for several years after the 1959 earthquake. Detailed consideration of Great Fountain Geyser's history is beyond the scope of this study; see Marler [1973] and Vachuda [1989].

Geyser activity within the White Creek Group has been unimpressive throughout most of recorded history. From 1959 to 1996, A-2 Geyser was usually the most visible geyser in the area (aside from Great Fountain), splashing to a height of 3 meters for several minutes once an hour [Bryan, 1995]. A-2's crater, surrounded by a broad shallow splash basin several meters across, is easily visible though the sinter decorations have crumbled since 1996.

A-1 Geyser is a few meters north-northwest of A-2, and connected with it underground. During A-2's eruptions, the water in A-1's crater would ebb 45 centimeters and then rise during the following half hour. On the rare occasions when A-2 Geyser was dormant, A-1 would have small eruptions of its own [Marler, 1973]. The only recent years in which A-1 is known to have been active are 1970, 1971, 1988, and 1993 [Bryan, 1989; SPUT 7:4]. A-1 Geyser's crater is also visible despite its long inactivity, and is similar in size and depth to A-2's. It is easy for the casual observer to confuse the two dry holes in the ground. A-1 is nearer the roadway and, unlike A-2, does not have a prominent splash basin and runoff channel.

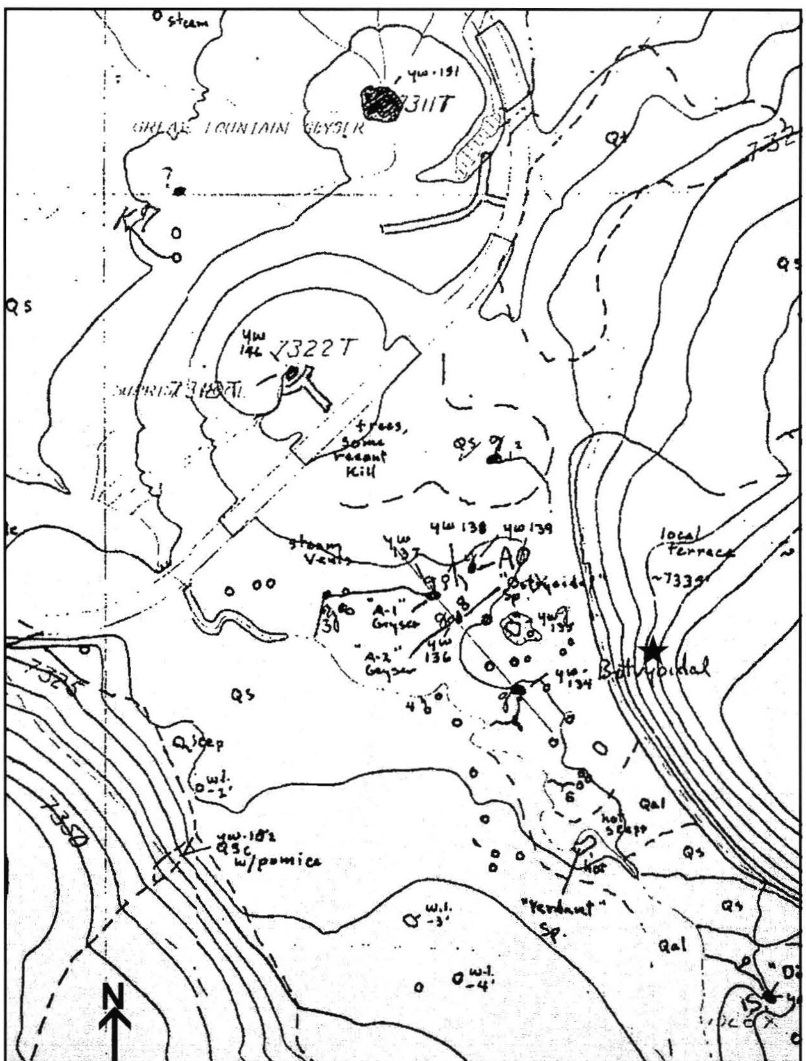

Figure 2. Map showing the lower White Creek Group. Great Fountain Geyser is at the top of the image. The hill from which the photo of Figure 1 was taken is indicated by the close contour lines toward the lower right of the map (star shows photo site). Scanned from U. S. Geological Survey, Thermal Map III.B.2. "White Creek." Scale of 1 inch = 200 feet, north up.

For most of recorded history, Botryoidal Spring, some 25 meters southeast of A-2, was a constantly boiling spring with occasional brief surges to one or two meters above the pool surface. According to Marler [1973] the only periods of complete quiet were immediately after an eruption of A-2 Geyser. Botryoidal Spring has always had the greatest water discharge of any feature in the area, estimated by Marler at 80 liters ("20 to 25 gallons") per minute. A-1 and A-2 do not discharge unless active, A-0 does not discharge at all, and Logbridge Geyser (both described below) and the small springs below Verdant Spring on the south bank of White Creek contribute only trickles most of the time. Botryoidal's large deep iron–stained crater, surrounded by a flat terrace and well–used runoff channel, is unmistakable.

The area between A-1 and Botryoidal Spring is dotted with countless small holes. Several of these have briefly been active as small geysers, but these were never named or described in detail before 1996. Some of these craters emit steam, but most are overgrown with grass and wildflowers.

By contrast, the flat area northeast of A-1 Geyser is less pockmarked with small vents. A-0 Geyser erupts from the only significant crater in this area, nearer to the road than any of its neighbors. Its heavily beaded crater walls slope inward with a cone shape, then drop away vertically around a small central vent. It is difficult to see the beautiful crater, except by climbing the hill east of the Howard Eaton Trail and using binoculars. A-0 was apparently not known as a geyser to Marler, and before 1996 most observed eruptions lasted only a few seconds and took place at erratic intervals.

The northeast corner of the study area is marked by a pool filled with brownish bacteria. Its trickle of discharge does not form a runoff channel but has built up a gently sloping mound several meters across. It has no known eruptive history, and has not changed in appearance in several years.

Logbridge Geyser, about 35 meters west of the other geysers and partially separated from them by a stand of lodgepole pines, was a small perpetual spouter until 1985, then erupted as a geyser every few hours to 1 to 2½ meters for up to five minutes [Bryan, 1995].

The other thermal features of the White Creek Group, upstream from Verdant Spring and downstream to Surprise Pool and Firehole Pool, were not part of this study.

The lower White Creek Group was largely ignored by geyser gazers from the time of the author's first involvement in geyser research in August 1988 until 1996. The only features regularly reported were Tuft and Spindle Geysers, more than 200 meters farther upstream and not included in this report.

There are only three reports from lower White Creek in *The Geyser Gazer SPUT* dated before 1996, and these are all very brief. From June 1992, A-2 Geyser was "seen at least once" on Memorial Day weekend [6:3]. From August 1992, there was a report of increased activity, but no details:

> Upstream from Great Fountain has been another case of rejuvenation. Eruptions have been seen in every named geyser of the lower area except A-1, including Logbridge as well as A-0, A-2, and Botryoidal and a whole bunch of unnamed features" [Sput 6:4].

This may represent an increase in activity in summer 1992, or it may mean that activity which started during the winter of 1991–1992 (or sooner) wasn't noticed by earlier observers.

In 1993 there was a report of new but unspectacular activity from A-1:

> A-0, A-1, A-2, Logbridge, and Botryoidal were all active in the nearer portion of the White Creek Group. Most notable is A-1. In the past, its activity has resulted in the near dormancy of A-2. But now A-2 seems unaffected while A-1 has had observed intervals as short as 72 minutes. Its eruptions are quite weak though; those I saw weren't more than 2 feet high, and the duration was only a minute or so [SPUT 7:4].

(In previous active cycles, eruptions of A-1 lasted 5+ minutes and reached 6+ feet high.) More extensive observations were made at Great Fountain Geyser in 1993 (by Lew and Jan Johns and Tomáš Vachuda, among others) than in 1992 or 1994.

1996 and 1997: Major changes

Beginning sometime in July of 1996, people started paying more attention to the White Creek Group:

> White Creek was the focus of several reports. There is a new geyser on the north side of the creek (across from Verdant Spring) that erupts black muddy water to about 8 ft for 2-3m every 30-40m (extremes of 7 and 41m). "Great thumping" or "popping" make the geyser audible as well as visible; the hillside above the lower part of the group seems to be the vantage point of choice. From Todd Singleton... Botryoidal is also erupting every few minutes to 2+m/7ft; A-0 and A-2 are active, as well as a small new UNNG [unnamed geyser] between them that erupts as a slender jet to 1+m initially, after which it recedes quickly. Paperiello reports four more small new geysers in the area and speculates that all six may be the result of tremors that hit the area a short time ago. [SPUT, 10:4]

By August 1996 Botryoidal Spring's eruptions grew in intensity, reaching 3 to 5 meters high and as much as 5 meters wide. They began with the entire surface of the pool doming upward in a single bubble that burst in all directions [SPUT 10:5]. Hobart [1998] presents a series of spectacular photos. Meanwhile, activity in the rest of the group waned. The last report of the "new geyser up White Creek" was on 24 August 1996 [SPUT 10:5]. The last entries in the National Park Service logbook for A-1 and A-2 are 09 and 04 August 1996 respectively. Rocco Paperiello [SPUT 12:2] states A-2 "began having occasional long period of quiet, sometimes many hours in length" in the summer of 1996.

Since the fall of 1996, no eruptions of A-1, A-2, or Logbridge have been reported in the Park Service logbook or *The SPUT*. The new geyser near Verdant Spring has almost disappeared. On the other hand, A-0 Geyser and one of the reactivated craters north of Botryoidal Spring remained regularly active, and were observed every season from 1997 to 2003.

Goals of this Study

This study addresses four issues relating to the post-1996 activity in the lower White Creek Group:

1. Look for evidence to support or refute the hypothesis that earthquakes in summer 1996 are the cause of, or contributed to, the group's sudden changes in activity.

2. Revisit Jack Hobart's prediction that activity would taper off and gradually return to "normal" within several months to a few years.

3. Describe the current activity patterns of A-0 Geyser, Botryoidal Spring, and the unnamed geyser northeast of Botryoidal Spring.

4. Attempt to determine if sufficiently close underground connections exist between A-0, Botryoidal Spring, the unnamed geyser, and Great Fountain Geyser for them to influence each other's eruption patterns.

Methods

All data collection was done visually, from locations accessible to the general public without a special permit. These include the shoulder of Firehole Lake Drive, the Howard Eaton Trail, and the non-thermal hillside above the trail. Observations of eruption times and durations were made to a precision of one second when possible. No remote sensing devices were employed.

Additional data on Botryoidal Spring are from Hobart [1998], Gryc [1998], and Cross [2003]. Data for other Lower Geyser Basin geysers are from the NPS logbook maintained by the Old Faithful Visitor Center staff. Data on earthquake epicenters and magnitudes are from the University of Utah seismic network's web site.

Throughout this paper, the term "interval" denotes the time between successive starts of eruptions, as recommended by Fix [1939]. (Some sources such as Bryan [1995] call this the "period" and use "interval" for the time from the *end* of one eruption to the start of the next.)

Most of the analysis is via standard statistical techniques, including a two-sample z-test or the calculation of a correlation coefficient. For each significance test appearing in Tables II, III and VIII, four values are reported: the observed difference in some variable between two sets of data; the standard error of that observed difference; z, the standardized difference (the observed difference divided by its standard error); and p, the probability of observing a difference that large by chance, if no change has actually occurred.

There are, however, two complications in the analysis to address:

1. There is so little variation in A-0 Geyser's durations, and Botryoidal Spring's durations and intervals, that the imprecision of each measurement contributes significantly to the uncertainty of the summary statistics, and must be accounted for when estimating errors. Adjusted standard deviations are given by:

$$s = \sqrt{\frac{SSE}{n-1}}\text{, where}$$

$$SSE = \sum (observation - mean)^2 + \sum (error\ in\ each\ measurement)^2$$

A measurement recorded to the nearest second was treated as having a standard error of 1 second, and added 1 sec² to the SSE, while a measurement recorded to the nearest five seconds was treated as having a standard error of 3 seconds and added 9 sec² to the SSE. Durations were always recorded to the nearest second or not at all; however some intervals based on start times recorded only to the nearest five seconds (for Botryoidal) or 15 seconds (for the unnamed geyser) were used in the calculations.

2. Because Great Fountain Geyser erupts approximately twice a day, there are many cases where an eruption is missed overnight, but the interval between one eruption and the *second* subsequent eruption is known accurately. To obtain the best possible estimate of the mean interval and its standard deviation, data from single and double intervals can be combined:

$$\bar{x} = \frac{n_1 \cdot \bar{x}_1 + n_2 \cdot \bar{x}_2}{n_1 + 2 \cdot n_2};\ s = \sqrt{\frac{SSE}{n_1 + 2 \cdot n_2 - 1}};$$

$$SSE = (n_1\text{-}1)(\text{std.dev. of single intervals})^2 + (n_2\text{-}1)(\text{std.dev. of double intervals})^2 + (n_1\text{+}2n_2\text{-}1)(\text{std.dev. of } \bar{x}_1 \text{ and } \bar{x}_2)^2$$

This method can be extended to include exactly-known triple or quadruple intervals, and approximate intervals based on eruptions not seen from the start.

In the above formula, terms are: n_1 = number of single intervals; $\bar{x}_1$ = mean of observed single intervals; n_2 = number of double intervals; $\bar{x}_2$ = mean of observed double intervals.

Were the 1996 changes caused by an earthquake?

Following the 17 August 1959 Hebgen Lake earthquake, it was recognized for the first time that many geysers changed their behavior following significant earthquakes. Most of the changes occurred almost immediately, and many affected thermal features returned to their pre-earthquake status within a few hours to a few weeks. However, some of the earthquake-induced changes were permanent, and some changes in activity the next year were attributed to earthquake impacts on the underground hydrothermal system that didn't manifest themselves at the surface immediately. Marler [1964] examined 38 springs in the Great Fountain, White Creek, and White Dome groups in autumn 1959, and found *none* of them exactly as it had been prior to the earthquake, including eruptions from ten thermal features not previously known to erupt.

Changes were seen throughout Yellowstone following the M7.2 Borah Peak earthquake of 1983, and at Norris and West Thumb after a M6.1 event on 30 June 1975. Several M4–5 earthquakes occurred in Yellowstone in the 1980s and 1990s. Most of these were followed by several simultaneous changes in activity in areas nearest the epicenters. Even a very small earthquake occurring very near a geyser area has been credited with altering geyser activity: a M2.1 event ~1km east of Biscuit Basin and 2-3km north of Geyser Hill on 09 January 1998 [SPUT 12:2; Schwarz, 1998].

A useful rule of thumb for small to moderate earthquakes is as follows. For an earthquake of magnitude M that is D kilometers away from a thermal area, if $M - 2\log_{10} D > 2$, then changes to thermal features are almost certain. However, if $M - 2\log_{10} D < 1$, then there is likely to be no detectible change at all [Bower, 2002].

Only for the largest earthquakes is it possible to see direct proof that geysers have been affected, such as cracks in formations or discharge of muddy water indicating underground changes within the plumbing system. For small to moderate earthquakes one must rely on accurate before–and–after observations, and decide if "more changes than usual" occurred at the time of the earthquake. Since

Table I. M>3 events in the earthquake swarms of June and July 1996

Mag.	Latitude Longitude	Time and Date
M3.7	44°33' N 110°56' W	0401 MDT 30 June
M3.0	44°33' N 110°57' W	1820 MDT 15 July
M4.2	44°34' N 110°57' W	2210 MDT 15 July
M3.2	44°35' N 110°57' W	2302 MDT 15 July
M3.6	44°34' N 110°56' W	2306 MDT 15 July
M3.6	44°34' N 110°57' W	2309 MDT 15 July
M3.5	44°34' N 110°56' W	1031 MDT 17 July

thermal activity changes over time, even without any clear cause such as an earthquake, making such a decision can be subjective.

Common sense suggests that if an earthquake caused widespread changes on White Creek, then it probably also would have affected other thermal areas, especially those nearer to the epicenter. It should be possible to find earthquakes large enough to cause the changes in an earthquake catalog, then examine data from several other geysers to see when (if at all) their activity changed.

In late June and in mid July, 1996, two swarms of earthquakes occurred west of the Lower Geyser Basin, about 12 kilometers from the White Creek Group. The epicenters of both swarms were clustered in the same place. The nearest thermal features were the Sentinel Meadows group 6 kilometers to the east and Imperial Geyser 7 kilometers to the southeast of the epicenters. These swarms included a total of seven M3 or larger events (Table I.) Only one other significant earthquake occurred in Yellowstone during that summer, a M3.9 event at 22:26 MDT 10 July, 24 kilometers from Old Faithful and 32 kilometers south of the White Creek group.

The epicentral region is much closer to the Lower Geyser Basin than any of the other major geyser basins, and the earthquakes are near the smallest magnitude at which there is a historic basis for ex-

Table II. Great Fountain Geyser intervals, summer 1996

		01-29 Jun	01-10 Jul	16 Jul - 15 Aug	
Single intervals #		27	11	18	
	Mean	10h45m	10h31m	10h41m	
	SD	1h17m	1h04m	1h13m	
Double intervals #		12	4	19	
	Mean	21h13m	19h33m	20h18m	
	SD	1h34m	54m	2h02m	
Triple intervals #		—	—	3	
	Mean			28h46m	
	SD			1h59m	
Approximate and inferred intervals:					
	#	9	4	9	
	Mean	10h41m	10h03m	10h36m	
Total # eruptions		60	23	74	
Best estimate of mean:		10h41.0m	10h10.8m	10h10.7m	
Best estimate of SD:		1h12.7m	59.7m	1h23.4m	
Std error of est.mean:		9.5m	12.5m	9.7m	
Significance tests:					
		Difference	Std Error	z	p
June vs Early July:		-30.2m	15.7m	1.92	.054
June vs late Jul/Aug:		-30.3m	13.6m	2.22	.026
Early vs late July:		-0.1m	15.8m	.01	.995

pecting geysers 12km away to be affected. Only three geysers in the Lower Basin were recorded in the Old Faithful Visitor Center geyser logbooks for summer 1996 with any degree of consistency: Great Fountain Geyser, Pink Cone Geyser, 1km north-northeast of White Creek, and Fountain Geyser, 2km north-northwest. All three of these features responded dramatically to the 1959 earthquake [Marler, 1973; 1974]. The Fountain Geyser Complex also responded to a M4.9 event on 26 March 1994 [Bryan, 1995]; there are no data for Great Fountain and Pink Cone from spring 1994 prior to Memorial Day weekend.

Great Fountain Geyser

In 1959, Great Fountain Geyser's average interval was 12h 46m before the Hebgen Lake earthquake, but shortened its intervals to between 3 and 6 hours immediately after the quake. While occasional longer intervals were seen as soon as September 1959, its average interval remained below 6 hours until 1964. [Marler, 1973] Might Great Fountain have shown a similar, if less dramatic, change following the 1996 swarm?

The average interval for Great Fountain Geyser was computed for three periods: 01–29 June, 01–10 July, and 16 July–15 August (Table II). There were not sufficient data from 11–15 July to formally study a fourth subset of data spanning the time after the 10 July earthquake but before the 15 July swarm.

Great Fountain's intervals became shorter (at 95% level of significance) between June and July 1996. The data strongly suggest that this change happened between late June and early July, with no further change in mid-July. Furthermore, the average interval does not appear to have started to decrease before the end of June: the average for 1–15 June is 10h 36m, for 16–29 June, 10h 45m.

Six intervals from 11 to 13 July averaged 10h06m, providing anecdotal evidence against any change occurring on 10 July. Great Fountain experienced its shortest interval of the 1996 season the night of 17–18 July, a double interval of 15h 33m. (There is a remote possibility that this is the *longest* interval of the season. However, as there are many examples of intervals between 8 and 9 hours in late July, but none at all exceeding 13 hours all summer, this is far more likely to represent a short double interval than a very long single interval.)

Pink Cone Geyser

Pink Cone Geyser, like Great Fountain, dramatically increased its activity in 1959. Intervals before the earthquake averaged two days; afterward it erupted constantly for ten days. Pink Cone erupted every 1 to 3 hours in late 1959, then gradually slowed down in succeeding years. A further abrupt shortening followed by gradual lengthening of intervals occurred after the 1983 earthquake [Marler, 1973; Bryan, 2001].

Pink Cone Geyser's intervals were irregular throughout the summer of 1996. Single intervals ranged from 12½ to 22½ hours, and double intervals from 27 to at least 37½ hours. Because of the

Table III. Pink Cone Geyser intervals, summer 1996

		01-29 Jun	16 Jul - 24 Aug		
Single intervals #		6	15		
	Mean	20h20m	17h32m		
	SD	1h55m	2h54m		
Double intervals #		4	7		
	Mean	30h43m	29h48m		
	SD	4h55m	2h48m		
Total # eruptions		14	29		
Best estimate of mean:		17h29m	16h16m		
Best estimate of SD:		2h53m	2h44m		
Std.error of est.mean:		46m	31m		
Signficance test:		Difference	StdError	z	p
		-1.23h	1.19h	-1.04	.298

wide variability it was not possible to determine how many eruptions had been missed if more than 40 hours passed between reported eruptions. Approximate intervals accurate to about ±1 hour based on sightings of eruptions already in progress were included in the calculations, because there are so few exact start-to-start intervals. Best estimates of Pink Cone's intervals for 01–29 June and 16 July – 24 August are reported in Table III. (The data were not cut off at 15 August because the highest quality observations of Pink Cone all season were made between 16–23 August, with data from more than two-thirds of the eruptions that occurred during this time.) There were insufficient data to calculate Pink Cone's mean interval for 01–10 July or 11–15 July.

The results are inconclusive. The decrease in interval between June and July–August is not large enough to be significant at the 95% level — nor are the data from early and late summer so similar as to emphatically rule out the possibility of a change. The shortest intervals of the season were reported in late July and mid-August. Late August and September 1996 brought the first-ever reports of minor eruptions (full strength, but lasting only 5-30 minutes instead of the usual 1½ hours) from Pink Cone [SPUT 10:5].

Fountain Geyser

Fountain is connected underground to several neighboring geysers. Changes in its activity, earthquake–driven or not, can take many forms other than changes in Fountain's average interval. The changes in the Fountain Geyser Complex in 1959 and 1994 manifested themselves most spectacularly in Clepsydra and Morning Geyser. Nevertheless, because data for Fountain were available for summer 1996, it was examined in the same way as Great Fountain and Pink Cone.

The summer of 1996 did not bring any reports of unusual activity from Morning though a satellite vent, "Morning's Thief," was active occasionally through the summer [SPUT 10:4]. Fountain erupts more frequently and regularly than Pink Cone does,

Table IV. Fountain Geyser intervals, summer 1996

		01-29 Jun	01-16 Jul		20 Jul – 02 Aug
Single intervals #		10	8*		6
	Mean	7h42m	7h36m	(7h05m)	6h36m
	SD	1h00m	1h35m	(32m)	41m
Double intervals #		5	5		5
	Mean	14h30m	14h00m		14h27m
	SD	37m	42m		1h16m
Triple intervals #		8	4		4
	Mean	21h42m	22h07m		20h41m
	SD	1h59m	1h55m		2h11m
Total # eruptions:		44	30	(29)	28
Best estimate of mean:		7h21m	7h18m	(7h11m)	6h57m
Best estimate of SD:		1h01m	1h09m	(39m)	1h04m
Std.error of est.mean:		9m	12m	(7m)	11m

* - A single interval of 11h20m, the only interval of 9 or more hours reported for the season, occured on 06 July. Figures in parentheses were re-calculated with the outlier removed.

but this means that at least one eruption is missed overnight every night, and not every day are two consecutive daylight eruptions witnessed. As a result there are no useful data on Fountain's intervals for 8–12 July, 16–19 July, and 02–15 August. Table IV summarizes observations of Fountain for the periods before, between, and following the earthquakes. As with Pink Cone, a majority of the reports were of eruptions already in progress, not of start times. Approximate intervals with uncertainties up to ±30 minutes are included in the data. It was not possible to determine how many eruptions were missed if reports were more than 24 hours apart.

The shortening of Fountain's interval between June and late July is significant at the 90% level, but not at the 95% level.

Anecdotal Reports

Azure Spring and Diadem Spring

Azure Spring, in the River Group, 4 kilometers northwest of White Creek and 9 kilometers from the earthquake epicenters, had an "eruption on July 11, then was found to be a murky green on July 31, as was Diadem, with both pools down by ~8 in" [SPUT 10:4]. This is the only reported eruption from Azure Spring in the period 1988–2002. Not included in the first two editions at all, Azure is listed in the third edition of Bryan [1995] as usually being an intermittent spring with rare eruptions. Marler [1973] describes "eruptions" in 1972 as "little more than heavy pulsations," contrasting this with constant boiling to three feet following the 1959 earthquake. The water can also become murky by runoff after heavy rainstorms, but a rainstorm would not also cause the water level to drop 20cm.

Diadem Spring has neither erupted nor even overflowed since 1976. Prior to that it was an intermittent spring. According to Marler [1964] it was murky following the 1959 earthquake, and was seen to erupt once in late 1959. In recent years the water level normally has hardly varied at all.

Artesia Spring

Artesia Spring is on the shore of Firehole Lake, 1½ km northeast of White Creek. In 1959 this was a dormant crater before the earthquake, but it erupted constantly with heavy discharge from August to October of that year [Marler, 1964]. In the 1980s and early 1990s it was a small, insignificant perpetual spouter. In late summer 1996 it more than doubled the size of its eruptions, washing away soil from the adjacent slope. It has maintained the increased activity to the present (2002). The exact date of the increased activity was not recorded.

The gravels underlying Firehole Lake are known to be unstable. This was one of few places in Yellowstone where the 1959 earthquake opened cracks in the ground. During the 1960s research drilling program, drillhole Y-2 at Firehole Lake suffered more trouble from steam blowouts and lost casing sections than any of the other drill sites, even those in traditionally "unstable" areas like Norris [White *et al.*, 1975].

Summary of earthquake evidence

In summary, significant changes are known to have occurred in at least three distinct areas of the Lower Geyser Basin at the same time in summer 1996. This supports the hypothesis that the seismic activity caused the changes observed on White Creek.

Based on the shift in Great Fountain Geyser's interval at or around 01 July, and the fact Azure Spring was already active by 11 July, the M3.7 event on 30 June appears to be the one responsible for initiating the changes, although it was not the largest event. The later events may have contributed to making the changes on White Creek and at Firehole Lake semipermanent. Whether a geyser is affected by a small or moderate earthquake seems to depend more on whether some threshold level of shaking is exceeded than on *how much* it is exceeded [Bower, 2002].

Has the activity on White Creek stabilized?

Many post-earthquake changes in thermal activity are temporary. For instance, Twin Geysers at West Thumb erupted for only two days following the 30 June 1975 earthquake before returning to

Table V. Botryoidal Spring intervals, 1996–2003

Date	Interval	Comments	Observer	Source
12 Aug 1996	avg 1m54.4s	n=35, SD=3.1s	Jack Hobart	Hobart 1998
late June 1997	avg 2m46.5s		Jack Hobart	SPUT 11:6
07 Aug 1997	avg 2m54s	n=15, SD=22s	Steve Gryc	Gryc 1998
28 Sep 1997	avg 2m50.4s	n~106	Jack Hobart	SPUT 11:6
17 Aug 1998	2.5-3.5 min		Paul Strasser	SPUT 12:5
11 Jan 1999	3-5 min		Mike Keller	SPUT 13:1
June 1999	avg ~3min	n~20	Steve Gryc	SPUT 13:4
22-24Oct 1999	avg 2m46.8s	n=91, SD=9.9s	Gordon Bower	This study
29 Jan 2000	~3min		Mike Keller	SPUT 14:1
09-12 Oct 2001	avg 3m19.5s	n=31, SD=11.2s	Gordon Bower	This study
25-27 May 2002	avg 3m56.9s	n=86, SD=19.4s	Gordon Bower	This study
07-08 June 2003	avg 3m53.9s	n=15, SD=15.7s	Tara Cross	Cross 2003

Table VI. Botryoidal Spring durations, 1996–2003

Date	# eruptions	Average Duration	StdDev	Observer	Source
12 Aug 1996	36	14.6s	1.6s	Jack Hobart	Hobart 1998
07 Aug 1997	16	16.4s	2.9s	Steve Gryc	Gryc 1998
22-24 Oct 1999	67	17.3s	2.1s	Gordon Bower	This study
09-12 Oct 2001	14	20.7s	2.1s	Gordon Bower	This study
25-27 May 2002	42	24.7s	2.5s	Gordon Bower	This study
07-08 June 2003	16	26.4s	2.1s	Tara Cross	Cross 2003

Table VII. Botryoidal Spring percent time in eruption, 1996–2003

Date	Time in eruption	Std. Error
12 Aug 1996	12.74%	0.24%
07 Aug 1997	9.42%	0.43%
22-24 Oct 1999	10.36%	0.20%
09-12 Oct 2001	10.38%	0.30%
25-27 May 2002	10.42%	0.19%
07-08 June 2003	11.30%	0.30%

dormancy [Bryan 1995]; Artesia Spring was only active for two months after the 1959 earthquake [Marler 1964]; and when Cascade Geyser in the Upper Geyser Basin reactivated after the 09 January 1998 earthquake, intervals started to lengthen the very next day and eruptions ceased four months later.

Great Fountain Geyser, on the other hand, did not immediately return to its pre-earthquake activity in 1959. Before the earthquake, eruptions looked much like those of today and intervals averaged more than 12 hours. Immediately after the earthquake, intervals as short as 3h 10m were seen, and the pre-eruption overflow periods and the eruption durations were also much shorter than those seen previously. Intervals slowly lengthened through December 1959; but then the average remained under 8 hours for the next ten years, instead of quickly returning to, or continuing a steady rise toward, the pre-earthquake figure [Marler, 1973].

Marler also reports both A-1 and A-2 geysers "erupted with marked frequency for a period of about three weeks" after the 1959 earthquake, and that it was "not until the 1965 season that the geyser action in the White Creek flat quite closely assumed its pre–earthquake character." He does not, however, provide any additional details about exactly *what* the geysers on White Creek did from 1960 to 1965.

Most of the unusual activity in summer 1996 came to a quick end. The impressive "new geyser near Verdant Spring" and the small unnamed geysers around A-1 and A-2 all were dormant before the spring of 1997. Most observers expected that Botryoidal Spring's large eruptions would also taper off and eventually cease. But Botryoidal Spring was still erupting in 1997. If its activity was declining, it was doing so gradually.

Botryoidal Spring

Botryoidal Spring's intervals dramatically lengthened between 1996 and 1997. Jack Hobart reported an average interval from August 1996 of 1m 54s. Describing Botryoidal in September 1997 he wrote:

> The heat input to the geyser continues to diminish as predicted. The start–to–start period has increased from 166.5 sec at the end of June to 170.4 sec now. It remains spectacular and undiminished in intensity when it does erupt [SPUT 11:6].

Given the standard deviations of only a few seconds that Hobart was observing, the change from June to September may well have been statistically significant. However, a continuous steady rise in interval through September 1997 is not the full story: data from August 1997 show a longer average interval, and a higher variability [Gryc, 1998]. Table V is a listing of all post-1996 reports of Botryoidal Spring's interval of which the author is aware.

For six of these twelve occasions, data on durations are also available. These are reported in Table VI. One measure of the intensity of a geyser's activity is to calculate the percentage of time the geyser is in eruption, dividing the average duration by the average interval (see Table VII).

Botryoidal Spring did significantly decline in frequency and regularity between 1996 and 1997, but has maintained about the same level of activity since then. After 1997, intervals remained constant near 3 minutes for several years. In 2002, intervals were longer than at any time since 1996, but durations had also increased, so that the total amount of heat and water released appears to have remained constant.

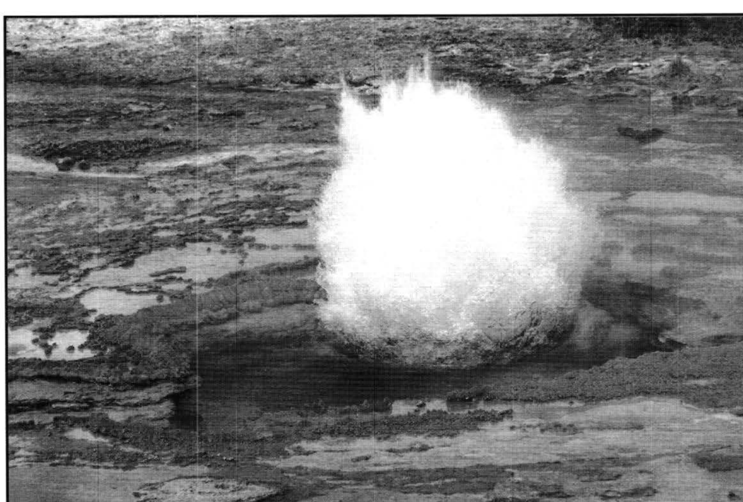

Figure 3. Botryoidal Spring, showing the blue–bubble burst that typically begins an eruption. [Photo by Robert Bower]

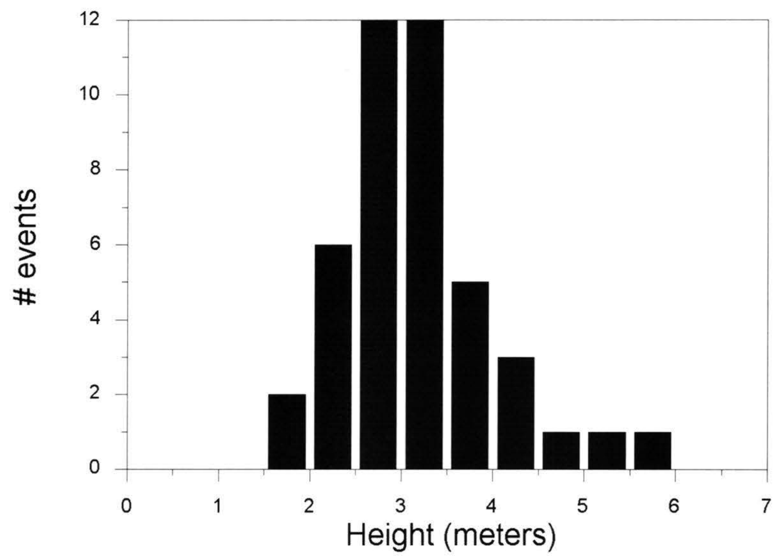

Figure 4. Histogram of Botryoidal Spring's height, May 2002.

Steve Gryc's comment of 12 June 1999, "the geysers along White Creek seem very much the same as when I saw them last in the summer of 1997" [SPUT, 13:4], is typical of the reactions of almost all observers since 1997.

The height of the eruptions also appears to have stabilized. Most reports from 1996 list maximum heights of only 2 or 2½ meters; most observers since 1997 have consistently claimed heights ranging between 3 and 5 meters. There have been a few reports of exceptionally weak and strong eruptions. Mike Keller in January 1999 writes, "We saw one eruption which was over 15 feet and another over 12 feet, but the rest were 6 to 8 feet high" [SPUT 13:1]. Scott Bryan in June 1999:

> Botryoidal is still doing really nice things. I never saw any apparent relationship between the force of the eruptions and the activity of anything else, but there certainly was variation: around Memorial Day Paul Strasser and I uniformly saw bursts to 15 to 20 feet high (maybe even more), yet a week or so later I don't think any burst exceeded 10 feet [SPUT 13:4].

Some of the reported variation in heights from 1996 to 2001 may be due to differences in observers' ability to estimate heights, or to watching only a very few eruptions, rather than actual change in the activity. None of the observers from 1996 to 2001 reported having made formal measurements.

To enable quantitative study of eruption heights in the future, the author returned in 2002 armed with compass and clinometer, and measured the heights of 43 eruptions. The mean height was 3.1 meters, with standard deviation 0.9 meters. The bulk of the eruptions were between 2½ and 3½ meters, but some were as small as 1.6 meters, and two exceptional eruptions reached 5.1 and 6.0 meters. Figure 4 shows the distribution of observed heights.

A-0 Geyser

There were not sufficient data for A-0 Geyser and the unnamed geyser between A-0 and Botryoidal Spring prior to this study to do the same

Table VIII. A-0 Geyser, 1999-2002

	1999	2001	2002
Duration			
#observations	10	5	15
Mean	36.2s	36.0s	38.9s
StdDev	2.4s	5.7s	3.0s
Interval			
#observations	9	3	11
Mean	22m59s	24m39s	26m22s
StdDev	1m17s	2m05s	1m15s
% time in eruption	2.63%	2.43%	2.46%
StdError	.07%	.19%	.06%

Significance tests, 1999 vs 2002:

	Difference	StdError	z	p
Duration	2.7s	1.1s	2.49	.013
Interval	3m23s	34.2s	5.94	2.9×10^{-9}
%IE	-.163%	.095%	1.71	.087

Figure 5. The new unnamed geyser northeast of Botryoidal Spring. [Photo by Robert Bower]

type of analysis of whether their activity changed between 1996 and 1999. Anecdotal evidence [Cross, 2002; and others] is that it did not.

From 1999 to 2002, A-0's durations and intervals both increased slightly but significantly, while the change in percentage of time in eruption was not significant (Table VIII). Cross [2003] reported closed intervals of 24, 26 and 27 minutes in June 2003, suggesting no major change occurred between 2002 and 2003 either.

No qualitative difference in the height of A-0's eruptions was noticed between 1999 and 2002. A-0 is too small and too far from the road to measure its height by clinometer with any useful degree of precision.

UNNG northeast of Botryoidal Spring

As noted above, almost all of the small geysers that appeared in summer 1996 had ceased activity before spring 1997. The notable exception is the crater closest to the Howard Eaton Trail, about 25 meters west of the trail and 30 meters northeast of Botryoidal Spring. This feature is shown in Figure 3. No specific reports were made about this feature in 1997 or 1998, but notes that only one of the small unnamed geysers from 1996 remained active presumably refer to it.

In 1999, there was no standing water visible in the central pool. Eruptions then consisted of 3 or 4 episodes of strong "chuffing" of steam with droplets shot to about 1m in two places above the central crater. The other vents, visible in Figure 5 as a fissure just behind the pool and as small craters at far right and lower right, would also puff steam under pressure. The episodes lasted approximately ten seconds, and the whole eruption took 45 to 65 seconds. Intervals were very regular, averaging 9m45s with a range of 9m 15s to 10m 20s. There also were occasional splashes to about 20 centimeters above the surface during the quiet period.

In 2001, the central pool filled with water before each eruption. The side vents still ejected steam under pressure, but the main pool pulsated and sloshed, and the eruption culminated with just one or two small splashes, doming the whole pool surface but rarely exceeding 30 centimeters. Intervals in 2001 were very consistent at 10½ minutes. New iron oxide stains appeared around the central pool, where two years before there was only weathered greyish–white sinter.

In May 2002, this feature was no longer erupting regularly. Instead, the pool level rose and fell slowly over time, but remained higher than it had been in 2001. Occasionally a single splash occurred in the main vent at times of high water. The iron oxide staining had become noticeably darker and more extensive in the space of eight months.

These three different kinds of activity could reflect ongoing evolution of the geyser. Alternatively, the geyser's plumbing system and energy supply might be stable, with the changes caused by the seasonal variation in the water table: drowned in the spring, erupting under normal conditions, reduced to a steam vent with a few water droplets in times of very low water.

Webb [2003] reported eruptions in September 2003 that were virtually identical to those seen in October 2001. "The pool itself rose and flooded the formation every 10-12 minutes," while there were "two little bitty sputs on the back left of the formation." This latest observation supports the claim that the geyser itself has stabilized and is responding to how much non-geothermal water makes its way into the system. Such seasonal changes are common in features with limited water supplies such as paint pots and "seasonally drowned fumaroles" like Red Spouter. A few features with significant discharge of their own, such as Aurum Geyser in the Upper Basin, also respond to changes in the surface water supply.

Other Features

There was no change in the status of the other geysers from spring 1997 to spring 2002. Logbridge Geyser remained a quiet continuously discharging spring. A-1 and A-2 Geyser both remained dormant. The consensus among geyser observers is that the ongoing strong activity of Botryoidal Spring is the cause of the continued dormancy of both A-1 and A-2 Geysers since sometime in the winter of 1996-1997 [SPUT 12:2; SPUT13:4].

The only other geyser activity the author witnessed in the lower White Creek Group was a sput near the east side of A-1's crater in 2002, occasionally jetting a thin stream of droplets to about 50cm. This may or may not be the same vent that was reported as a "small new UNNG between A-0 and A-2 that erupts as a slender jet to 1+m initially, after which it recedes quickly" in 1996 [SPUT 10:4].

Patterns in time series

For many geysers, the durations and intervals of consecutive eruptions are not independent. The most commonly recognized pattern, exhibited by Old Faithful, Grotto, and Great Fountain Geysers, is that the duration of one eruption will control the length of the interval to the next eruption. The opposite relationship, longer or larger eruptions tending to follow longer intervals, occurs at Cliff and Flood Geysers, and on a longer but more dramatic scale at Hekla volcano in Iceland [Thorarinsson and Sigvaldason, 1972]. Some geysers also have longer–term patterns in their activity, such as Old Faithful's tendency in the early and mid 1990s to alternate between 60– and 90–minute intervals.

Theoretically, if a geyser's eruption is always triggered when the system fills to a specified level, but ends at a random time, intervals should be controlled by the preceding duration; if the eruption begins at a random time but always continues until the system drains to a specified level, intervals should control the following duration. If both the starting and ending conditions are variable, some "memory" from one cycle to the next is possible (perhaps in addition to correlations between durations and intervals). If neither condition can vary, the geyser is expected to be almost clockwork-like.

Both A-0 and Botryoidal Spring show very little variation in their durations and intervals, and present a clockwork-like "feel" to the casual observer. On the other hand, eruptions begin almost without warning, then grind slowly to a halt as the geyser runs out of energy, so a "duration controlled by preceding interval" pattern would not be surprising.

Data from 1999, 2001, and 2002 were examined for both geysers, searching for relationships between interval and preceding duration; duration and preceding interval; and interval and preceding interval. For Botryoidal Spring the same analysis was also done using the data from Hobart [1998].

For A-0 geyser, no statistically significant correlations among any of the variables were found within any one year.

For Botryoidal Spring, statistically significant correlations between durations and intervals were seen only in the 24 October 1999 data set. This was the longest set of continuous observations, 2h 40m long, used in this study. This was caused by a drift in the average interval over the course of the observation period, accompanied by a corresponding increase in the average duration. It did not reflect any tendency for a single long eruption to be preceded or followed by a longer than normal interval.

As noted in the previous section, height measurements were made for the first time in 2002.

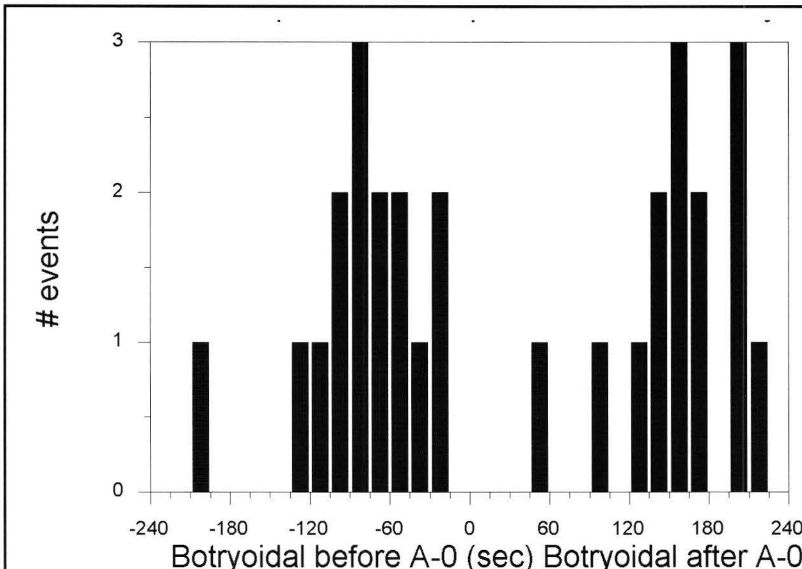

Figure 6. A plot showing the time between A-0 Geyser's eruptions versus the previous and subsequent Botryoidal eruption, May 2002.

Eruption height was not correlated with eruption duration, the preceding or following interval, or with the height of the preceding or following eruptions. Combined functions of duration and height (such as $D \cdot H^2$, which might be expected to be proportional to energy release) also failed to correlate with intervals. In short, no prediction method for Botryoidal Spring better than "the next interval will be about the same as the previous one" was found.

The one significant correlation that does exist in both the 1999 and 2002 data is a positive correlation of adjacent intervals, with $r = .4$ to $.5$. If this were due only to a drift in the average interval over a time scale of hours, a similar correlation should also exist between intervals 2 cycles apart, and decay only slowly with increasing separation in the time series. It does not; whatever causes this effect operates over a time scale of just a few minutes.

This might be something internal to Botryoidal's plumbing system, or it may be weather-related. Botryoidal was much more regular (standard deviation 7.9 seconds vs. 13.6 seconds) on 09 October 2001 when the weather was calm and sunny than on 12 October 2001 when it was snowing with a gusty wind. It was also windy during the May 2002 observation period, during which even higher standard deviations were observed. Strong winds have been known to negatively impact both frequency and regularity of geysers elsewhere, especially those with large surface pools [Landis, 1988; Bower, 1994; Bryan, 1995].

A full understanding of how Botryoidal Spring's intervals rise and fall over a period of hours or days will not be possible until either a continuous series of observations much longer than 2 hours is recorded, or many more short series are collected in the space of a few days.

Underground connections

Before 1996, underground connections were known to exist among A-1, A-2, and Botryoidal Spring. Is there evidence for an underground connection between A-0 and Botryoidal also? The observations in May 2002 strongly suggest that the answer is yes.

Out of 14 observed eruptions of A-0 Geyser in May 2002, thirteen of them started during the *first* half of Botryoidal's interval, and the fourteenth only a few seconds later. Not a single eruption occurred during a window a full two minutes long, from the middle of Botryoidal's interval until shortly after the next eruption of Botryoidal finished (Figure 6). This is statistically significant, with a probability of occurring by chance of only .0006 according to Rayleigh's test.

One statistically significant correlation did exist in both the 1999 and 2002 data, a weak positive correlation (r^2»0.2) between consecutive intervals. It is not clear if this is an artifact of a drift in average interval over several hours, or caused by some other process acting over a time scale of just a few minutes. One potential candidate is wind; strong winds have been shown to impact both frequency and regularity of other geysers with large surface pools [Landis, 1988; Bower, 1994; Bryan, 1995]. Lending support to this hypothesis, Botryoidal was more regular on 09 October 2001 in calm sunny weather than it was three days later when it was windy and snowing (standard deviation 7.9 seconds vs. 13.6.) A full examination of

Table IX. Botryoidal Spring intervals (in seconds) near the time of A-0 eruptions, May 2002

Before A-0	Difference:	Across A-0	Difference:	After A-0	Difference:	Next after A-0
—	—	231	-17	214	-16	198
228	+47	275	-5	270	+27	297
227	-5	222	-1	221	+6	227
~211	-2	~209	+6	~215	+25	~240
252	-22	230	—	—	—	—
277	-24	253	-26	227	+10	237
~235	+8	~243	-12	231	+38	269
239	+19	258	-16	242	-17	225
259	-27	232	—	—	—	—
198	+40	238	+6	244	—	—
230	+27	257	-48	209	+9	218
~253	+11	264	-11	253	-11	242
222	+16	238	-13	225	+10	235
240	+6	246	+14	260	-39	221
n =	13		12		11	
Mean	+7.2s		-10.3s		+3.3s	
Std.Dev.	23.2s		16.5s		23.0s	
Std.Err.	6.4s		4.8s		6.9s	
z=	1.13		-2.15		0.48	

how Botryoidal's average interval drifts over the course of several hours, and of whether it is influenced by the wind, is not possible until much larger data sets have been collected.

Great Fountain Geyser

One possible cause for Botryoidal Spring's activity to vary over a period of hours is the twice-daily eruptions of Great Fountain Geyser. Great Fountain overflows for 1 to 1½ hours before each eruption, then erupts with gradually declining force for an hour, then recharges over the next several hours.

The data collected for Botryoidal Spring from 1999 to 2002 can be divided into 4 subclasses according to Great Fountain's status: before Great Fountain reached overflow, during Great Fountain's overflow, during Great Fountain's eruption, or after Great Fountain's eruption concluded (Table X). In every case, Botryoidal's average interval is longer during Great Fountain's overflow period than either before overflow began or after the eruption began. The data from 22 October 1999, standing alone, are significant at the 95% level. The data from other days are only significant if pooled.

This trend was discovered at the end of the 2001 field season, and the two long data collection sessions on 25 May 2002 were intended to help resolve the mystery. Unfortunately, Botryoidal's interval and standard deviation had increased enough that observing a single Great Fountain cycle was insufficient to achieve statistical significance, and Great Fountain was uncooperative on the 26th and 27th, erupting at the wrong time of day for a second complete series of data to be collected.

Until field data are collected for another season, an underground connection between Great

Table X. The realtionship between Botryoidal Spring's intervals and Great Fountain Geyser's eruption cycle status

Data subset	Interval			Duration			%IE
	n=	Mean	S.D.	n=	Mean	S.D.	
22 Oct 99							
In overflow	11	2m51.3s	10.4s	9	17.0s	1.9s	9.92±.42
in eruption	15	2m42.6s	9.8s	9	15.9s	1.5s	9.78±.35
23 Oct 99							
Before overflow	4	2m41.3s	5.4s	2	16.0s	2.0s	9.92±.89
in overflow	7	2m42.4s	7.8s	7	16.6s	1.7s	10.22±.44
24 Oct 99							
In overflow	22	2m48.8s	12.0s	16	17.1s	1.8s	10.13±.31
In eruption	20	2m43.3s	8.2s	12	16.9s	1.7s	10.34±.32
After eruption	11	2m53.0s	8.2s	12	19.8s	1.6s	11.44±.44
09 Oct 01							
In overflow	13	3m20.8s	7.9s	11	20.6s	1.9s	10.26±.31
In eruption	7	3m14.1s	15.0s	-	-	-	-
12 Oct 01							
(not in ovfl.)	15	3m17.0s	13.8s	3	21.0s	2.0s	10.66±.62
25 May 02							
Before overflow	30	3m55.6s	21.9s	23	24.4s	2.7s	10.36±.30
In overflow	5	4m06.0s	22.9s	5	24.8s	1.6s	10.08±.51
in eruption	19	3m57.2s	13.6s	15	25.1s	1.9s	10.58±.25
After eruption	8	3m45.0s	16.6s	6	24.3s	1.5s	10.80±.39
27 May 02							
Before overflow	32	3m56.0s	20.0s	-	-	-	-

Fountain and White Creek can only be classed as suspected, but not firmly established. Additional data may also shed light on whether the relationship between A-0 and Botryoidal is seasonal or permanent.

The rest of the White Creek Group

It is tempting to cite the dormancy of Logbridge Geyser since 1996 as evidence for a connection to the A-1/A-2/Botryoidal Complex. The reports of A-0 as "infrequent and irregular" before 1996 might also be taken as evidence that eruptions of A-2 Geyser suppressed the activity of A-0 just as they did A-1 and Botryoidal. These are risky conclusions to draw, since the earthquake swarm caused changes throughout the Lower Geyser Basin. Just because the energy supply to these features shifted at the same time is not proof that they are related closely enough for their day–to–day activity to affect one another.

Conclusions

The earthquake swarm of 30 June 1996 is the most likely cause of the changes on White Creek, including the recent spectacular activity of Botryoidal Spring. Temporary effects of the earthquakes ended over the winter of 1996–1997, after which the system has remained stable for at least six years.

Underground connections between A-1, A-2, and Botryoidal Spring were known prior to this study. In 2002, A-0 and Botryoidal also appeared to be connected. Additional fieldwork is necessary to prove or disprove the existence of a connection with Great Fountain. Additional data are also needed before hours–long cycles, seasonal changes, and gradual permanent changes can be distinguished.

Acknowledgements

Fieldwork in May 2002 was funded by the Frontier Research System for Global Change, International Arctic Research Center, University of Alaska Fairbanks. Photographs are courtesy of Robert Bower, Idaho Falls Post Register.

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A–0 Geyser (far left center) as it appeared in July, 1997. This photograph was taken from the old Howard Eaton Trail, at about the position of the word "unnamed" on Figure 1. The motorhome beyond A–0 is parked on Firehole Lake Drive. [Photo by Mike Newcomb; Tracie Newcomb is sitting at far right]

The Bimodality of Bead Geyser,
Pink Cone Group, Lower Geyser Basin

by Gordon R. Bower

Abstract

Bead Geyser has an "every half hour like clockwork" reputation, yet its shortest and longest intervals on a single day often differ by as much as ten minutes. Most of these intervals fall into two tightly-clustered groups, one set being four minutes longer than the other set. Bead's preplay is characterized by episodes of strong convection over the vent four minutes apart. This suggests an explanation for the interval distribution, and for how it is possible for Bead to appear highly regular at times and quite irregular at other times.

Introduction

Bead Geyser is located at the eastern edge of the Pink Cone Group in the Lower Geyser Basin, 10km north–northeast of Old Faithful. Its eruptions are easily viewed from Firehole Lake Drive, which passes immediately south of the Pink Cone Group. However, the crater is on an elevated sinter terrace some 30 meters from the road, and there are no boardwalks in the Pink Cone Group. This makes it difficult to see into the crater (or even to see exactly where the crater *is* when it isn't in eruption, if you are unfamiliar with the area).

For the past fifty years, Bead has been one of the easiest geysers in the Lower Basin to see, erupting about every half hour to 5 to 10 meters for 2 or 2½ minutes. The first and last splashes just dome the water over the vent, but most of the duration is full strength, a mixture of vertical spikes and angled splashes — something like an oversized Anemone or miniature Sawmill. A typical eruption and a closeup view of the crater are shown in Figures 1 and 2.

Bead Geyser was named by the 1872 Hayden expedition for the attractive geyserite–coated pebbles lining the edge of its crater. Most of these "geyser eggs" were removed by curiosity seekers many years ago. After its initial fame for its "geyser eggs" in the early days of the park wore off, it attracted very little attention.

"The most regular geyser in the park"

In recent times, Bead's primary claim to fame has been the clockwork-like nature of its eruptions— at times, its intervals have been reported to have standard deviations of less than 30 seconds. However, Bead has not always been noted for the exceptional regularity of its eruptions. In fact it apparently had quite the opposite reputation as far as the frequency of its eruptions.

After not mentioning Bead at all in the 1915, 1921, 1924, or 1929 editions, the 1941 and 1949

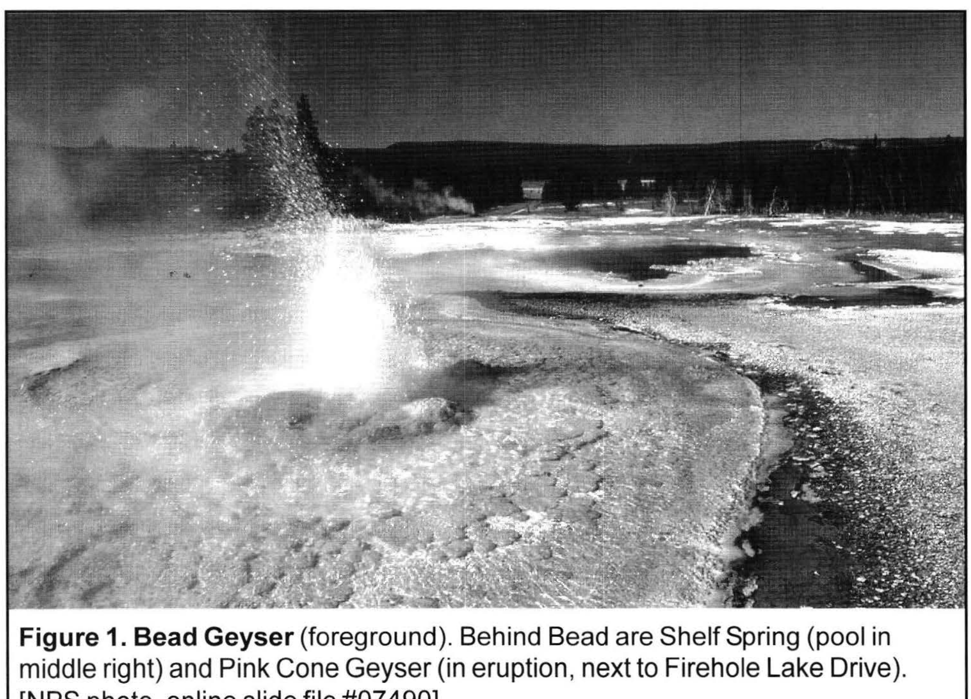


Figure 1. Bead Geyser (foreground). Behind Bead are Shelf Spring (pool in middle right) and Pink Cone Geyser (in eruption, next to Firehole Lake Drive). [NPS photo, online slide file #07490]

Haynes Guides states: "Bead Geyser at the right is very irregular but when in action erupts 10 to 15 feet in height." (The Firehole Lake Loop was one way north to south then, opposite to the modern traffic flow, so that the entire Pink Cone Group was to the right of vehicles.) In 1951 this changes to: "Bead Geyser at the right erupts 2 or 3 feet high several times a day." Haynes repeats this new information unchanged in the editions of 1953 and 1956.

Apparently the first to document Bead's regularity was Marler in 1958. In the *Inventory* [1973] he writes:

> The records are very scanty on the nature and frequency of Bead's eruptions. During June, July, and August of 1958 I determined the time of 20 intervals. As a result of this record I came to the conclusion that if the observed activity were representative of its behavior it was the most regular geyser in the Park. The 20 determined intervals revealed it was erupting at a near set time. Eleven of these intervals were 33 minutes; nine 33.5 minutes. The duration of all eruptions was essentially the same — 2.5 minutes. During the 3 seasons preceding the 1959 earthquake none of the observed intervals varied by more than 1/2 minute. The duration of an eruption was as fixed as the interval, being 2.5 minutes. The height of the eruption is between 20 and 25 feet. Its character does not seem to vary.

Marler goes on to describe the intervals for several subsequent years, not giving any details of his observations, but in every case reporting a very narrow range of variation:

> Following the earthquake [of 17 August 1959] Bead began playing on near hourly intervals –60 to 63 minutes. With the longer intervals there was a marked increase in the length of the active phase, an increase of from 2 1/2 to 11 minutes.
>
> After about 6 weeks of the above pattern of activity the eruptions began coming on greatly shortened intervals, which varied between 15 and 16 minutes. The duration shortened to the previous 2 1/2 minutes.
>
> For the remainder of 1959 it continued on this pattern, manifesting about two times the thermal energy it did before the earthquake.
>
> During the 1960-61 seasons Bead erupted on 20 to 21 minute intervals. During 1962 the intervals increased to 30-31 minutes, with 2 1/2 minutes for duration of activity. From 1962 through the 1970 season the minimum and maximum interval ranged between 27 and 30 minutes. During the 1971 season the intervals were from 20 to 22 minutes. Just why the pattern of duration from longer to shorter intervals occurs, then vice versa, is unknown.

Marler tells essentially the same story in his 1964 paper on the effects of the Hebgen Lake earthquake, with the numbers slightly changed: 32 to 33 minutes before the earthquake, 55 to 60 minutes for August and September 1959, and 15 to 16 minutes for October–December.

The "records are very scanty" remark makes it sound like Marler didn't believe he was seeing something new in 1958 and was blaming the previous reports on inadequate or even completely incorrect data. (The modern reader might wonder if Haynes's 2–foot eruptions several times per day in the 1950s were misidentified eruptions of Box Spring.) By 1964, the Haynes guide goes back to a height of 10 to 15 feet and adopts Marler's 1961 interval of 20 to 21 minutes.

The first edition of *The Geysers of Yellowstone* [Bryan, 1979] cites five consecutive intervals from 1974, all very near 23 minutes, as evidence of Bead's great regularity. Other guidebook writers appear to have just repeated the "most regular geyser in the Park" line without letting Marler's hedge "if the observed activity were representative of its behavior" get in the way of a good story.

The fairy tale begins to unravel

The author got his first hint that Bead might not be as regular as commonly believed in the summer of 1991, when he collected eruption data on Bead as he spent half a day waiting out a closed interval on Labial Geyser. That data is presented as Table I.

The eruption at 1356 was noticeably "late," and stuck out like a sore thumb from all the 32-minute intervals that came before it. Labial started having preliminary overflow cycles around 1245, and the long-awaited eruption happened at 1404. Labial's morning eruption had been at 0838 with overflow beginning sometime before 0730. This put the author on the wrong scent: the "obvious" conclusion

Table I. Bead Geyser — 14 June 1991

Time	Duration	Interval
0645.58	2m46s	36m20s
0722.18	2m29s	~32m
0754	~2½m	~31m
0825.33	2m30s	32m03s
0857.36	2m39s	32m54s
0930.30	2m37s	32m54s
1003.24	2m47s	32m27s
1035.51	2m29s	33m07s
1108.58	2m42s	31m36s
1140.34	2m36s	32m18s
1212.52	2m31±5s	32m58s
1245.50	2m28s	32m52s
1318.42	2m33s	37m43s
1356.25	2m20s	—

was that a previously unknown underground connection between Bead and Labial had been discovered, Bead's long intervals coinciding with the rising pressure head in Labial as the water level approached overflow for the first time.

Discussions with other geyser gazers familiar with the Pink Cone Group brought the disappointing news that people had seen Bead behave perfectly normally at the time of Labial's eruptions many times. That news (plus being confined to cycling distance of Old Faithful by lack of a car) meant plans for more extensive study of the Pink Cone Group got shelved, and the mystery of the abnormal Bead intervals was filed away in the back of the author's mind as a freak occurrence.

Enlightened by the full moon

Over the winter of 1993–1994 the author developed a new device for logging geyser eruptions electronically, capable of greater precision than the once-a-minute temperature loggers but cheaper and more portable than the solar-powered infrared monitors. By the spring of 1994 it was ready to be field-tested, and Park Geologist Rick Hutchinson gave permission to work off trail to deploy the monitoring equipment. Bead Geyser was an ideal candidate, erupting frequently enough to collect a good test data set in one day, regular enough that there was a real need for better than one-minute precision, and convenient enough to make visual observations to compare with the electronically logged data.

Bead's preplay is all but unknown to most geyser gazers. From the roadway, all that can be seen is that the water level rises during the interval, and the eruption begins with a couple of small splashes that quickly build into a full eruption. Seeing anything more than that requires a close approach to the crater. (Doing so is illegal without park service permission, and is also dangerous if you aren't cautious. To the north and west there are thin overhangs over Shelf and Box Springs; to the northeast there are inactive vents that won't boil you, but stand ready to twist the ankles of anyone circling around from behind Labial.) Before the splash that starts the eruption, there are several seconds of strong upwelling and convection over the vent — not enough to break the surface or cause any sound, but visibly doming the water over the vent and quickly filling the surrounding terraces to near overflow. Sometimes this convection leads immediately to an eruption, while at other times there are about ten seconds of upwelling, followed by a falling back of the water level and about four minutes of quiet refilling before the convection resumes.

The author first observed this preplay while deploying the new logger for the first time late on a brightly moonlit night in June 1994. While the sensor wires were being positioned in Bead's runoff channel at the east edge of the crater, there was a sudden unexpected reflection of moonlight off the previously calm and dark pool of water in the crater. This caused a hasty retreat to a safe distance in expectation of an eruption that didn't come. After the convection stopped, the job of placing rocks on the wires to hold them in place was finished, keeping one eye on the surface of the pool the whole time. The time of the previous eruption was not known. The next evening when the probe was retrieved, preliminary convection was seen again around the 30–minute mark of a 33½–minute interval.

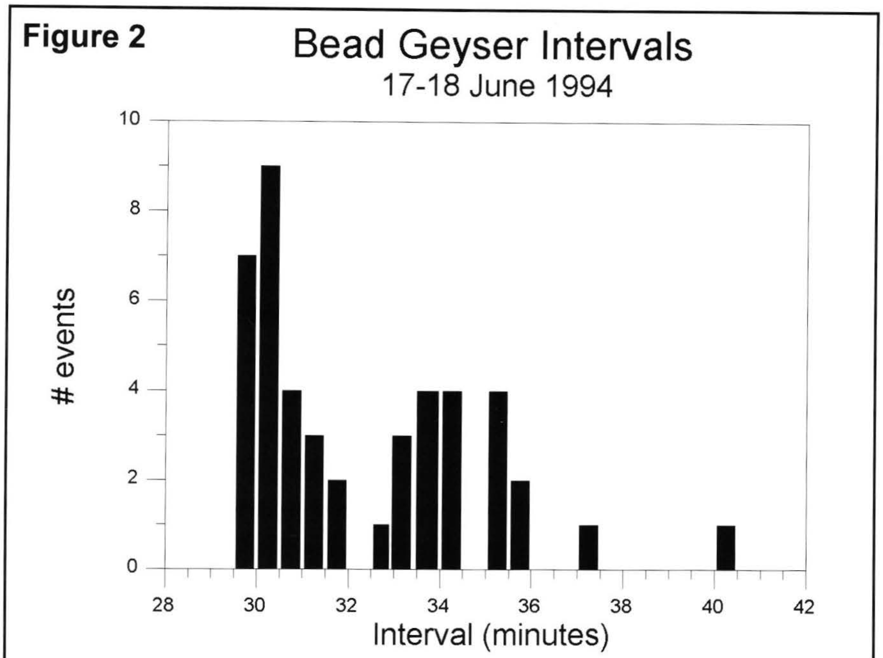
Table II. Bead Geyser — 17–18 June 1994

Visual (eruption):			Electronic (runoff):			Lag:	
Time	Dur	Intvl	Time	Dur	Intvl	Start	End
2254.56	2:32 -	2255.30	3.26	30.28	0.34	1.28	
-		2325.58	3.23	29.43			
—			2355.41	3.22	29.44		
—			0025.25	3.36	31.20		
—			0056.45	3.36	33.56		
—			0130.41	3.26	33.11		
—			0203.52	3.38	30.19		
—			0234.11	3.23	35.16		
—			0309.27	3.35	31.11		
—			0340.38	3.24	34.06		
—			0414.44	3.48	30.08		
—			0444.52	3.33	30.35		
—			0515.27	3.28	31.29		
—			0546.56	3.26	31.33		
—			0618.29	3.35	30.06		
—			0648.35	3.38	31.47		
—			0720.22	3.33	29.54		
—			0750.16	3.34	33.56		
—			0824.12	3.45	33.16		
—			0857.28	3.34	30.56		
—			0928.24	3.40	30.13		
—			0958.13	3.04	30.24		
—			1028.37	3.44	34.05		
—			1102.42	4.03	29.43		
—			1132.25	3.38	34.06		
1205.56	2.33	35.33	1206.31	3.40	35.34	0.35	1.42
1241.29	2.24	30.41	1242.05	3.43	30.22	0.36	1.55
1312.10	2.12	30.38	1312.27	3.58	—	0.17	2.03
1342.48	2.21	—	—	—	—		
—			1418.52	3.37	29.46		
—			1448.38	3.54	33.16		
(1521, OFVC log book)			1521.54	3.46	32.38		
—			1554.32	3.44	40.12		
1634.21	2.35	35.15	1634.44	4.07	35.28	0.23	1.55
1709.36	2.37	—	1710.12	3.48	30.51	0.36	1.47
—			1741.03	3.34	30.04		
—			1811.07	3.30	30.22		
—			1841.29	3.34	35.30		
(1918, OFVC log book)			1916.59	3.30	29.59		
—			1946.58	3.44	34.20		
—			2021.18	3.46	33.05		
—			2054.23	3.27	30.01		
—			2124.24	3.40	37.07		
—			2201.31	3.43	33.30		
2234.29	2.40	34.40~	2235.01	3.41	—	0.32	1.33
2308.10~	—		—	—	—		

Bimodal data from 1994

The new electronic logger performed well, reliably detecting the start of eruptions 17 to 36 seconds after the observed eruptions began, and reporting durations of 3½ to 4 minutes. This is consistent with what a device placed in a runoff channel should record. Start times will be delayed a few seconds while the crater fills to the brim and water begins to enter the runoff channel. End-of-runoff times will lag farther behind end-of-eruption times because the channel takes some time to drain after water quits being poured into it. The data from that first deployment are shown in Table II.

Figure 2



The data collected during that 24-hour test session revealed a striking pattern (Figure 2). More than half of the observed intervals were tightly clustered around 30 minutes; most of the rest were tightly clustered around 34 minutes. Only one eruption fell isolated in the gap between the two clusters, and two eruptions were significantly longer than any in the second cluster. Differences between consecutive intervals were usually under one minute or over three minutes.

Summary statistics for Bead's intervals are shown in Table III.

The means of the two interval clusters were about four minutes apart, with the longer-interval cluster having a somewhat higher standard deviation. The two observed episodes of preliminary convection both happened about four minutes before eruptions.

A reasonable hypothesis is that this extra convection episode is what distinguishes the two types of intervals from each other. Assuming this is true,

Table III. Summary statistics, 17–18 June 1994

	All	Short	Long	Very Long
N =	45	24	18	2
Mean	32m20s	30m25s	34m16s	(38m40s)
Std. Dev.	2m28s	39s	59s	(2m11s)
Std. Err.	22s	8s	14s	
Minimum	29m43s	29m43s	32m38s	37m07s
Lower Quartile	30m19s	29m54s	33m40s	-
Median	31m29s	30m19s	34m05s	-
Upper Quartile	34m05s	30m51s	35m16s	-
Maximum	40m12s	31m47s	35m47s	40m12s

convection episodes that do not lead to eruptions are estimated to have caused delays averaging 3m 37s.

The two longest intervals observed were both between 7 and 8 minutes longer than the preceding interval, and about 4 minutes longer than the following interval. This is consistent with an eruption being preceded by not one but two episodes of convection.

Additional observations since 1994

Eruptions of Bead make it into the Old Faithful Visitor Center logbook at least a few days per month every summer. Usually there are a few times each season when several consecutive eruptions are observed. The logbook data, however, are recorded only to one minute precision. The noise introduced into the data by round off error is just enough to conceal a one– to two–minute–wide band in which almost no eruptions fall. Bead has been monitored electronically on several occasions since 1994 too — but again, most temperature loggers unfortunately are set with sampling rates too low to expose the bimodality. Data from the May 2002 NPS logbook are presented in Table IV as an illustration.

Table IV. Sample NPS logbook data

26 May 2002 Time	Interval	27 May 2002 Time	Interval
0705	32	0650	35
0737	30	0725	31
0807	32	0756	28
0839	32	0824	—
0911	32	——	—
0943	35	0922	34
1018	30	0956	33
1048	33	1029	31
1121	31	1100	28
1152	30	1128	—
1222	29	[Labial: 1128]	
1251	29		
1330	35		
1405	—		
[Labial:1414]			
1614	36		
1650	—		
1956	31		
2027	30		
2057	—		
[Labial: 2126]			

There is still a hint of the bimodal pattern here, with no 32–minute intervals on May 27, and each of the 35– and 36–minute intervals on May 26 being surrounded by others at least three minutes shorter, but it would be difficult to convince the nonbeliever using this type of data. It may not even occur to someone to *look* for a bimodal pattern, if he has only seen data recorded to the nearest minute.

The perception that Bead is the "most regular geyser" has slowly been fading. The 1995 edition of Bryan was changed to read "one of the most, if not the most, regular." As of 2003, the GOSA web site states "one of the most regular geysers in Yellowstone. Eruptions often occur within seconds of the current average" — true enough, it is very common for consecutive intervals to be almost exactly the same. But no published source has yet mentioned bimodal intervals at Bead, and it doesn't seem to have been spreading by word of mouth among the geyser gazing community either.

Why is Bead more regular some years than others?

The observed preplay cycles suggest an explanation for why Bead can be regular as clockwork some years, markedly irregular in others. The author believes that Bead *attempts* to erupt during the first convection episode of every interval, which in recent years happens around the 30– to 32–minute mark. During the June 1994 data collection period, Bead succeeded in erupting on 55% of its first tries and about 90% of its second tries.

It would take only the tiniest change in the amount of energy available to the geyser to dramatically alter the odds of the first convection episode leading immediately into an eruption. It is very believable that there could have been years in the past when eruptions happened on the first try almost every time, or at least more like 80 or 90% of the time. (Marler's twenty identical intervals would not be a statistically significant anomaly, if Bead's success rate on the first try exceeded 86% in 1958.)

The concept of a geyser recharging quietly for much of its interval, then having a series of evenly spaced "hot periods" during each of which it has some chance to erupt, is familiar to geyser gazers. Classic examples include Grand, Oblong, Atomizer, and Fan and Mortar Geysers in the Upper Basin, and Pocket Geyser in the Lower Basin. Commonly the chance of an eruption is very low the first few cycles, and then rises until the chance of an eruption during the next cycle approaches 50%. The only difference here is that Bead's chance of erupting isn't so very low during the first cycle.

Bead tends to be associated in people's minds with the other highly regular and predictable geysers. But its behavior is actually quite different: Daisy, for instance, when having short and regular intervals slowly fills, begins preplay, and erupts right around the time it achieves overflow, without any cyclical pattern to the preplay. Castle's major eruptions are sometimes preceded by a few false starts or even an hour of "sloppy play", but there is no clear tendency for each false start to be followed by a fixed–length pause before another attempt.

Editorial Note: This was not true in 2004, when Daisy was erratic in its intervals and frequently was seen to undergo "false" or "aborted" eruption starts.

Bead also doesn't display two completely different types of eruptions as some bimodal geysers do, such as Narcissus.

In years to come, it will be interesting to see whether Bead returns to always erupting on the first cycle, or starts to frequently wait for third or subsequent cycles.

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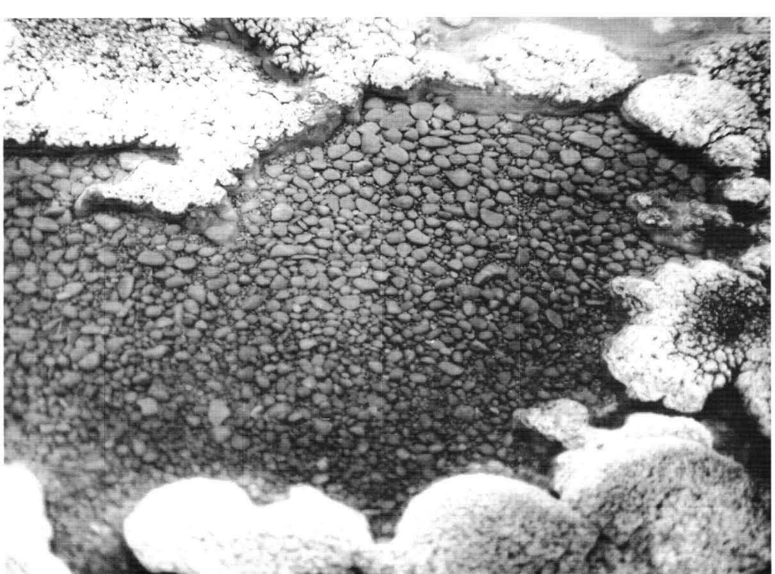
OFVC log book, 1994 and 2002, Handwritten log book of geyser data maintained at the Old Faithful Visitor Center.



"Geyser eggs" similar to the ones shown in this photograph led to the naming of the Lower Geyser Basin's Bead Geyser.

Although labeled as **Geyser Eggs near Sawmill Geyser**, the gray–green coloration of this hand–tinted lantern slide (Haynes #14016) implies that some other location is shown, perhaps Artemisia Geyser.

Geyser Activity in the Kaleidoscope Group Lower Geyser Basin

With Comments on Activity of Selected Geysers in the Sprinkler Group

by Mike Keller

Abstract

The Kaleidoscope Group of geysers is one of Yellowstone's most dynamic and changeable clusters of hot springs, but it is difficult to study because of restricted access. Here the group's recent geyser activity is described, as well as the activity of selected geysers in the nearby Sprinkler Group.

Introduction

The Kaleidoscope Group continues to be one of the most dynamic in all of Yellowstone. The activity observed in this area since 1988 is unprecedented in Yellowstone's documented history. When I began my study, there were 26 "main" springs in the area. Since then, another nine have broken out, six in areas where no vent was previously known, so the dynamics in the area can change at any time. Several of the geysers in this area erupt to heights of 20 feet or more.

With permission, I have been studying the features in the Kaleidoscope Group since the fall of 1988. Access into the Kaleidoscope Group requires advance approval from the National Park Service. Given this area's high visibility from the main highway and the Fountain Paint Pot trail, access is only allowed at night or in the early morning hours. All visitors must either be volunteers or employees of the National Park Service, or have a valid research permit with written permission to enter the area.

For those without such permission, perhaps the best vantage point from which to watch this fascinating area is the overlook above Fountain Geyser. From there, you can easily see all parts of both the Kaleidoscope Group and the Sprinkler Group.

1A. Kaleidoscope Geyser

Kaleidoscope continues to be one of the largest geysers in the entire group. Beginning in 1988, when it awoke from a long dormancy, it has continued to behave in a manner never seen or documented before. Kaleidoscope lies within a large basin measuring 16 feet by 25 feet. Within this basin are a number of geyserite "biscuits," implying a prehistoric period of activity with much higher water levels than have been seen in the last 17 years. In the center of this large basin is Kaleidoscope, its vent measuring 3 feet by 4 feet.

Since 1994, Kaleidoscope has been cyclic with long periods of activity followed by long pauses in activity. When it is active, the water level in its vent is within three inches of overflow. A few minutes before it erupts, the water will rise and boil up

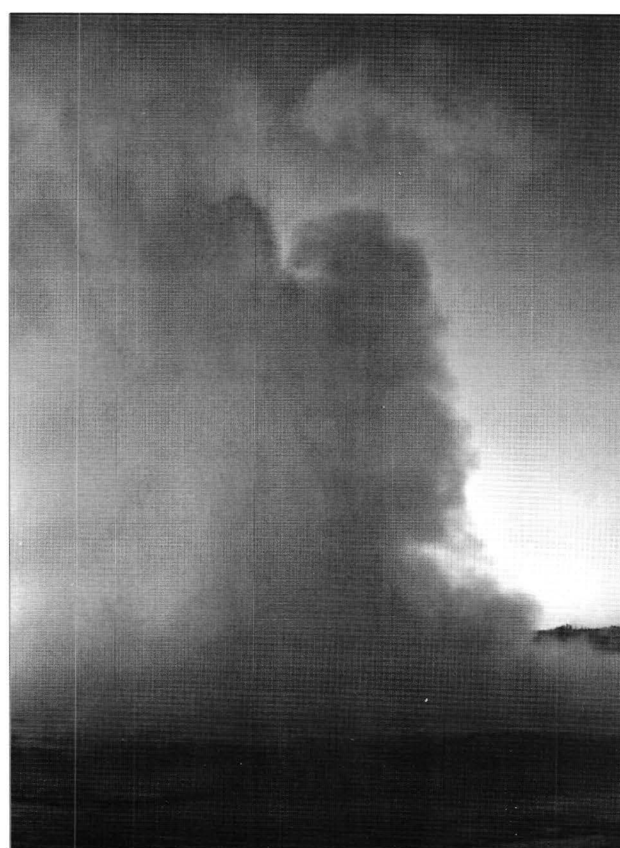
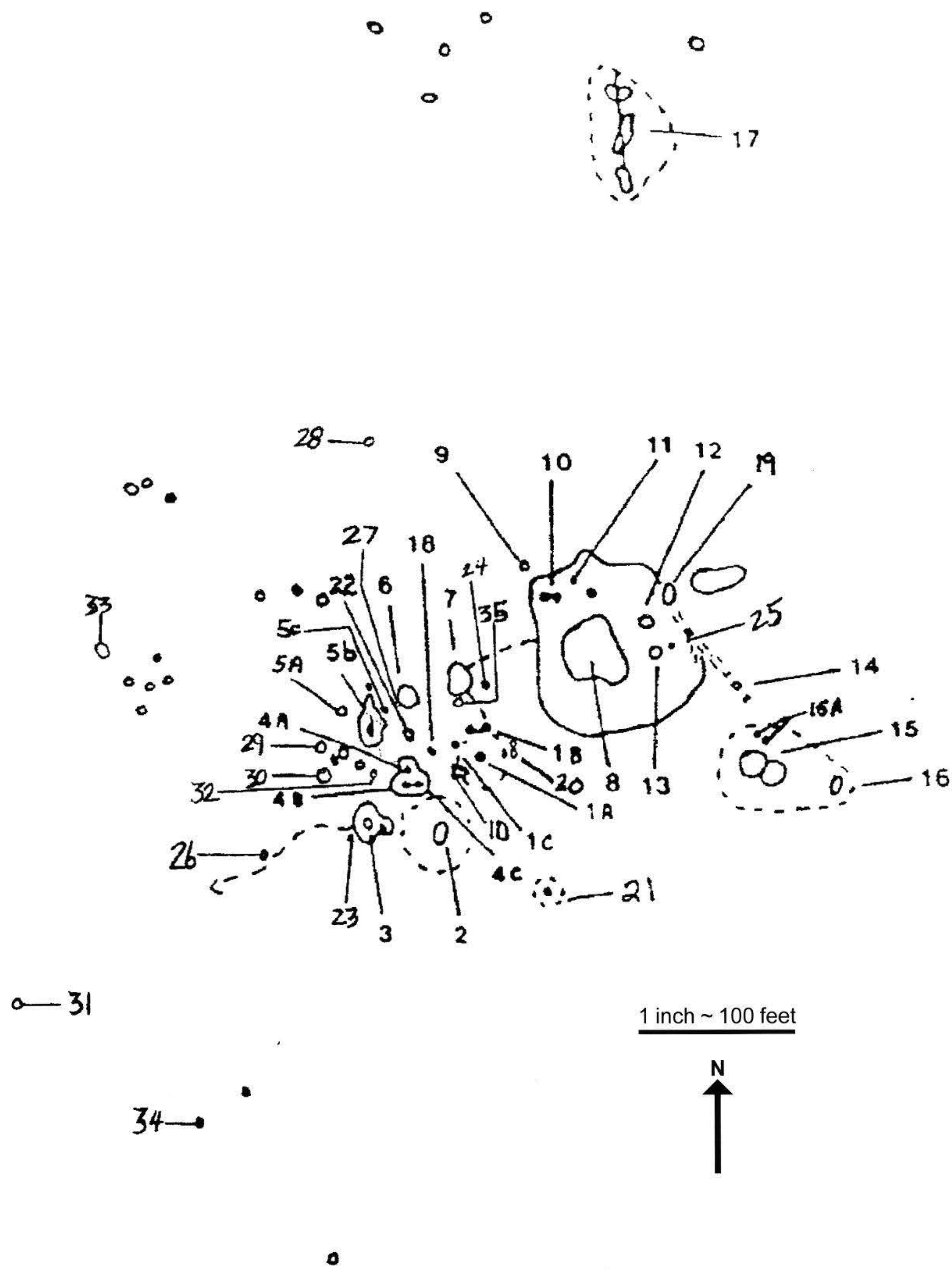


Figure 1. Kaleidoscope Geyser, an initial eruption in August 1990. [photo by Mike Keller]



Sketch Map of the Kaleidoscope Group. Map numbers correspond to the numbered spring descriptions in the text and in Table I. [Original by Rocco Paperiello, most recently updated by Mike Keller on August 20, 2004]

Table I. Summary of Geyser Activity in the Kaleidoscope Group, 2003–2004

Name (number)	Interval	Duration	Height (feet)	Comments
"Blowout Geyser" (6)	dormant	minutes	10 to 50	
"Collapse Geyser" (5b)	dormant	15–45 sec	20 to 40	
"Coral Spring" (22)	dormant	4 to 7 min	8	
Deep Blue Geyser (8)	18 to 65 min	3 to 7 min	1 to 40	Exchanges w/12 and 13
Drain Geyser (7)	4 to 70 min	5 to 15 sec	1 to 100	Cyclic–varies w/ Kaleidoscope
The "Firehose" (14)	8 hrs to days	30 min to weeks	6 to 25	Exchanges w/12 and 13
Honeycomb Geyser (15)	12 to 60 hrs	7 to 25 min	15 to 50	
Honey's Vent Geyser (16)	12 to 35 min	5 to 8 min	5 to 15	
Kaleidoscope Geyser (1A)	1 to 90 min	25 to 60 sec	40 to 110	Cyclic–varies w/ Drain
Old Surprise Spring (17)	near steady	near steady	1 to 3	Subterranean
"Three Crater Geyser" (4)				
UNNG (4a)	dormant	10 to 30 sec	10 to 50	
UNNG (4b)	hours	hours	1 to 10	
UNNG (4c)	rare	varies	3 to 6	
UNNG (1b)	20 to 120 min	3 min	5 to 30	
UNNG (1c)	dormant	seconds	2	Buried in 1991
UNNG (1d)	dormant	seconds	1	Pressure pool for Kaleidoscope
UNNG (2)	dormant	unknown	unknown	
UNNG (3)	15 to 35 min	6 to 12 min	3	
UNNG (5a)	dormant	perpetual	1	
UNNG (5c)	dormant	5 to 10 min	inches	
UNNG (9)	perpetual	perpetual	1 to 3	
UNNG (10)	near steady	near steady	1	
UNNG (11)	15 to 40 min	5 min	1 to 3	
UNNG (12)	hours	20 to 30 sec	70 to 140	Exchanges w/ Firehose
UNNG (13)	min to hrs	14–29 sec	3 to 40	Exchanges w/ Firehose
UNNG (15a)	12 to 60 hrs	hours	1	
UNNG (18)	days	hours	1 to 4	
UNNG (19)	dormant	10 to 40 sec	10 to 50	
UNNG (20)	30 min to hours	2 min	1	
UNNG (23)	perpetual	perpetual	1	
UNNG (24)	perpetual	perpetual	1 to 2	
UNNG (25)	perpetual	perpetual	1 to 4	
UNNG (29)	dormant	1 to 2 min	5 to 12	
UNNG (30)	dormant	6 to 8 min	10 to 25	
UNNG "NTFL" (31)	4 to 12 min	seconds	10 to 40	
UNNG (32)	dormant	1 to 4 min	1 to 5	
UNNG (34)	dormant	steady	2 to 8	
UNNG (35)	4 to 15 min	2 min	4 to 8	

several feet. During this boiling, the pool suddenly domes, and explosive rockets of water shoot from 40 to 80 feet into the air. Eruptions last about a minute. Sometimes there can be a second or third eruption following the initial within 2 to 5 minutes. During the eruption, the water drains to the east and west, into UNNG 2 and Drain Geyser. Once the series is done, the water level will drop back to its pre–eruption level. The interval between series varies from 30 to 90 minutes. The total duration of an active series can vary from 4 to 36 hours. Eruptions early in a series, following a long period of inactivity, are usually the strongest. I have seen eruptions as high as 110 feet in 2003 and 2004.

When Kaleidoscope is dormant or between series, the water in its vent is normally a foot or more below overflow. These pauses between active series can vary from 4 to 24 hours. During these times, nearby Drain Geyser is usually full.

1b. UNNG (Unnamed geyser)
While the activity from 1b has changed over the past 17 years, it is still a reliable indicator for activity in nearby Kaleidoscope Geyser, and so has been called "**Kaleidoscope's Indicator**." In the late 1980's it would start erupting to a few feet a couple of hours before Kaleidoscope would start a series. A thick sinter shelf covered its vent at that time. In the early 1990's, the shelf was broken away and the geyser began erupting vertically to as high as 30 feet. This activity has remained relatively unchanged. In 2003 and 2004 the intervals between eruptions in UNNG 1b varied from 20 to 120 minutes, and the eruptions would last about 3 minutes when Kaleidoscope was active. When Kaleidoscope was inactive, no eruptions were seen from 1b.

1c. UNNG
This geyser's vent was filled in with gravel during the powerful activity of Drain Geyser in 1991. A warm depression remains, but there has been no activity from this feature since it was buried.

1d. UNNG
This feature was given the name "**Triangulum Spring**" by George Marler in the 1940's. It is located 14 feet west of Kaleidoscope. Over the years it has been an excellent indicator for activity from Kaleidoscope. The water levels in this feature and in Kaleidoscope are always within an inch of each other. Unless the water level in this vent reaches a point about 7 inches below overflow, Kaleidoscope will not erupt. During eruptions of Kaleidoscope this vent is flooded with water and acts as a drain. While 1d was known to have small eruptions in 1991, I have not seen activity from it since then.

2. UNNG
This feature was a large geyser in the early 1970's. A large circular berm of old broken sinter is still evident today. This geyser has not been active during the past 15 years. I have never measured its temperature above 148°F. Since the late 1990's the vent is slowly being filled with gravel with each eruption of Kaleidoscope.

3. UNNG
This is one of the few geysers in the area that discharges water away from the entire group instead of into any nearby feature. I have never seen it dormant in the 17 years I have been studying this area. Intervals in 2003 and 2004 varied from 15 to 35 minutes. During the eruptions, which last from 6 to 12 minutes, there is heavy overflow. The largest bursts reach about 3 feet. Between eruptions, the water level in this geyser is below overflow.

4. "Three Vent Geyser"
This geyser lies about 30 feet west of Kaleidoscope. Its basin is roughly gourd–shaped and contains three vents. In the early 1990's, one of its vents (4A) was frequently active with eruptions reaching up to 50 feet. Activity was also seen from the other vents in the crater. Since the late 1990's, most of the activity has been confined to 4B.

4A. UNNG – No eruptive activity was seen in 2003 or 2004. At most observed times, the water from vents 4B and 4C was flowing into its crater.

4B. UNNG – This geyser was active throughout 2003 and 2004. The intervals between eruptions are many hours long. When it is inactive, the water level is down in its crater several inches. When it is active, it overflows into the other two vents. Eruptions consist of periods of steady roiling in the crater reaching 1 to 4 feet, with some play reaching as much as 6 to 10 feet.

4C. UNNG – The only time I found this geyser active was between September 14 and September 22, 2003, when it was steadily erupting silt–laden water to about 3 feet and was overflowing into the vents of 4A and 4B. The rest of the time, the water level rested a few inches below overflow.

5A. UNNG

This feature serves as an excellent example of why it is dangerous to be off trail in a thermal area in Yellowstone. The ground in all directions around this feature is nothing more than a thin crust of old sinter. It is not more than 3 inches thick and in many places is as thin as half an inch. In the center of this thin sheet is a small opening, and about 18 inches below it is the actual vent. It played as a perpetual spouter while UNNG 4C was active in September of 2003. The eruption erched up to ground level. That was the only recent time I observed activity from it. Otherwise there was hot water in the vent, but I never found 5a in eruption.

5b. "Collapse Geyser"

Collapse Geyser was a long–buried feature until it began erupting through sinter–cemented gravel in June 1990. Over a two month span the activity eroded and caused the surrounding ground to collapse into the developing crater, which contained two vents. The eruptions were very powerful, reaching as high as 40 feet and being as wide as 120 feet! When sinter slabs above the western vent collapsed, they blocked the vent and it no longer played with the other. Collapse has been dormant since 1999.

5c. UNNG

Beginning in the fall of 2001, the ground just north of "Collapse Geyser" began having periods when a fumarole would puff heavily. With this, a small, buried vent just inside the basin would start pouring water into "Collapse." This activity continued in 2002 and 2003 but was not seen in 2004. The interval between these events was frequent, usually being 15 to 25 minutes. The activity would last from 5 to 10 minutes. Once the water level in "Collapse" rose high enough to cover the vent of 5c, the eruption would stop. While splashing water could easily be heard from the covered area, this feature has yet to break through the debris over its vent.

6. "Blowout Geyser"

No eruptive activity has been seen from this feature since 1991. The water in its crater slowly rose and fell, but it always remained three to six feet below overflow unless nearby Drain Geyser was active. Then it would fill, but only because of the overflow from Drain's eruptions.

7. Drain Geyser

Throughout the period of observation, Drain Geyser was active. Its behavior is closely tied to that in Kaleidoscope and UNNG 1B. When Kaleidoscope is in an active series, the water level in Drain will rise and fall every 30 to 90 minutes. When Drain is full, it can have single (non–series) eruptions that reach 15 to 40 feet and occasionally 80 feet high. When Kaleidoscope is in a pause between its active series, Drain remains full, overflowing and filling "Blowout Geyser" until the two are connected at the surface, creating one large pool of water. Drain's intervals are shorter during this time, usually varying from 4 to 70 minutes, with most being from

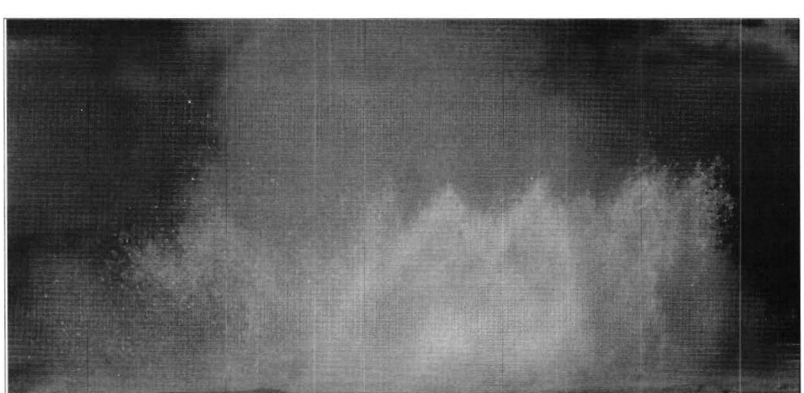


Figure 2. "Collapse Geyser" in eruption in August 1991. [Photo by Mike Keller]

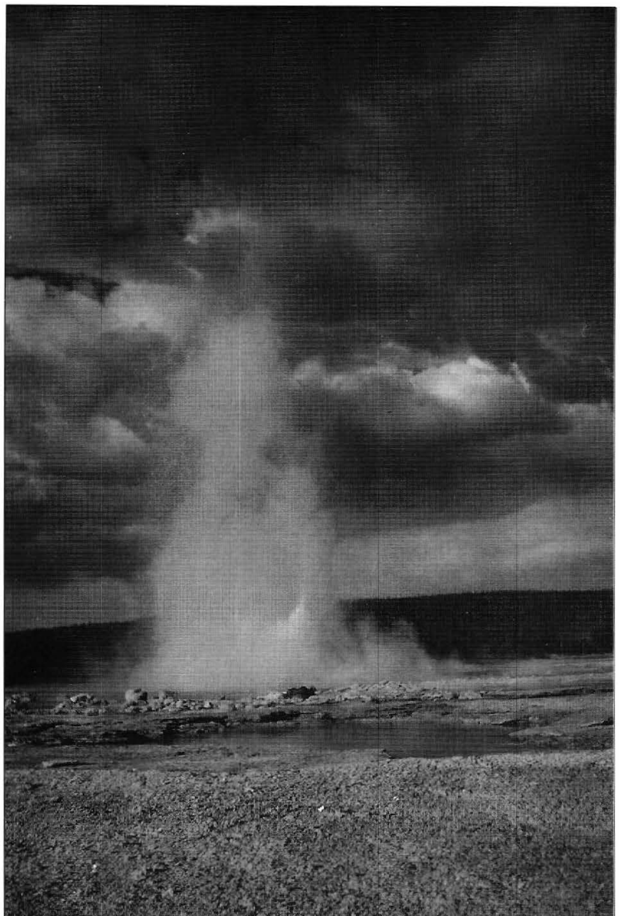


Figure 3. A powerful eruption of **(Kaleidoscope) Drain Geyser** in September 1991. [Photo by Mike Keller]

20 to 30 minutes long. These eruptions tend to be more powerful, with many bursts reaching 30 to 70 feet and rarely as high as 100 feet. Oddly, however, Drain can also go into periods where all it will do is roil up only a foot or two instead of having the powerful bursts. I have seen no correlation between these weakened eruptions and the start of a series in Kaleidoscope.

8. Deep Blue Geyser

The pool of well–named Deep Blue Geyser is one of the prettiest in all of Yellowstone. Both the "Firehose" and Kaleidoscope Geyser closely affect its activity. I have never seen Deep Blue active when the "Firehose" was dormant. When Kaleidoscope is active, if either geyser is ready to erupt and the other plays first, then there will be a 10 to 20 minute pause in the activity of the other geyser.

Prior to mid August of 2003, Deep Blue erupted every 18 to 65 minutes, with 35 minutes being the average. The eruptions lasted either 3 minutes or 7 minutes. During the first few minutes of an eruption, there would be a series of powerful thumps. With these thumps would come large, doming bursts of water reaching from 1 to 40 feet high. If the eruption lasted longer than 3 minutes, the play in Deep Blue would change from bursting to steady boiling, similar to the eruptions of Oblong and Artemisia Geysers in the Upper Geyser Basin. From mid August of 2003 until early June of 2004 I never saw any activity from Deep Blue. With the reactivation of the "Firehose" in 2004, Deep Blue would occasionally erupt when the "Firehose" was on.

9. UNNG

This feature is the largest of the many small perpetual spouters that are found on the west and northwest sides of Deep Blue's basin. Its play reaches from 1 to 3 feet. When the water level in Deep Blue is low enough to expose this vent, it acts as a powerful fumarole sending spray several feet into the air.

10. UNNG

Along the northeast side of Deep Blue is a fracture about 40 feet long. Along this are several small perpetually erupting vents. Most of the time they

Figure 4. Deep Blue Geyser, July 2002. [Photo by Mike Keller]

are erupting through a few inches of water of Deep Blue Geyser's pool. UNNG 10 is the vent farthest east on the fracture. The only time it would pause was during the first few minutes following a 6–plus minute eruption of Deep Blue. Its play reaches about 1 foot.

11. UNNG

Going from east to west, this feature is the third vent along the same fracture that includes UNNG 10. This is the only periodic geyser on this fracture I have seen not affected by Deep Blue. In the early 1990's it could vary from true geyser to perpetual spouter. Intermittent activity was seen from it in both 2003 and 2004. The intervals varied from 15 to 40 minutes, with eruptions lasting about five minutes and reaching from 1 to 3 feet.

12. UNNG

This geyser is the largest I have seen in the Kaleidoscope Group. Its vent lies within the east side of Deep Blue Geyser's basin. Both this geyser and UNNG 13 exchange function with Deep Blue and the "Firehose." When active, UNNG 12 is very irregular. It can be seen several times on one day, then go many days or weeks before erupting again. The only indicator I have seen for it is steady boiling over its vent. I have never seen it erupt unless this boiling is present. I have also been near this geyser for many hours while it is boiling, only to be disappointed by not seeing an eruption. Eruptions are very quick, lasting from 20 to 30 seconds. The play is angled slightly to the southeast and reaches from 70 to 140 feet high. The column of water is so massive that many eruptions flood the gravel area south of Deep Blue. Prior to August 2003, UNNG 12 was dormant, but it was then active for the remainder of 2003 and through all of 2004.

13. UNNG

This feature also lies within the basin of Deep Blue Geyser, its vent being only about 4 feet south of UNNG 12's crater. Since the late 1980's, it has been known to exchange function with the nearby "Firehose" and Deep Blue, being active when Firehose is not. When UNNG 13 became active in August of 2003, the eruptions came in a series, with the interval between series being several hours long. Once a series started, it would erupt every 5 to 10 minutes and reach 3 to 40 feet high. It was briefly dormant in June of 2004 but was active again by that August. Reflecting the frequency of change in the area, this active phase by UNNG 13 had series separated by as little as 15 minutes, rather than hours. Occurring at intervals of just 1 to 1½ minutes and having durations of 14 to 29 seconds, there were five to seven eruptions per series.

Figure 5. A major eruption by **UNNG 12**, the tallest geyser in the Kaleidoscope Group, July 1991. [Photo by Mike Keller]

14. The "Firehose"

In the spring of 1988, the "Firehose" was first seen playing near the east side of Deep Blue Geyser. The steady play reached as high as 50 feet. In the early 1990's two new vents formed in the gravel around the original vent, and through the rest of that decade they steadily enlarged their craters. As these vents grew, the energy coming from the

Figure 6. "**The Firehose**," as it appeared in July 1990. [Photo by Tom Dunn]

"Firehose" lessened. Today the main vent jets 10 to 25 feet high at an angle toward the north, while the newer vents burst to about 6 feet.

In 2003, the "Firehose" was steadily active until the middle of August. During that time, Deep Blue Geyser was also active. With the cessation of activity in the "Firehose," both UNNG 12 and UNNG 13 reactivated. From mid August 2003 through early June 2004, "Firehose" was never seen in eruption. Starting in early June of 2004, and continuing for the rest of the year, the "Firehose" would have periods of activity lasting several minutes to hours. During these active phases, UNNG 12 and UNNG 13 would fall dormant, the water level in Deep Blue's pool would slowly drop several inches, and Deep Blue would occasionally erupt. When the "Firehose" stopped, UNNG 12 and/or UNNG 13 would erupt within a short time, and any activity in Deep Blue would cease.

15. Honeycomb Geyser

Honeycomb Geyser continues to be one of the largest geysers in the Kaleidoscope Group. It is connected with nearby Honey's Vent Geyser and UNNG 15a. Honeycomb sits within a large circular basin, roughly 80 feet in diameter. In the center of this basin are two vents, one about 18 inches higher than the other. Following a major eruption, both of these vents are calm. A few hours later the upper vent will start boiling and overflowing into the lower vent. As an eruption of Honey's Vent approaches, the overflow from the upper vent will get heavier and the boiling will become stronger. If Honey's Vent starts, then the upper vent will stop boiling and drop a few inches, ending the overflow into the lower vent. If the vents of nearby UNNG 15a begin erupting and the interval in Honey's Vent suddenly becomes erratic, then there is a good chance that Honeycomb will erupt within a few hours. Over the past 15 years, the intervals between eruptions have varied from 6 hours to 10 days or more; in 2003 and 2004 they ranged from 12 to 60 hours.

At the start of an eruption the upper vent begins bursting to 15 to 30 feet high and the water level rises to quickly fill the entire basin. Over the next 7 to 25 minutes, this vent will continue to have a series of bursts every 30 seconds or so. The play toward the end of eruptions with longer durations can reach as high as 50 feet. Although the lower of the two vents has been known to erupt (1988, 1989, and 1993), it was not seen in 2003 or 2004.

Figure 7. Eruptive activity in one of the new outbreaks at "**The Firehose**" in June 1997. [Photo by Mike Keller]

15A. UNNG

This feature is a collection of several small

Figure 8. Honeycomb Geyser in a major burst, June 1998, with GPS mapping volunteers visible at the lower right. [Photo by Mike Keller]

vents within the northern side of Honeycomb's basin. When dormant they are merely cracks in the geyserite, but in the past several years they have served as a fairly reliable indicator for Honeycomb Geyser — I have never seen an eruption of Honeycomb begin without activity from these vents. In the past 10 years the duration of 15a's activity has varied from year to year. During 2001, when Honeycomb was very active, I never saw these vents on for longer than 3 hours without resulting in an eruption by Honeycomb. However, with the longer intervals of Honeycomb in 2003 and 2004, these vents could erupt for several hours before an eruption of Honeycomb finally took place.

16. Honey's Vent Geyser

Eruptive activity in Honey's Vent has remained unchanged over the years. While the intervals become erratic a few hours before an eruption of nearby Honeycomb Geyser, they typically vary from 12 to 35 minutes. The eruptions are violent, with jets of water forcefully shooting in all directions and reaching from 5 to 15 feet high. As an eruption progresses and the water level in Honey's Vent drops, the play progressively becomes angled to the east. The only time Honey's Vent is not active is for the first few hours following an eruption of Honeycomb.

17. "Old" Surprise Spring

This feature was once one of Yellowstone's largest geysers, but it has not had a major eruption in over 100 years. It contains three vents along a fracture within a larger, old basin. The southernmost crater is filled with gravel and no longer has visible water in it. The middle crater is the largest of the three. Cyclic superheated geyser activity that boils up to a few feet above the pool was seen from it in 2003 and 2004, and this is likely the cause of billowing puffs of steam that observers occasionally report; eruptions higher than the surrounding ground level have not been seen. Also, I measured the temperature in this vent as low as 130°F (in 1992 and 1996). When the middle vent was active, the third (northernmost) vent was a small perpetual spouter.

18. UNNG

This feature lies halfway between Kaleidoscope Geyser and UNNG 3. Over the past 15 years I have never observed it to be dormant. It is only active during the occasional hours–long pauses when neither Kaleidoscope nor "Drain" erupts. At most times the eruptions are subterranean, but on occasion I have seen it spray droplets about 3 or 4 feet above ground level.

19. UNNG

This geyser lies on the same fissure as the "Firehose." It is the northernmost vent on this fis-

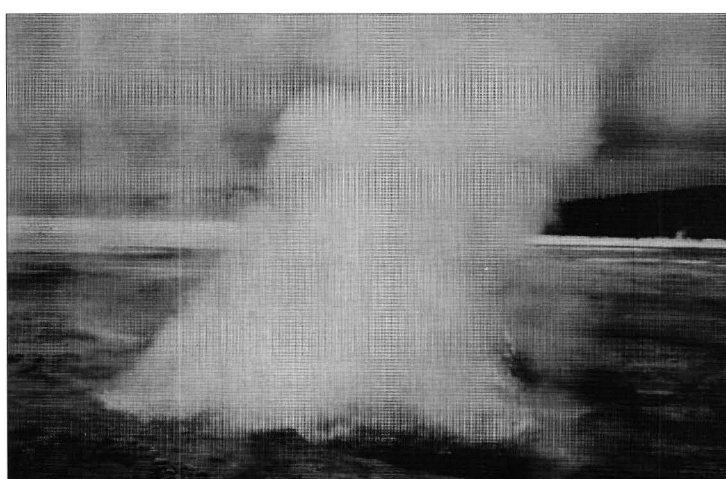


Figure 9. A typical eruption of **Honey's Vent Geyser**, December 2001. [Photo by MikeKeller]

sure and is located on the very edge of Deep Blue Geyser's basin, from where it overflows to the north and east. In the early 1990's this feature would be active when the "Firehose" was dormant. Since dormancy started in 1993, the crater has filled with gravel and is now difficult to find.

20. UNNG

Prior to 2001 this feature was a small perpetual spouter, but beginning that year it would erupt only during major eruptions of nearby UNNG 1b. This trend continued in 2003 and 2004. During minor eruptions of 1b, the water level will rise several inches within the vent of UNNG 20, but it will quickly recede if 1b does not erupt. When 1b does start a major eruption, however, UNNG 20 will begin splashing to a little over 1 foot high. Following the eruption, the vent drains completely.

21. UNNS (Unnamed spring)

This spring is located in the gravel–covered area 90 feet southeast of Kaleidoscope. It is nothing more than a small depression that is occasionally filled with tepid water. I have never seen evidence of eruptive activity from it.

22. "Coral Spring"

Although this spring has been active as a geyser in past years, no eruptions were seen from "Coral" in 2003 or 2004. During active cycles of Drain, when Drain was high enough to overflow into and fill "Blowout Geyser," "Coral" would also be filled. Also, "Coral's" basin is empty whenever Kaleidoscope is active.

23. UNNG

This small perpetual spouter lies just southwest of UNNG 3, next to its main runoff channel. I have never seen it dormant. The play reaches about 1 foot high.

24. UNNG

This small perpetual spouter lies just east of Drain Geyser's vent. When the water level is low in Drain, it plays as much as 2 feet high. When Drain is active and full, the vent of UNNG 24 is underwater and feebly splashes through Drain's pool to a few inches.

25. UNNG

Near the north end of the same fissure that includes the "Firehose" are six small vents. Some degree of activity from them was observed as early as 1982. When the "Firehose" is inactive, up to 4 of these vents can erupt. The largest sends spray up to about 4 feet.

26. UNNS

UNNS 26 is a crater about 3 feet deep that formed along the runoff channel about 40 feet from UNNG 3 in the winter of 1997. During eruptions of UNNG 3, some of its water flows into this crater. I have never seen it erupt, but it steadily puffs steam.

27. UNNS

This spring lies on the west edge of "Blowout Geyser." I have never seen it erupt, but the jagged nature of the crater implies that it formed explosively. When overflow from Drain fills "Blowout," their combined flow then fills this spring. When "Blowout" is drained, this feature still contains water but at a level about a foot below overflow.

28. UNNS

This spring is 110 feet northwest of Deep Blue Geyser. It has not been active in many years. I observed water in it in 1989 and 1990, but by 1991 it had dried up. During recent winters I have not seen it emit steam even on the coldest days.

29. UNNG

During July and August of 1999, new hot ground began forming west of "Three Vent Geyser." In early September, the first of two new geysers started to form there. UNNG 29 definitely was a geyser sometime in the past. As it eroded away the gravel and sinter over its vent, an old crater became clearly visible. In 1999 and early 2000, it would erupt every 10 to 20 minutes and reach as high as 5 to 12 feet. When nearby UNNG 30 broke out in 2000, UNNG 29 would simultaneously erupt to a few feet. It has been dormant since the fall of 2001.

30. UNNG

In the early summer of 2000, a second geyser, UNNG 30, formed in the area west of "Three Vent Geyser." After its emergence, UNNG 30 com-

Figure 10. Author Mike Keller standing next to the jagged crater of **UNNG 29** shortly after its emergence, August 1999. The crater of **UNNG 3** is in the background. [Photo by Cynthia Keller]

pletely took over the activity in the area and all independent activity in UNNG 29 came to an end. The eruptions were much larger than its neighbor's, frequently reaching 10 to 25 feet high. The intervals were erratic, but were normally between 1 and 2 hours long. This feature stopped erupting in August 2001 and has not been active since.

31. UNNG ("NTFL")

Near the tree line far to the left of the main cluster of Kaleidoscope Group springs is "NTFL." This name is an acronym for "New Thing Far Left." Prior to 1998 there was no indication of any vent or hot ground in this area. The crater formed sometime during the winter of 1999–2000. Scattered around the crater were broken slabs of sinter and superheated water was churning in the vent about 15 feet below ground level. During 2000 NTFL erupted every few minutes and reached 10 to 40 feet. In the fall of that year it went dormant and was not active again until 2002. Since then it has continued to erupt in a manner similar to that of 2000, with intervals of 4 to 10 minutes, followed by seconds–long eruptions that reach 10 to 40 feet above ground level. The eruption is angled to the west, towards the trees.

32. UNNG

With the outbreak of UNNG 30, a small area of ground 14 feet to its east started sizzling. Over time, this feature formed at that spot. In 2001 and 2002 it would erupt as high as 5 feer in concert with UNNG 30. As the activity continued, it excavated an old vent covered by about 2 feet of compacted sinter and gravel. In the spring of 2003 it was still weakly active despite UNNG 30 being dormant, but by late June of that same year it too was dormant. It has not been seen in eruption since.

33. UNNS

West of the main group of springs in the Kaleidoscope Group are a number of old craters. All have been inactive for many years, but UNNS 33 still steams heavily. No water has ever been seen in this feature.

34. UNNG

About 120 feet southwest of UNNG 3 is a collection of small vents. In the summer of 2003, one was designated as UNNG 34 when it took over the activity for the entire area. It erupted perpetually from 2 to 8 feet high until a new steam vent broke out next to it in June 2004. The steam vent has remained active since, with no further play being seen from UNNG 34.

35. UNNG

A new vent about 2 feet in diameter broke out in the spring of 2003 on the southern side of Drain Geyser. Throughout 2003 it erupted perpetually to a height of about 2 feet. In January of 2004 the vent enlarged further and the play changed from perpetual to periodic. The crater on January 22, 2004 was 3.5 feet in diameter, and on August 11, 2004 it had enlarged to nearly 5 feet in diameter. Intervals have varied from 4 to 15 minutes. The eruptions last about 2 minutes and reach as high as 8 feet.

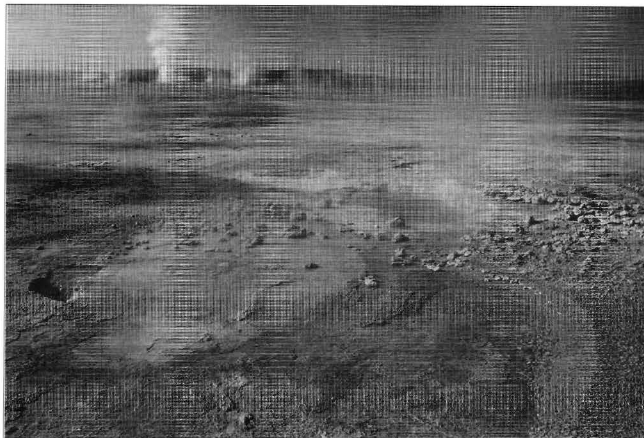


Figure 11. The 2002 outbreak in the Angle Complex, in July 2002 shortly after it formed. Note the angular debris that was thrown to the southwest by the explosion. [Photo by Mike Keller]

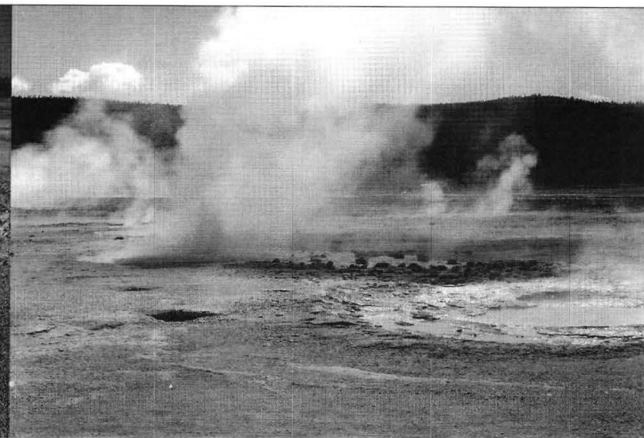


Figure 12. The 2002 outbreak in the Angle Complex in eruption, July 2002. [Photo by Mike Keller]

Sprinkler Group

Although I haven't spent as much time in the Sprinkler Group as in the Kaleidoscope Group, I have made observations of some of the major features in the area. Here is a quick overview of the activity.

The Angle Complex

A series of new vents began breaking out in the Angle Complex starting in the spring of 1999. Between then and the spring of 2004, at least 4 new geysers broke out in and around this area. The first two outbreaks were small, but the third, which took place in March 2002, completely took over the activity for the entire area. Several hundred pounds of rock were thrown across an area roughly 50 feet wide and 30 feet long. Every 15 to 45 minutes, muddy water would erupt from the new outbreak to as high as 25 feet. Many times, rocks and broken sinter could be seen being tossed out of the crater. This new geyser was very active in 2002 and 2003, but went dormant in the early spring of 2004 when a fourth vent broke out in the area. While the new vent has been very erratic, its eruptions can reach as much as 30 feet. Each of the new outbreaks has been east of Angle Geyser. In fact, Angle was partially buried by the first outbreak in 1999. I have not seen it active since 1998, and the vent has been lined with orange cyanobacteria since then.

West Sprinkler Geyser

In 2001, this geyser went dormant for the first known time since 1959. It reactivated sometime in the spring of 2003. Since then it has behaved much as it did prior to its dormancy. Eruptions recur every 5 to 12 minutes, durations of about 20 seconds and splashing bursts that reach 4 to 10 feet high.

"Little Crack Geyser"

This geyser is the tallest I have seen in the Sprinkler Group. It is located on the same fracture as "Horizontal Geyser" and Impatient Miser Geyser. It was very active in the early 1990's but has been rarely seen since, except during an eight–day span in August 2003. At that time it erupted every 30 to 180 minutes to a height of about 35 feet. Apart from that period of activity and one eruption seen on February 20, 2004, it has been dormant.

"Horizontal Geyser"

Horizontal was frequently active in the early and mid 1990s but has not played in several years. It is the easternmost feature on the fissure that also contains "Little Crack" and Impatient Miser Geysers. It was given the name "Horizontal" in jest, because it was the only geyser on this fissure to erupt a vertical column of water. When it was active, the play recurred as often as every 20 minutes, lasted several minutes and reached as high as 10 feet.

Impatient Miser Geyser

The activity in Impatient Miser has been consistent for many years. Every 90 to 120 minutes, it will have a series of eruptions. Early in the series, the interval between the eruptions is 1 to 3 minutes, but after 10 or 15 minutes the series ends with a final eruption that lasts more than 20 minutes. Once this long eruption ends, the basin drains and the geyser is quiet for 40 to 80 minutes. Eruptions are 8 to 12 feet high.

"Meadow Geyser"

On the southwest edge of the Sprinkler Group, about 140 feet from Impatient Miser Geyser and in the flats away from any other significant thermal feature, is "Meadow Geyser." I gave it this name because it is in the meadow, apart from the rest of the area. Although this geyser has had periods of dormancy over the past 15 years, it has been active since 2002. Intervals vary seasonally over the course of the year, usually being longer in the spring than in the fall. In 2003 and 2004 the spring intervals were around 90 minutes, steadily shortening to around 30 minutes by late fall. The eruptions last about 3 minutes and reach 6 feet high.

Figure 13. An eruption of **West Sprinkler Geyser** at dawn in September 1997. [Photo by Mike Keller]

Earthquake Geyser

While still superheated, this feature has not had a major eruption since 1960. At times the play can reach up to 3 feet above ground level.

Ferric Geyser and "Tangerine Spouter"

At the northwest end of the Sprinkler Group is a fissure that trends from north to south. These two perpetual spouters are located on this fissure. As the names imply, one is red in color and the other is orange in color. Both have built up small cones with highly detailed beading. I have always seen them perpetually active, the play of both reaching about 2 feet.

Acknowledgements

Permission from the National Park Service to conduct studies in this sensitive, off–trail area is highly appreciated. Also to be thanked are those who occasionally helped during field work and the contributors of some photographs used in this article.

Sources of Information

The majority of the observations cited in this article are from the personal observations of the author. Historical data has been obtained from miscellaneous unpublished National Park Service reports and from:

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Geyser Activity of Taurus Spring
and water fluctuations in the Orion Group
Shoshone Geyser Basin, Yellowstone National Park

by Clark Murray

Abstract

Taurus Spring has had a history of rare eruptions in the years since the 1959 earthquake. This activity is described, as are aspects of water level variations observed within the Orion Group of hot springs of which Taurus is a member.

Introduction

Taurus Spring is located in the Shoshone Geyser Basin in the backcountry of Yellowstone National Park, Wyoming. It is a member of the Orion Group of hot springs, in the southern part of the basin. It is at best a very rare performer. Major–scale eruptions were triggered by earthquake activity in 1959 and 1997, and occurred again (without tremors) in 2003. Much smaller minor eruptions were witnessed during the early 1970s and in 1991.

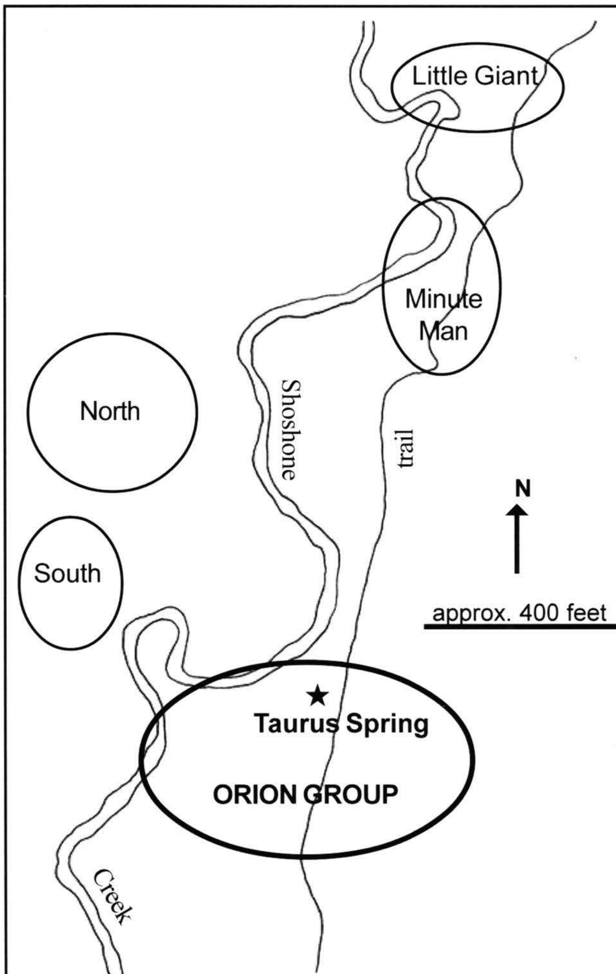
There may also be other uncommon events that can cause equally rare geyser activity. A loss of surface water and unusual water level fluctuations have been observed in the Orion Group throughout the years and these may have contributed to the activity of Taurus Spring.

Descriptions

The Orion Group is home of two of the largest and most impressive geysers located at Shoshone Geyser Basin, and two of the most impressive in all of Yellowstone. Shoshone Creek to the west, Shoshone Lake to the east, the Sulphur Hills to the North and the Camp group to the South all border the area. The group may have been named for the constellation Orion, with Union Geyser representing the belt of Orion.

Taurus Spring was named by either Gustavus Bechler or Dr. Frank H. Bradley of the Hayden Survey in 1872, then described by Dr. A. C. Peale in 1878 and Walter Weed in 1883. Although originally named Taurus Geyser, no actual eruptions were described by any of those observers. The version of the name as Taurus *Spring* is the officially approved form.

Taurus Spring is a superheated and a very deep hot spring. It is situated on a prominate mound high above Shoshone Creek. An orange–colored, raised scalloped rim surrounds the vent, and the pool is dark in color because of its great depth. It lightly overflows from a low point in the rim and is cur-



Map A. Index Map of the central portion of the Shoshone Geyser Basin. The individual named hot spring groups are schematically shown. [Map © T. Scott Bryan]

Figure 1. Taurus Spring as it normally appears. [Photo by Clark Murray]

rently one of the very few springs in the Orion Group that produces any overflow.

1959 — Post–Earthquake Activity

After the 1959 Hebgen Lake earthquake, Taurus Spring was reported as active for the first time in history. Mebane [1959] wrote:

> The general thermal activity seems to be somewhat intensified. Taurus Geyser [*sic*] now erupts to about 50 ft., its heavy discharge eroding the soil and sinter around the vent.

Given that Taurus had no previous record of eruptions of any kind, this is a remarkably brief report. How often it might have been seen playing is unknown, but it probably was active at least on October 3, when Mebane's field partner (a Mr. McIntire) photographed erupting Little Giant Geyser.

Early 1970's Minor Activity

Taurus was active for a short time in the early 1970's, when a few splashing eruptions up to 4 feet high were seen; the duration was only a few seconds and the frequency of the play was not recorded [Bryan, 2004].

Reduction of water levels in the Orion Group since 1980

Sadly and for unknown reasons, the Orion Group lost most of its water supply sometime in the late 1970's, causing the dormancy of Shoshone Geyser Basin's greatest star, Union Geyser. The surface water temperatures have remained very hot, and for a short period in the mid 1990's there were subtle signs that a limited recovery was taking place. Unfortunately, the recovery was short–lived and not very dramatic. Now the loss of water in the group is worse than it has ever has been.

1991 Minor Activity

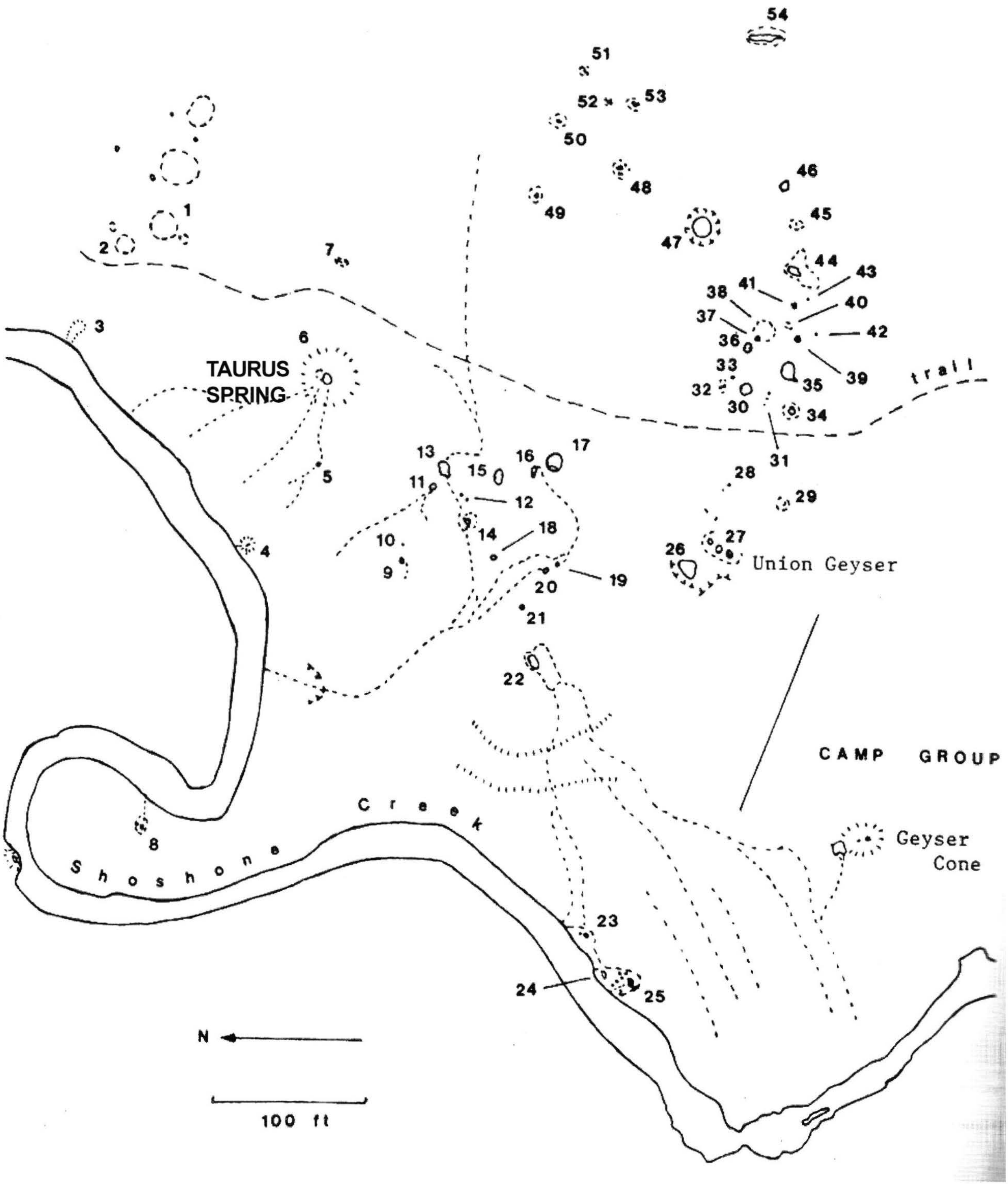
Several four–foot minor eruptions were observed in Taurus Spring throughout the day during a visit in early July 1991. A substantial increase in overflow was also noted. No full sized eruptions occurred however.

Orion Group water fluctuations in the mid–1990's

In 1995, I observed that "Sea Green Pool" (#30 on Map B) as well as several nearby features had observable water level fluctuations over the course of several hours. For example, in July 1995, the water levels changed from three–quarters full to only one inch below overflow and then dropped over the same amount of time. During that same period, Union Geyser's water level also fluctuated within its cone somewhat in synchrony with the other features on the east side of the group.

For the last half of the 1990's White Hot Spring (#35) also was observed at varied water levels, but the changes were not as rapid as those seen during 1995. At that time it was observed that the water levels fluctuated from one–quarter full to one–half full over a period of several hours. The change in water level seemed to be independent of the changes seen in both Union Geyser and "Sea Green Pool."

In 1997, White Hot had become a three-foot spouter that had cyclic increases in activity every six minutes. In 1998, I found it to be dormant but with the highest stationary water levels I've yet observed. Unfortunately, by 1999 it was still dor-



Map B. The Orion Group. Spring numbers, as referred to in the text, were devised by Rocco Paperiello [1992]. Taurus Spring was designated as #6. [Map © Rocco Paperiello]

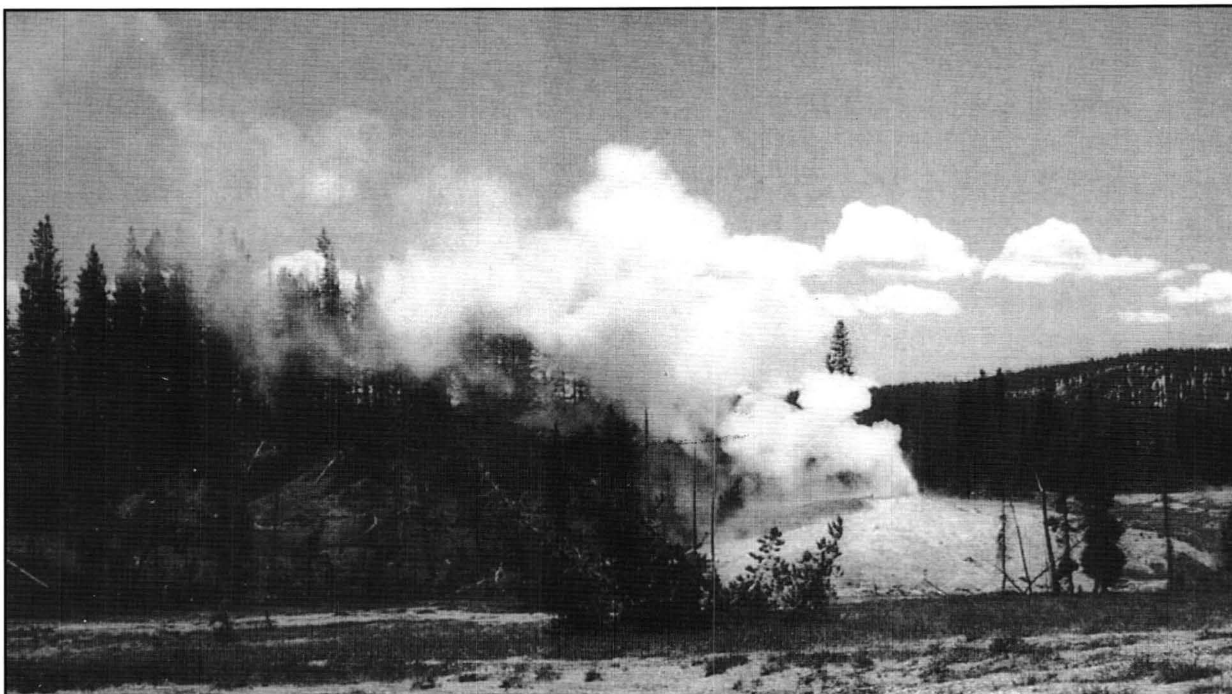


Figure 2. Taurus Spring, late in the eruption of July 4, 1997. It is all–but–certain that this is the only photograph ever taken of Taurus Spring in eruption. [Photo by Clark Murray]

mant and the water levels had dropped, exposing the shallow sinter platform. The remaining water in the neck was hot and boiling with a thumping hollow cavernous sound. The outer shallow platform was exposed and dry. The water level was very low and boiling could be heard at depth. By the summer of 2003 the activity had reduced to nothing.

In 1995, "Fifty Geyser" (#39) was found active for the first time in many years, as a frying pan–type feature spouting from its gravel filled vent. In 1997, I found it inactive, but only three days later, Jeff Cross found it in action once again. Since then I have not observed any type of activity at all. By 1998, Fifty was again buried in the gravel, and now it is almost impossible to find any trace of it.

In 1998, Marble Cliff Spring (#54) was very near overflow, but like many features that year there was no longer any intermittence in water levels, at least in the short term, such as those seen from 1995 to 1997. Water levels remained high, but stable. By 1999, the water levels had dropped and have continued to drop until the present where ultimately they have reached their lowest levels yet observed.

1997 Taurus Spring eruption series

In late June of 1997, there was a Richter magnitude 4.2 temblor on the nearby Pitchstone Plateau. Taurus awakened and was observed in eruption on the Fourth of July 1997. There was ample evidence of previous large eruptions when I arrived at about 09:00 that morning, including tepid water in the washed runoff channels and a strong fish–like odor from the dying bacterial mats. Milky–colored water in the crater was about one foot below overflow and highly superheated.

Later that day, at 12:51, I was startled by what sounded like a cracking whip. I was standing in the North Group when I looked up to see a fifty-foot high water column. Climbing rapidly, it soon reached its apex and almost immediately began to drop. The massive water column erupted as a dense solid mass of discolored gray water with no observed jetting — it was as if the entire contents of the pool was lifted as a solid body of water. The only thing I can compare it to is Strokker Geyser in Iceland. The eruption lasted less than 60 seconds. Large mounds of gravel were washed into the creek. Rocks, a small tree stump, and an old rusty pocket knife were also thrown out by the powerful eruption. I was able to snap a photo late in the eruption.

After the eruption ended a deep rumbling could be heard and pounding felt, from as far way as the North Group on the other side of the creek!

By 18:00 that evening the crater had refilled and another eruption seemed imminent. Unfortunately I was forced to leave because of approaching darkness. Markers placed that evening were found washed three days later, but by then all activity had stopped.

Figure 3. Taurus Spring and its surroundings shortly after the eruption of July 4, 1997. Note the heavily washed areas and the large amount of debris, including the large log to the right of the crater, that was expelled by the eruption. [Photo by Clark Murray]

1998 Orion Group "west side" resurgence

In the following summer (1998), much of the energy from the east side of the Orion Group had shifted to the west side. The water levels, especially west of the trail had risen to the highest seen in many years.

Kitchen Spring was hotter, and Black Boiler and "Fleur de Lies Spring" were overflowing. With this increase in activity, there were a few springs that did not recover. Strangely, they were often right next to the ones that did. Taurus Spring had obviously not erupted since the previous year, although it was having some nice boiling periods.

Union Geyser's water levels were higher than the preceding year, now down only two feet in the main vent and occasionally splashing to near the rim. That summer while investigating the Orion Group I kept hearing a deep pounding noise, and then it would be gone. I could find nothing in the group that seemed capable of producing such a noise. I started to think that maybe I had been out in the sun a little too long. That's when I re-checked Union Geyser and found the water was not boiling! A few seconds later the boiling and the sound like a drum resumed. One to two minutes of heavy boiling that could be heard as far away as Taurus, followed by thirty to forty-five seconds of quiet. Therefore Union was active as a geyser, albeit a very small one.

Jeff Cross reported on the "geysers" Internet list-server:

> I too, almost missed the activity in Union. I checked it, found the water levels higher, especially in the North vent, saw the boiling, and went to check the other features in the Orion Group.

Starting in 1999, the Orion group once again rapidly lost its water supply and water levels dropped to historically low levels.

Early July 2003 Activity

In early July 2003, I found the water levels in the Orion Group lower than at any other time. The only spring that overflowed was Taurus Spring, and that was just a trickle. Standing water often found on the trail though the group was gone. The spring listed as Paperiello #22, which is located on a terrace below Union and Impenetrable Spring, was found to be below overflow with its terraces and runoff channels dry. I believe this is the first time it has ever been seen not in overflow. The runoff channel was desiccated and all traces of any cyanobacteria were gone. It had obviously had been below overflow for some time. Two small geysers near the creek (Paperiello #23 & #25) were active, most likely because there was no runoff from the west side of the Orion Group flowing into them.

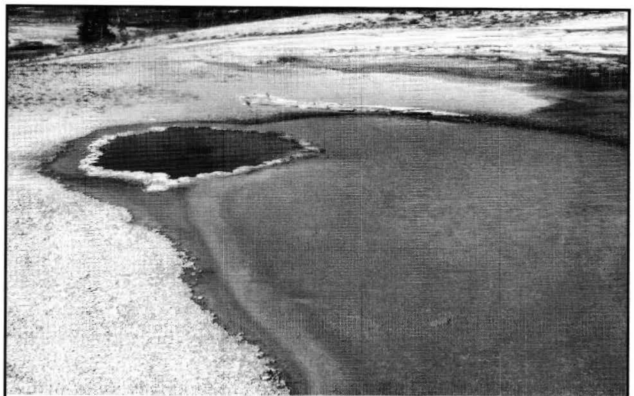


Figure 4. Spring Paperiello #22 in overflow, the spring's normal condition when it supports a wide bacteria–covered outflow area (right foreground). [Photo by Clark Murray]

Mid July 2003 Eruption

Ten days later, in mid July 2003, Jeff Cross and Tara Cross visited the area. Jeff found the trail though the basin was again wet. Spring Paperello #22 was in overflow and the west side of the Orion Group appeared much as it had in 2002. When he checked Taurus, Jeff was surprised to find that an unobserved major eruption had occurred. Because of lack of foot prints in the recently cut runoff channels, Jeff surmised that the eruption had occurred only a few day earlier. This time, however, there were no nearby earthquakes that might have initiated the activity. Perhaps the energy or the water on the west side of the group had shifted to Taurus in the early part of the month, causing the eruption before shifting back to the pre–eruption condition.

Possible Winter 2004 Eruption

Another earthquake on the Pitchstone Plateau, very similar to the one in June of 1997, occurred on January 17, 2004. This magnitude 3.1 quake hit at 00:29 (12:29 a.m.) and was followed by several minor aftershocks. This swarm of tremors did not result in an eruption of Taurus Spring, at least not immediately. However, when checked in July 2004, runoff channels in the sinter surrounding Taurus were well defined and fresh looking. Even though bacteria mats had formed within them, these channels were clearly caused by eruptive activity. Possibly, then, Taurus Spring erupted sometime during the winter following the January tremors.

Summary

Although the reason for the loss of water in the Orion Group is unclear, there appear to be long–term water level fluctuations occurring in the group. Dormancies of Union Geyser have occurred throughout its known history, although water levels have probably never been this low. Conversely the surface water temperature has remained very high.

Many thermal vents and cones are visible below the shore of the lake. Researcher Rocco Paperiello located a 1916 handwritten diary of Pat Quayle in the YNP Archives: He writes of "submerged springs and geysers in the lake"; one feature reportedly had logs placed around it in a fashion similar to Rustic Geyser at Heart Lake Geyser Basin. It would be interesting to know how much the lake level has changed over the years, and how it has affected the activity of Shoshone Geyser Basin, especially the Orion Group.

Due to its remote location and infrequent visitation by knowledgeable observers, it is difficult to track these water fluctuations to determine how frequently and to what extent they occur. Taurus Spring's unusual eruptions seem to be caused by either earthquake activity or as rare events related to these water supply variations.

Acknowledgments

Thank you to Rocco Paperiello and Marie Wolf for their detailed observational and map work at Shoshone Geyser Basin, and for Rocco's permission to use those maps in this paper. Also to T. Scott Bryan for his observations and reports, especailly from the 1970s, and to Carlton, Jeff and Tara Cross for their data collection and observation studies that are currently underway.

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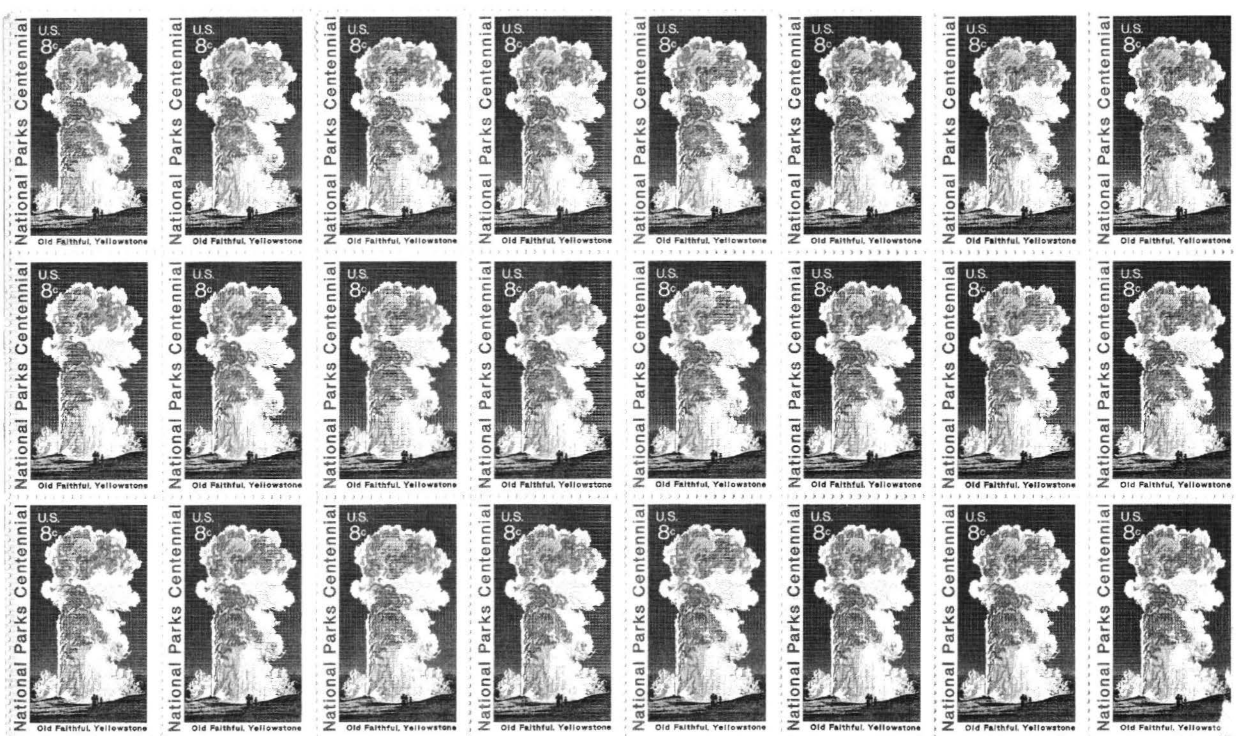


A sheet of the 8–cent "National Parks Centennial" postage stamps of 1972, shown at about two–thirds actual size. [Collection of Scott Bryan]

Geyser Activity at Heart Lake Geyser Basin, 1993–2003

by Jeff Cross

Abstract

Geyser activity observed at Heart Lake Geyser Basin from 1993 through 2003 is described. Most notable is the exchange of function between Rustic Geyser and a nearby unnamed geyser. A mode of eruption for Glade Geyser that has probably been occurring for many years is also described. The location and appearance of several probable fault scarps is also noted.

Introduction

This paper presents summary information about the geyser activity that was observed during a series of visits during eleven consecutive summer seasons. The data represents activity on the following specific dates of visitation:

08 July 1993
20 August 1994
09 August 1995
16 August 1996
02 August 1997
08 and 09 July, 02 August 1998
12 August 1999
05 and 06 July 2000
09 and 11 July, 12 September 2001
07 July, 12 September 2002
09 July 2003

All identification numbers applied to individual springs (such as "#2" for Rustic Geyser) are from Paperiello [1989], whose maps are reproduced in this report. Spring names that are given within quotation marks are informal.

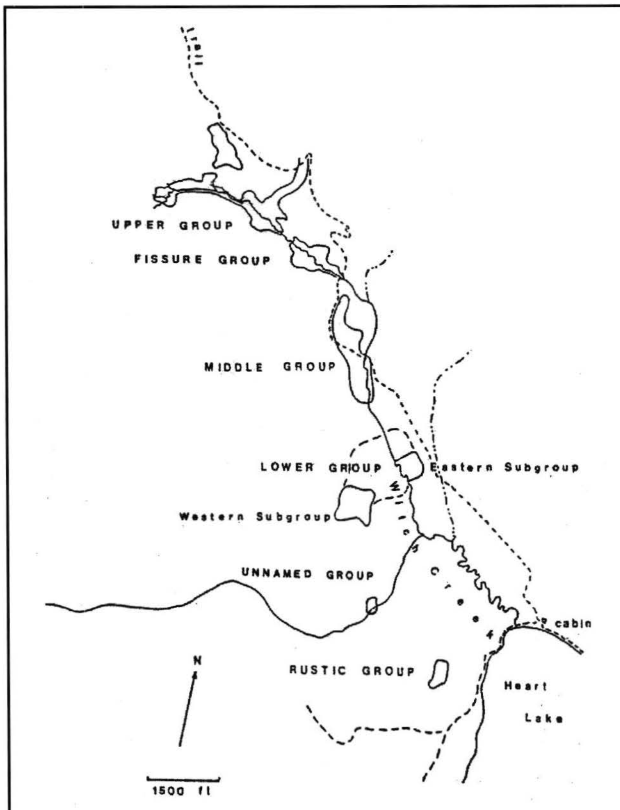
RUSTIC GROUP

The Rustic Group lies near Heart Lake itself. Although it is the farthest from the trailhead, it is generally the first Heart Lake area described because of the presence of Rustic Geyser, often the largest in the Heart Lake Geyser Basin.

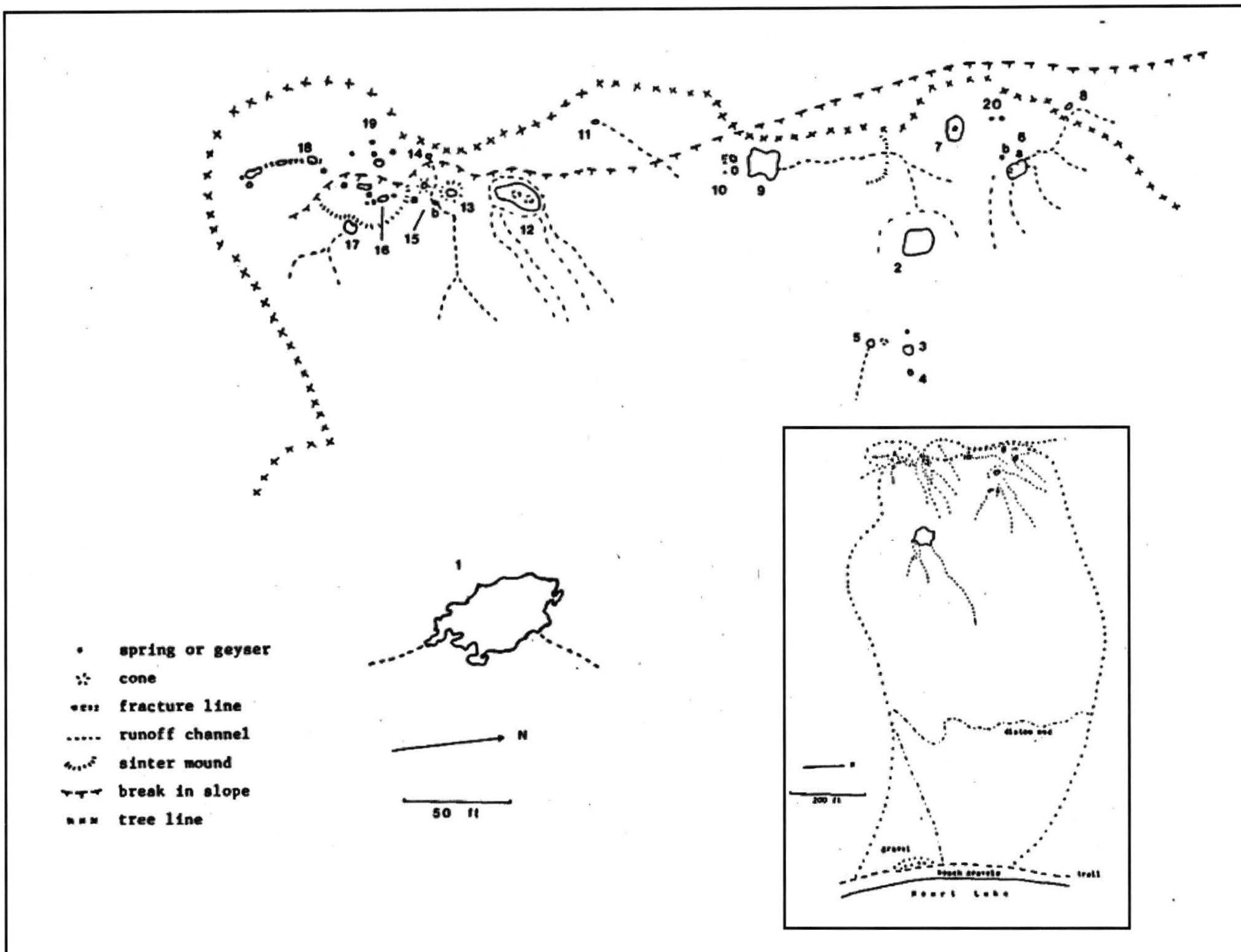
#2 Rustic Geyser

Rustic Geyser is the star performer of the Heart Lake Geyser Basin. The maximum eruption height is 20 to 40 feet, and the 26 to 36 minute intervals and 43 to 51 second durations have remained generally consistent. One unusually long interval of 40 minutes was seen in 1998, and an unusually short interval of 18 minutes was seen in 1999.

Rustic's dormancies in 1985–1996 and in 2003 occurred when nearby #6 "Composite Geyser" was active, a clear example of exchange of function. When in a dormant state, Rustic's water level varied from just below overflow to 18 inches below



Map 1– Heart Lake Geyser Basin. This and all other maps in this article are reproduced from Paperiello [1989], with permission.



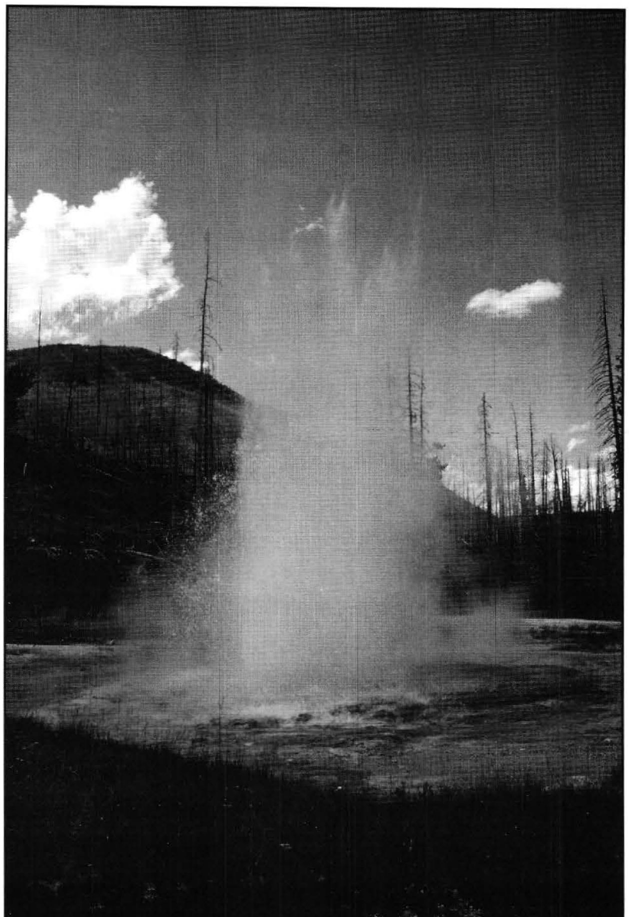
Map 2 – Rustic Group. Note the small scale inset that shows the group's setting with respect to Heart Lake. The key to the symbols apples to all maps in this report.

overflow. From observations it is uncertain whether Rustic's fill cycles bear any relationship to any of the geysers near it, although Rocco Paperiello saw a close relationship at a time when both Rustic and Composite were active (see below)—water in Composite fell shortly after eruptions of Rustic. Rustic's water levels in 1996 were higher than those seen during 1993–1995, perhaps indicating that a gradual shift of energy from #6 to Rustic was already underway.

On 09 July 2003, Composite was found to be active; Rustic was dormant, although the water level varied, at one point rising nearly to overflow. Ten days later on 19 July 2003, Rocco Paperiello found that Rustic was active; Composite tried but failed to erupt during an abnormally long 48–minute interval of Rustic. Damp runoff channels indicated that Composite had erupted earlier in the day. [Paperiello, 2003]. On 03 September, Clark Murray found Rustic active; Composite was inactive and had been for quite some time. However, a normal eruption of Rustic seen by Murray was preceded 10 minutes earlier by a very weak eruption lasting less than 10 seconds, suggesting that the hydrothermal system was still unstable [Murray, 2003].

#3

Activity was inferred from wash about the crater in 1998, and eruptions were seen in 1999 and 2000. Intervals were especially short in 2000, ranging fron 8 to 27 minutes with a mean of 19 minutes and lasting up to 40 seconds. A single eruption was seen in 1999; the interval preceding it was in excess of 60 minutes, and the duration was around



Rustic Geyser (#P2) in 1997.

1 minute. The main part of the eruption came from #3, but a smaller crater immediately downhill (#4) also splashed during the eruption. The largest jets from #3 reached 6 feet above ground level. By 2001 the geyser had returned to dormancy.

During the recent active phase, some eruptions were clearly larger than others, surging 10 to 15 feet high and flooding the runoff channel. These large eruptions caused nearby spring #5 to ebb several inches and also lengthened Rustic Geyser's intervals [Murray, 2004].

#6 "Composite Geyser"

This interesting geyser erupts from a shallow rectangular pool. It was active from 1985 [Paperiello, 1988] through the summer of 1996, and again during 2003. During 1994–1996, four closed intervals ranging from 61 to 103 minutes were noted. A 2–hour interval was extrapolated in 2003. Eruptions consisted of minor bursting, punctuated every few minutes by forceful surges lasting for 30 to 90 seconds and reaching a maximum height of 20 feet. The total duration was often difficult to estimate since the minor bursting died down gradually. A small hole immediately next to the crater also erupted in concert with the strongest activity from the pool, sending a thin jet to a comparable height.

The sinter sheet formed by the 1985–1996 activity weathered rapidly once eruptions ceased. The renewed activity of 2003 tore up numerous pieces of this layer, which were found to be 1.0 to 1.5 cm thick, suggesting an approximate deposition rate of 1.3 cm per decade.

#7

This formerly interesting geyser regressed to perpetual activity in 1985, concurrent with the exchange of function from Rustic to Composite [Paperiello, 1988]. Unfortunately, the 1997 exchange back to Rustic did not reactivate geyser activity in #7. From 1993–1996 major eruptions reaching up to 9 feet high followed the strongest

Heart Lake Geyser Basin, Rustic Group #P3 in September 1999. The uncommon major eruptions by this geyser affect several nearby springs, including Rustic Geyser (visible in the left foreground) whose eruption intervals are significantly lengthened. [Photo by Clark Murray]

"Composite Geyser" (#P6) in 1995.

implying an equally well–established dormancy. This geyser began erupting in 1978, significantly enlarging the crater, at the same time that nearby Prometheus Spring was first known to be dormant [Hutchinson, *in* Paperiello, 1988], implying that an exchange of function had occurred.

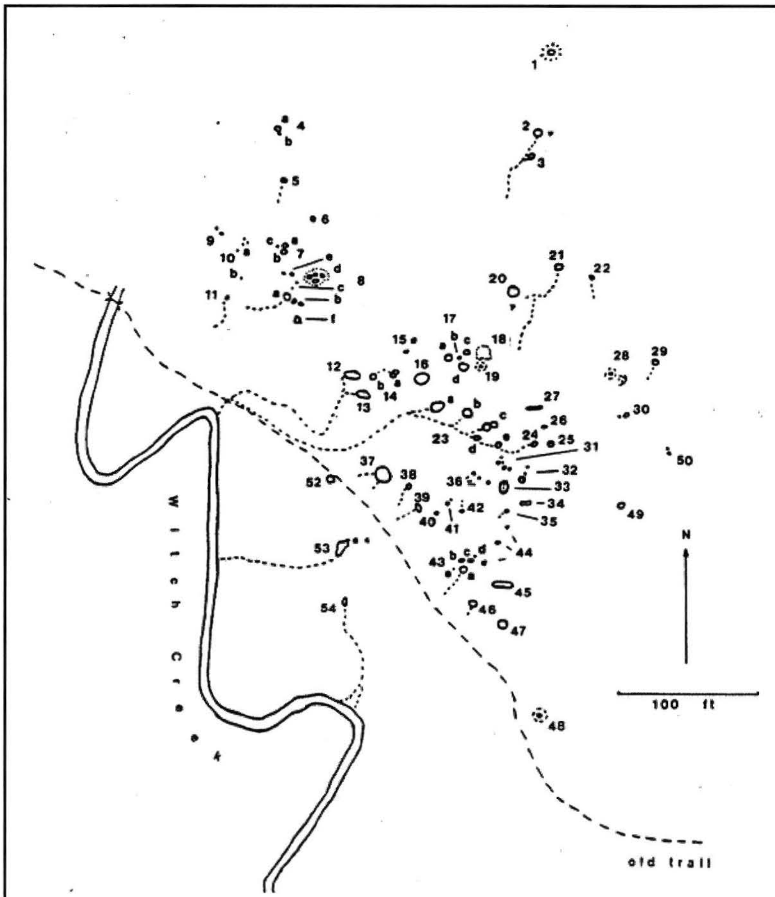
#15 "Threaded Geyser"

Named for the unique way in which the runoff stream from a perpetual spouter immediately upslope (#14) flows directly into its vent, then passes underground to reappear in a small intermittent spring just downslope, Threaded was active in 2002 with intervals of 7 to 11 minutes and durations of 2 to 4 minutes. The height was only a few inches. Geyser activity was also noted in 2001. In 2003, the eruptions were not well defined and it was difficult to identify the activity as that of a geyser.

activity in nearby Composite Geyser. Occasionally, these eruptions concluded with a loud steam phase. Similar activity was noted in the mid 1980's by Paperiello [1988]. Oddly, the one eruption of Composite Geyser seen by us in 2003 did not induce any such follow-up activity. Most typically, this geyser erupts to 1 to 2 feet nearly continuously. Occasional, brief pauses are more frequent as an eruption of Composite Geyser approaches.

#12

Although other observers have seen major activity from this feature, we have noted only perpetual spouting, primarily from the north vent. Major eruptions, last seen in 1997, came from the long fissured south vent [Paperiello, 1988; Murray, 2004]. In July 2003, grass and flowers were becoming established in the splash basins,



Map 3 – Lower Group.

#13

Just north of #15 is a crater with weathered sinter. The sound of water splashing deep within was periodic on long intervals in 2002.

"ANNEX GROUP" (Unnamed Group of Map 1)

This small and very infrequently visited group is located along both sides of a stream flowing off Mt. Sheridan north of the Rustic Group. A visit in July 2003 found one fumarole and a small complex of muddy reddish pools on the north side of the creek. On the south side of the creek was a single gurgling spouter.

LOWER GROUP

The Lower Group is divided into two subgroups, one on each side of Witch Creek. Most of the geyser activity is in the eastern subgroup; the western subgroup contains only one geyser [Paperiello, 1988, 1989], which was not erupting in 1999 or 2003 when we visited the area. One boiling spring (#15) was intermittent on very short cycles in 2003. Due to the lack of data on the western subgroup, it is not discussed further.

The eastern subgroup is completely structureless; the thermal features are seemingly scattered at random over a gentle slope. This, coupled with the absence of landmarks, can make thermal feature identification difficult, even with a map.

#43 "Ivory Geyser"

Ivory is the most prominent geyser in the Lower Group. Its 4–foot high major eruptions have occurred on intervals of 11 to 18 minutes with durations of 60 to 120 seconds in data collected between 1996 and 2003. In 1995 the intervals were 6 to 10 minutes and the durations were 48 to 74 seconds. The period between major eruptions is punctuated by frequent sputtering minor eruptions.

Also of interest are the pools surrounding Ivory, which drain during Ivory's major eruptions and slowly refill as the next major approaches. One of these vents, a tiny hole isolated from the others and perhaps 15 or 20 feet to the north, is an equally small sputtering geyser that is most active immediately before Ivory's major eruptions, when the complex's water levels are at a peak. Its height is only an inch or two.

#32–34 "Reciprocal Springs"

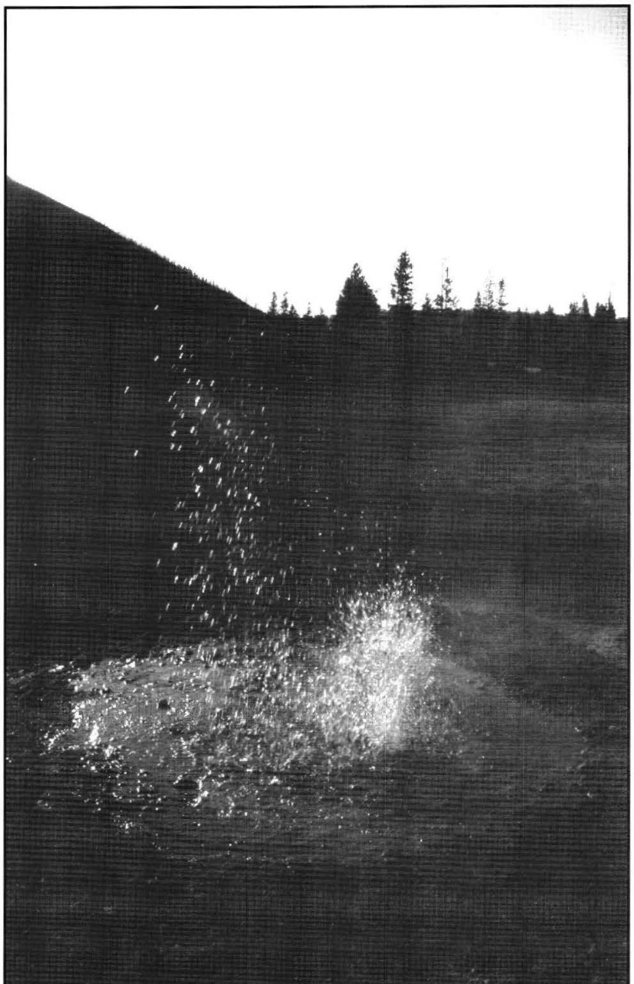
These three springs are intermittent. Intervals from 1996 to 2003 have consistently been 6 to 8 minutes. The water level is always high in #34 when it is low in #32 and 33, and vice versa, hence the name. Both #32 and 34 have erupted to 1 foot at times of high water. Due to the exceedingly weak eruptions, durations are indistinct.

#53

Although reported as a geyser by both Bryan [1995] and Paperiello [1988, 1989], we have not seen eruptions from this feature.

#19 "Calix Geyser"

Ivory Geyser in 1995.



Calix Geyser in 1998.

The vent of this geyser is only 1½ inches across and opens into a very small cup–shaped crater, hence the name. The activity has changed greatly from that described in Bryan [1995] in that the eruptions occur singly instead of in series. Clark Murray describes the activity as follows: "...the first year of increased activity from Paperiello #19 was 1993. I have two closed intervals that day of exactly 33 minutes each. The height was five feet... I have closed intervals from almost every year since, all 33–34 minutes, except 1999 when I got a 69 minute interval and a height of only three feet. I assumed at the time that I missed an eruption in between, but I have no way of knowing for sure" [Murray, 2003]. I obtained two intervals of 55 to 60 minutes in 1998, but in light of Clark's data, it is possible that each of these is a double interval. Observed durations have been just under a minute and heights have been 3 to 4 feet.

Eruptions were also noted in 2000, 1994 and 1995, although others certainly occurred while we were in the area. The brief duration and small height make this geyser very easy to miss.

#7a

The formation of this geyser contains three vents. The erupting vent is in a small pool, offset to one side of the low cone. Two other vents open along the sides of the cone. Although not noted as a geyser by either Paperiello [1988, 1989] or Bryan [1995], geyser activity was noted every year 1995 to 2001. In 2002 and 2003 it was nearly dormant. When active, intervals were 36 to 75 seconds, and durations were 13 to 49 seconds, showing very little variation in average values from year to year despite the wide variation in individual data points. This feature is in a small cluster of hot springs separated from the rest of the thermal area by a patch of swampy ground.

#8

Geyser eruptions have not been seen from this complex of vents at any time 1993 through 2003.

#1 "Turbine Geyser"

This imposing cone with prominent but weathered runoff channels shows all signs of having large eruptions in the past. Although the water level in the cone and the amount of discharge seems to vary from year to year, its modern activity has always been perpetual bursting up to 3 feet. The name was given by Clark Murray [2003]: "A couple of years ago I spoke to a gentleman who saw the cone up on the hillside erupt in the 1970's. He described it as having a spinning quality like a turbine..."

Unnumbered

Downhill from #1 and very near #2 and 3 is a small fresh–looking vent that in 2003 was having geyser eruptions a few inches high. The cycle time was not determined. It was active in 2000 as a perpetual spouter.

MIDDLE GROUP

The fault scarp that cuts the mountainside south of the Fissure Group.

The Middle Group has not been explored extensively. It is a small group that includes only a few small springs along the hiking trail and in a zone that extends southward into the adjacent forest. It was there that two geysers were observed in the 1980s [Bryan, 1996; Paperiello, 1988, 1989], but both were trampled out of identificable existence by elk. This author tried to find the site during 2003 but did not locate the geysers.

FISSURE GROUP

The Fissure Group is the most dynamic at Heart Lake. This is perhaps to be expected as Christiansen [1974] maps three faults cutting directly through the group. The scarp along the hillside to the south of the Fissure group is especially obvious toward late afternoon during the summer months. This is because the sun's rays strike the east face of Factory Hill at nearly the same angle as the slope, causing the scarp to stand out boldly as a deep black shadow. The visibility is enhanced by the lack of trees on the hillside, which burned in 1988 and was then swept clear of timber by a snow avalanche in 1997. The scarp continues for over a mile to the south. Other possible fault scarps stand out on the hillside northeast of the Fissure Group.

#6(?) "Black Velvet Geyser"

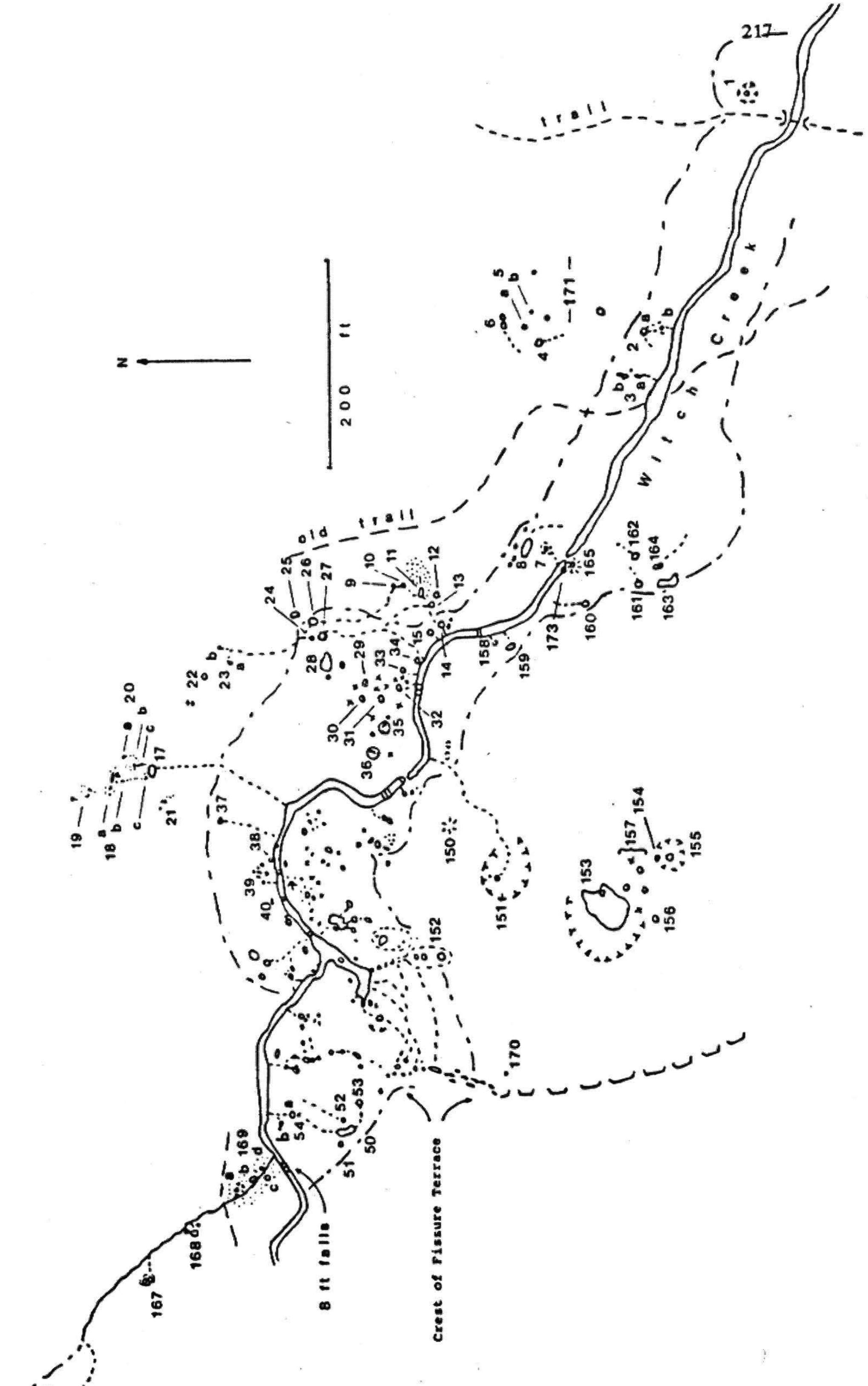
This vigorous small geyser is in eruption 75 to 85% of the time. The interior of the formation is jet–black, hence the name; the exterior is reddish. Eruptions from 2000 to 2003 have occurred at average intervals varying from 145 to 273 seconds, with average durations ranging between 108 and 234 seconds. In 2001 both intervals and durations were strongly bimodal, and in 2000 they were tri-modal. The maximum height is 1 to 2 feet.

It is unclear when the present activity developed at this feature. Although it was active as at least a perpetual spouter in 1998, I made no special note of the activity and it was not until 2000 that I saw it pause between eruptions. The identity of this feature is also unclear. The present feature's location and the direction in which the runoff flows match Paperiello's #6.

#7

A close investigation in September 2001 showed that the eruptions, though frequent, occurred with no apparent pattern. The eruption was often a single splash to 1 to 2 feet. Similar activity was noted in 1995, 1997 and 1998. Other observers have seen eruptions reach 4 to 6 feet [Murray, 2004].

"Black Velvet Geyser" in 2001.



Map 4 – Fissure Group.

#159

A single data set obtained in 2001 for this easily overlooked geyser showed that intervals were 26 to 39 seconds. The eruption was usually no more than an overflow, occasionally punctuated with a six-inch splash. Similar activity was noted in 1996, 1998 and 1999.

#35 "Pit Geyser"

Although known to be active in previous years, I did not observe eruptions of this geyser until 2000. Observations from 2000–2003 have shown that the intervals can be quite regular at times, although variation has been noted both short-term and long-term. For example, in July 2001 three intervals of 11 to 12 minutes were obtained. Two days later, four 6–minute intervals were obtained, then one of 10 minutes, another of 6 minutes, and finally an interval of 25 minutes. Intervals recorded at other times during 2002 and 2003 have fallen within the same range. Extreme regularity was shown in 2002, when a set of seven intervals varied by a standard deviation of only 2.5% of the 6.2–minute average. Durations are 23 to 33 seconds.

The eruption is quite unusual, since the vent is perhaps 6 feet below the ground surface at the edge of a large, empty crater with a flat, rubbly floor. The narrow jet rises at a significant angle, crossing the crater and occasionally spraying droplets over the rim toward Witch Creek. The maximum height is 8 feet above the vent with a 12 foot lateral throw.

Although the name "Pit Geyser" has found use in Yellowstone's Upper Geyser Basin, it is kept here because of use in (unpublished) written U.S. Geological Survey, National Park Service and other reports.

"Pit Geyser" in 2000, viewed with the water jetting across the deep crater, directly away from the viewer.

#151 "Glade Geyser"

The recent activity of Glade Geyser has been described in Cross [2003]. Additional data collected via automatic data logger placed under NPS permit showed that in July 2003, Glade erupted every 16.8 to 22.5 hours, with an average of 20.4 hours (11 intervals) and a standard deviation 9.6% of the average. This represents an increased eruption frequency over 2002, when the average intervals were 23 and 24 hours for two separate data sets. The 67–minute average obtained in 1997 and the 90–minute average obtained in 1998 remain unmatched, however.

Although the data logger temperature record had suggested that Glade's eruptions lasted longer when the intervals were many hours long, no visual observations to confirm this suspicion existed until the summer of 2003. That summer, Glade was seen erupting on two separate occasions [Paperiello, 2003; Murray, 2003]. Rocco Paperiello reported an eruption reaching 40 feet, with a brief pause 9 minutes after the start, and a restart lasting 5 minutes. Clark Murray reported at least four eruptions in series, with the second occurring 5 minutes after the first, the third occurring 6 minutes later, and after 16 minutes, the display ending with a protracted period of steaming and spraying. An eruption seen by us in 1996 was reported in Cross [2003] and is similar to these accounts. Additionally, another eruption seen by Clark Murray in September 1995 consisted of five eruptions. The first reached 50 feet high, and subsequent eruptions, occurring at increasing intervals of several minutes, reached 30 feet. The interval following this eruption was in excess of 5 hours [Murray, 2003]. The well-defined and comparatively brief eruptions seen during the short–interval activity of 1997 and 1998, with durations of around 2 minutes, stand in contrast.

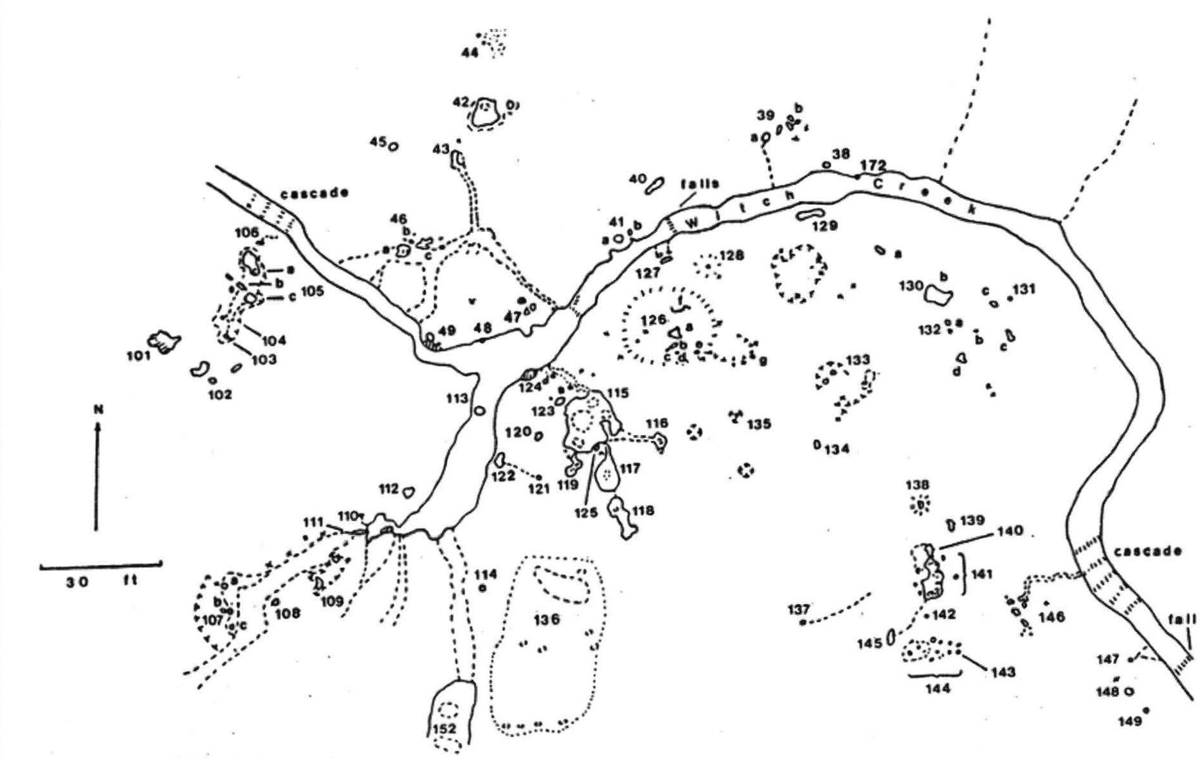
Heart Lake Geyser Basin, Fissure Group #P126, which is probably the historic "Puffing Spring" of T. B. Comstock in 1873, occasionally undergoes strong eruptions. This photo, taken in 1992, shows an eruption that reached fully 4 feet high and lasted over 10 minutes. [Photo by Clark Murray]

#138 "Wisp Geyser"

The only observed eruptions were seen in September 1993 by Clark Murray, one closed interval being just over 5 hours; a second interval was unknown but in excess of 6 hours [Bryan, 1995]. Wash about the vent was noted in 2000 and 2002, and light wash was noted in 2003, indicating further eruptive activity. If the geyser is active, the water will be no more than an inch below overflow [Murray, 2004].

#126 Puffing Spring

This feature has consistently functioned as a perpetual spouter, bursting violently from a low water level. A rock is wedged into the vent and has been in place for many years. Evidence of stronger eruptions was seen in 1987 [Paperiello, via Murray, 2003] and again in 1999. In 1992 an erup-



Map 5 – The central portion of the Fissure Group. Compare with Map 4 for location.

tion 4 feet high and lasting 10 minutes with moderately heavy discharge was seen (see photo); a subterranean vent at the base of the cone also participated in the eruption [Murray, 2004].

#115 Splurger Geyser

Splurger was active as a geyser in 1993, 1998, and 2000–2002. In 1994 and again in 2003 the activity may have been perpetual, but intermittent geyser action was observed in September 2003 [Murray, 2004]. In 1995 just overflow was noted. When active the pauses between eruptions have been shorter than the durations, with known pauses lasting less than half an hour. The maximum height is 4 to 5 feet.

#116

Located immediately upslope from Splurger, this geyser was known to be eruptive in 1996–1998, 2001 and 2003, although truly intermittent activity was noted only in 2001. It is possible that activity in other years was periodic with very long eruptions. The runoff stream flows directly into Splurger's crater.

#105 "Shell Geyser"

Shell Geyser's activity is quite disorganized. When active, individual surging eruptions can occur on intervals of seconds to minutes. The biggest splashes come from the bowl-shaped front crater and send water at a low angle over, and into, Witch Creek. Smaller splashes come from a fissure vent behind the main bowl. Heights are 2 to 6 feet. Shell was dormant during our visit in 1997.

#106

Although the small vent of this geyser opens on the front of Shell Geyser's formation, there is no obvious connection between the two. Small sputtering eruptions were noted in 1995, and also in 1998, 2001 and 2002. The activity seems to be highly cyclic; at times eruptions occur every few minutes and at these times the intervals may be reasonably regular, while on other occasions eruptions are not seen at all, or they occur on irregular intervals. Durations up to one minute have been noted, but 10 to 30 seconds is more typical. The height is up to 2 feet.

#103

An intermittent spring with frequent heavy, gushing discharge that cascades down the sinter wall above Shell Geyser. Paperiello [1988] notes small eruptions from this vent, but I have not seen any.

#101

Perched in a cave high on the sinter wall above Witch Creek just upstream from Shell Geyser, this geyser is very easy to overlook. The eruption is barely visible as a series of splashes drenching the roof of the cave. A data set obtained in 2001 showed intervals of 72 to 112 seconds and durations of 13 to 20 seconds. Similar activity has been noted each year from 1994 through 2003.

#57 "Fissure Springs Geyser"

When it was active in 2000, this was an impressive geyser erupting from a brightly-colored bathtub shaped crater to 10 feet vertically and 20 feet horizontally. Wash patterns suggested that unseen eruptions may have been larger. The eruptions were brief, lasting only 6 to 11 seconds, but were frequent, occuring every 197 to 315 seconds. At times, Fissure Springs Geyser demonstrated considerable regularity, erupting at an average interval of 242 seconds with a standard deviation of only 1.2% of the mean (9 intervals). A small 1–foot high spouter in the crater immediately north of Fissure Springs Geyser decreased its activity following individual eruptions of Fissure Springs Geyser in 2000. Fissure Springs Geyser was also active in a similar fashion in 1986 [Paperiello, 1988].

#67

Its vent more smoothly rounded than those in its neighbors, this geyser was reported active in 1973, but only infrequently since then [Paperiello, 1988]. At times, especially in 2000, it has been seen surging and occasionally overflowing heavily, but not erupting. Wash possibly indicating eruptions was noted in 1996 and 1997. Frequent geyser eruptions to 4 or 5 feet, flooding the slope below, were noted in September 1999 [Murray, 2004].

#68

In September 2002, this very long, narrow crack was erupting as a geyser every 16 to 28 seconds for durations of 10 to 18 seconds. More frequently the geyser is active as a cyclic perpetual spouter.

#69

This vent has generally functioned as a cyclic perpetual spouter, with a maximum height of 3 feet.

#70

By far the most prominent of the Fissure Springs, this spouter cycles widely, with a maximum height of 3 to 6 feet; pauses are indistinct.

#72

A heavily flowing spring. A barely–visible crack extends to the northeast. It oveflowed in 1987, when it was also seen spraying during strong surges from #70 [Paperiello, 1988]. The crack also overflowed during 1996.

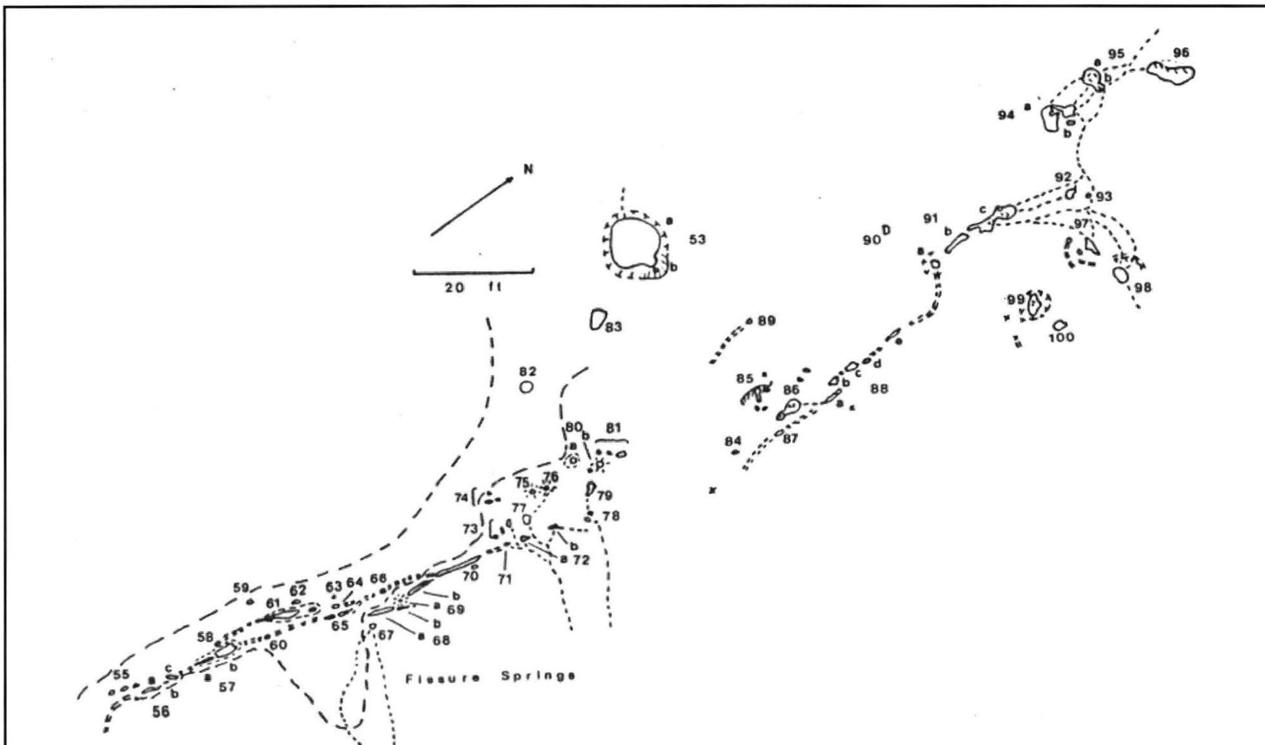
#80

In 2003, this geyser was erupting every 41 to 54 seconds; durations were 21 to 32 seconds. The main eruption came from a pair of vents next to a cone at the north end of the Fissure Springs. Although the geyser discharged no water, a small pool immediately next to it (#79) overflowed heavily during the eruptions. This was the first time I noted eruptions from this feature.

#78

This tiny geyser has been active on and off over the years. It was active during 1993, 1995, 1997, 1998, 2001, and 2002. The maximum height is 1 foot, although most of the eruption is merely a noisy sputtering to a few inches. There are three vents. The main vent is a tiny slot in the runoff stream from #79. Another small vent is surrounded by a cone, while a third vent acts as a drain for water erupted from the cone vent.

Intervals in 1993 and 1995 were 6 to 9 minutes, but in subsequent years the intervals were generally shorter, at less than 6 minutes and often as short as 1 to 3 minutes. Bimodal intervals were noted in 1998. And in 2002 the activity would occasionally shift to the drain vent, which would splash while the other two vents stopped erupting, demonstrating exchange of function on a very small scale. Durations have typically been 1 to 2 minutes, but are occasionally less than 30 seconds.



Map 6 – The Fissure Springs, at the crest of Fissure Terrace. See Map 4 for the location within the Fissure Group.

#85 and #86

Periodic activity was noted from these features in 1993 and 1994. Perpetual spouting was also noted in 1997, but since the mid–1990's these springs have looked very dilapidated.

#91

This feature erupts from four vents. Because the upper vent a) is in a cave its eruptions produce a low rumbling sound; b) is a fissure vent, usually violently boiling; c) is a calmer vent, and just beyond it is a small, pretty pool. Paperiello (1988) does not give this final vent a separate label, but I will call it d) since its activity is sometimes distinct from that of c). The eruption begins in vent b), progresses to vent a), and ends with surging in vent c) and a splash or two from vent d). Intervals in 1993, 1996, 1997, and 1999 were 2 minutes. Durations last for up to half the length of the intervals. The maximum height is 2 feet. When not active as a geyser the activity becomes perpetual, especially from vent b).

The water was noticeably cloudy in 1997, and in 1999 it was cloudy and had an offensive smell. In 2001 the water had an unusual red color.

#50 Shelf Spring

A landslide in 1992 filled Shelf Spring with silt. Shelf probably erupted later that year and, although the water had cleared by 1993, some silt still remains in the pool [Murray, 2004]. Low water was noted in 1998. By 1999 it had recovered, and in 2000 it was overflowing. In 2001 it had ebbed again, but in 2002 and 2003 it was full, overflowing and hot. Status prior to 1998 was not noted.

#52 "Siphon Geyser"

This geyser (informally referred to as "Siphon Geyser" by the author) is rarely seen. It was active in 1993, with a long cycle of numerous small eruptions followed by a long recovery period. In 1995 another long cycle of eruptions lowered the water level in nerby Shelf Spring, inspiring the informal name. Eruptions were again seen in 1999, reaching 2 feet high [Murray, 2003]. Siphon had fresh wash in 2003 and was full and boiling up 6 inches but it apparently had no sizeable eruptions for at least one month prior to 03 September 2003 [Murray, 2003]. The water levels have paralleled those in nearby Shelf Spring. Periodic overflow was noted in 1995–1997, but in 1998 the water level was low. By 1999 it had recovered, but in 2001 it had ebbed again. In 2002 the water was higher, and in 2003 the cone was full, boiling up 6 inches, and was surrounded by fresh wash.

#53

A large pit between Shelf Spring and the Fissure Springs, in September 2001 #53 was violently active from a vent under its north edge, blasting water onto the overhanging rim. The water was muddy and smelled acidic. By 2002 it had calmed down and was full of blue silty water. In 2003 it had a heavy flow through it from the north.

UPPER GROUP

Just north of the upper group, the trail follows an abrupt change in slope cutting across an otherwise quite flat land surface. It is possible that this is yet another fault scarp, since Christiansen (1974) maps a fault passing through the Upper Group and continuing northward for some distance.

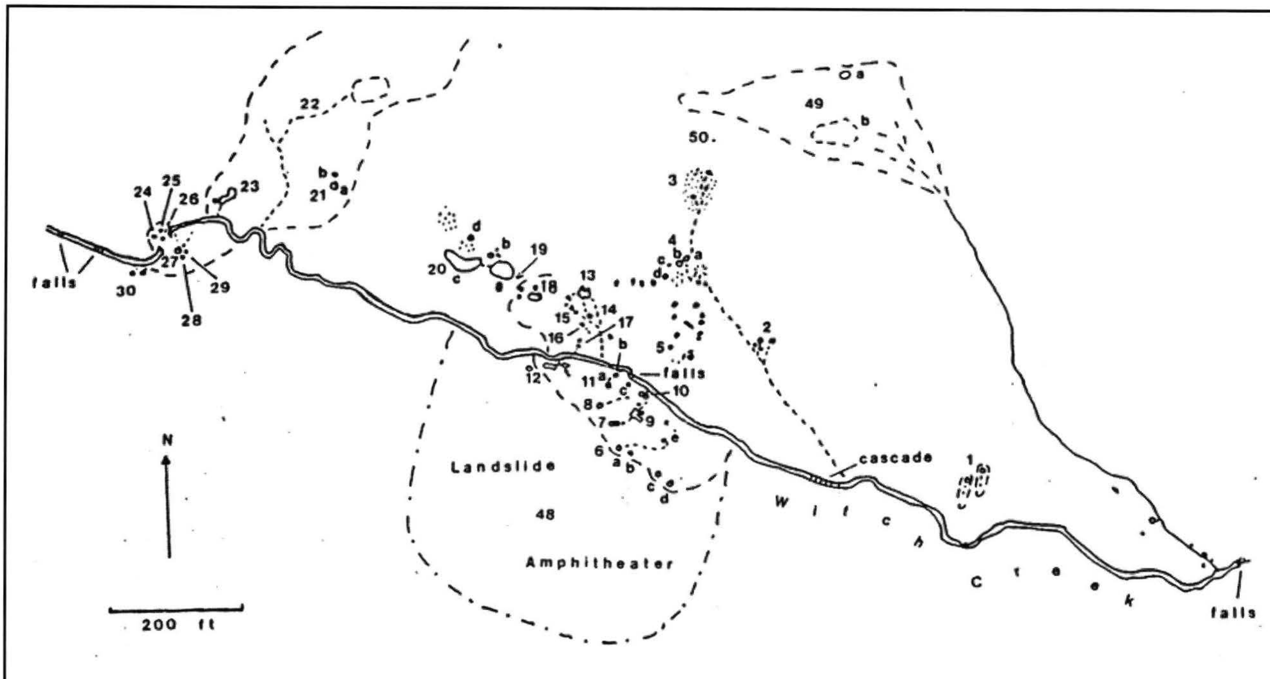
#13 Deluge Geyser

Deluge Geyser is properly an intermittent spring most of the time. I have never seen true eruptions from it, although in 1997 it boiled at times of high water and a ring of scalded grass was noted around the crater, indicating that larger activity had occurred unseen. By 1998, the scalded area supported a growth of thermal biota. Wash around the south edge of the crater was noted in 2000, suggesting that another episode of unusually powerful activity had occurred. Paperiello [1988] cites a similar instance of scalded grass in 1976. Deluge overflows every 6 minutes.

Data taken simultaneously on Deluge, #16 and #14 during 2001–2003 show that there is no obvious relationship between these features, despite their proximity to each other.

#16

This tiny geyser erupts every 4 minutes to 1



Map 7 – Upper Group.

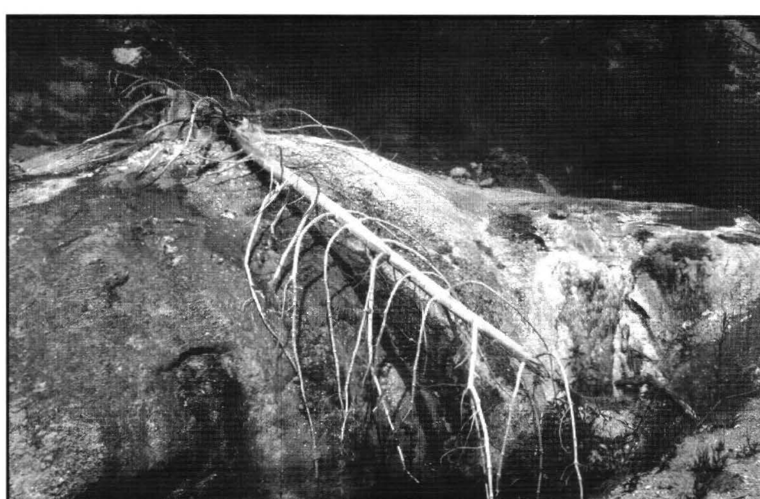
foot. The eruptions last for less than a minute, but the durations have become indistinct because a lowered water level has rendered most of the eruption subterranean. It has been active every year 1993 through 2003.

#14

Intervals recorded during 2001–2003 have been just under 4 minutes. There have been no signs of eruptions during 1993-2003, although eruptions may have occurred in 1986 [Paperiello, 1988].

#24 Spike Geyser

In 1994, Spike Geyser and the numerous small vents around it were highly active. However, by 1998 many of the side vents and especially those next to the sinter bridge over Witch Creek were not overflowing and the formations had dried up. Spike itself was still weakly active. This condition has persisted through 2003.



Spike Geyser in 1993.

Acknowledgements

I thank Carlton Cross, who accompanied me on nearly all trips to Heart Lake and collected data reported in this paper. Thanks also to Clark Murray for providing helpful information and photos, and to Rocco Paperiello for permission to use his maps in this paper. The author also thanks the National Park Service for granting the research permit under which the Glade Geyser data was collected.

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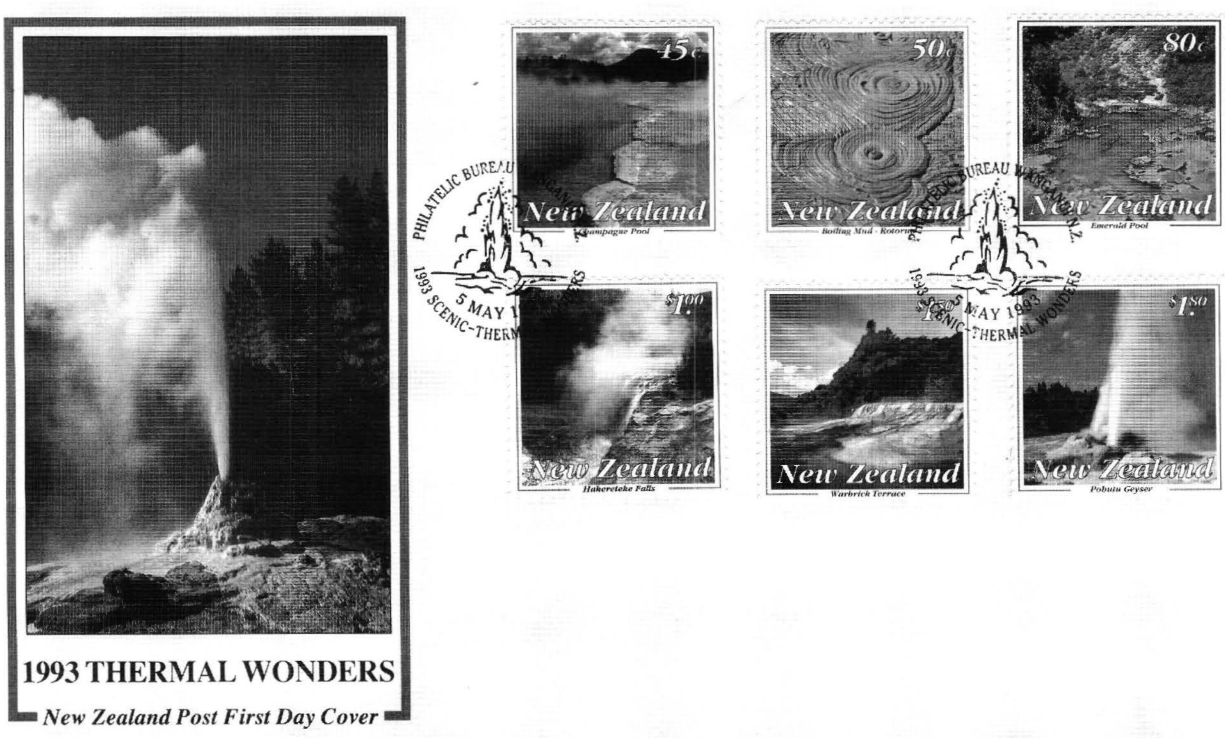


A first day cover of postage stamps cancelled on 5 May 1993 showing thermal features in New Zealand. The stamps, clockwise from the upper left, illustrate Champagne Pool (Waiotapu), Boiling Mud (Rotorua), Emerald Pool (Waimangu), Hakereteke Falls (perhaps Tikitere), Warbrick Terrace (Waimangu) ,and Pohutu Geyser (Whakarewarewa). The large photo on the left is the famous Lady Knox Geyser (near Waiotapu) undergoing its daily eruption. [Envelope in the collection of Scott Bryan, a gift from Ron Keam]

A Visit to Smoke Jumper Hot Springs,
Yellowstone National Park

by Mike Keller
all photos by the author

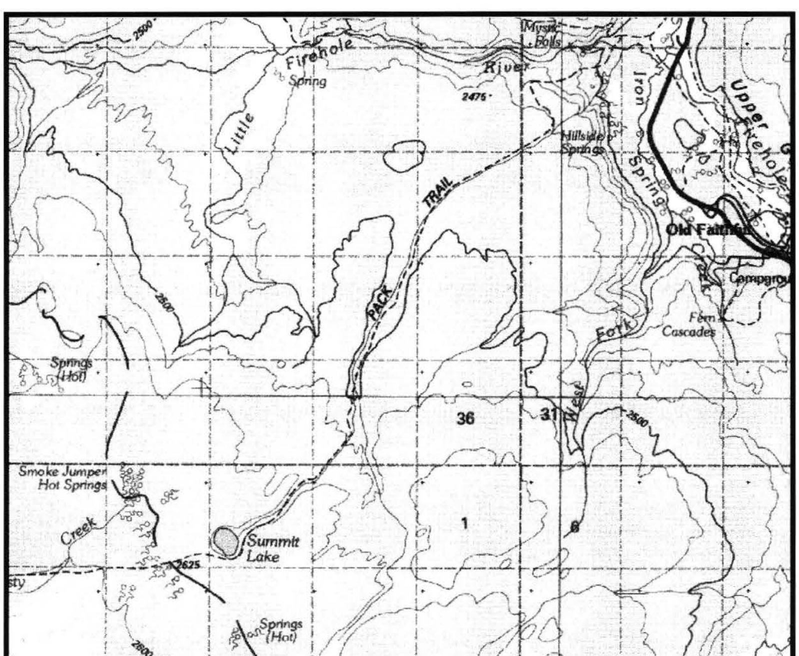
Abstract
This scattered area of acidic hot springs was investigated in September 2003 in order to document the thermal activity. As expected, no geysers were found, but there were fumaroles, frying pans and perpetual spouters among large, muddy pools.

Introduction and Background

On September 27, 2003, Rocco Paperiello, David Goldberg, and I hiked out to these seldom visited hot springs, located along the Continental Divide atop the Madison Plateau about seven air miles southwest of Old Faithful. Hiking access is via the Summit Lake Trail, which starts at Biscuit Basin (Map A). For Rocco and David, it was their first time in the area. I had visited these springs in 1991. The following is a review of the activity we observed in the main group of springs, plus other smaller pockets of activity extending over a mile to the north and south.

These springs were only briefly visited and described in passing during the 1872 and 1878 surveys of Yellowstone, and then apparently not again until 1930. In their classic work, *Hot Springs of the Yellowstone National Park* (Carnegie Institution of Washington, Publication No. 466, 1935), E.T. Allen and A.L. Day included a very short description of the Smoke Jumper Hot Springs under the simple heading of "Summit Lake." In fact, neither Allen nor Day actually visited the area, relying instead on a 1930 report by a forestry crew led by D.W. Ellsworth. Allen and Day related, in part:

> The barren ground is a narrow strip ½ mile west of the lake, about 2½ miles long by 1/8 mile wide. Fifteen springs were described, the majority of good size but shallow, muddy and acid to litmus. Several were yellow with precipitated sulphur and only three were said to be clear... most of the springs were above 85°C... it is practically certain that the area is predominately acid, though a very few springs may be alkaline or discharging mixed water... Summit Lake is one of the most elevated hot areas in the Park.



Map A. Smoke Jumper Hot Springs Location, near Summit Lake. Note the location of Old Faithful and the trail that leads from Biscuit Basin. [Scanned from USGS "Yellowstone National Park South" topographic map, 1982, Scale 1:100,000, here much reduced in size; dashed squares are 1–mile sections]

All of the individual groups of the Smoke Jumper Hot Springs lie at elevations above 8,500 feet. The modern name was not applied until 1956, after fire fighting smoke jumpers had used the barren tracts as parachute landing areas.

Readers should note that Smoke Jumper Hot Springs proper includes only Areas #2 through #6 of this paper. Areas #1 and #7 lie nearby and no doubt operate from the same subsurface geothermal source as do the other areas. However at the surface they are spearated by densely forested,

A view looking south across **Area #1** in 1991.

Rocco Paperiello at at one of the larger and hotter features in **Area #2** in 2003.

non–thermal ground. They are therefore considered to be separate, unnamed thermal units. Compare Map B with Map A.

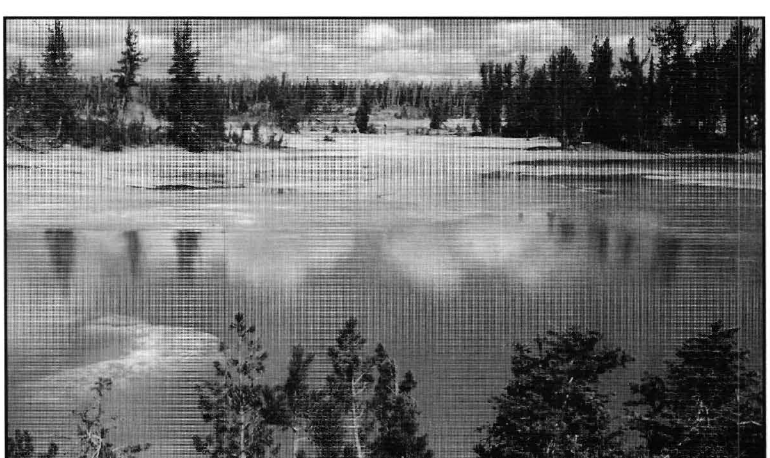
The Smoke Jumper Hot Springs area is reached via the "Summit Lake Trail," which begins at Biscuit Basin. The total distance to Summit Lake is about 7 miles and includes a total elevation climb of over 1,000 feet. Once at Summit Lake, you may wish to use compass or GPS headings to reach the individual areas but, having burned in the fires of 1988, undergrowth is minimal and travel is quite easy.

Area #1

This group of springs lies little over a mile northwest of the main group of springs at Smoke Jumper. It was not visited in 2003, but was visited by the author in 1991. At that time the area mainly consisted of fumaroles and occasional frying pan areas, but there were also two yellowish colored pools measuring several feet in diameter.

Smoke Jumper Hot Springs (Areas #2 through #6)

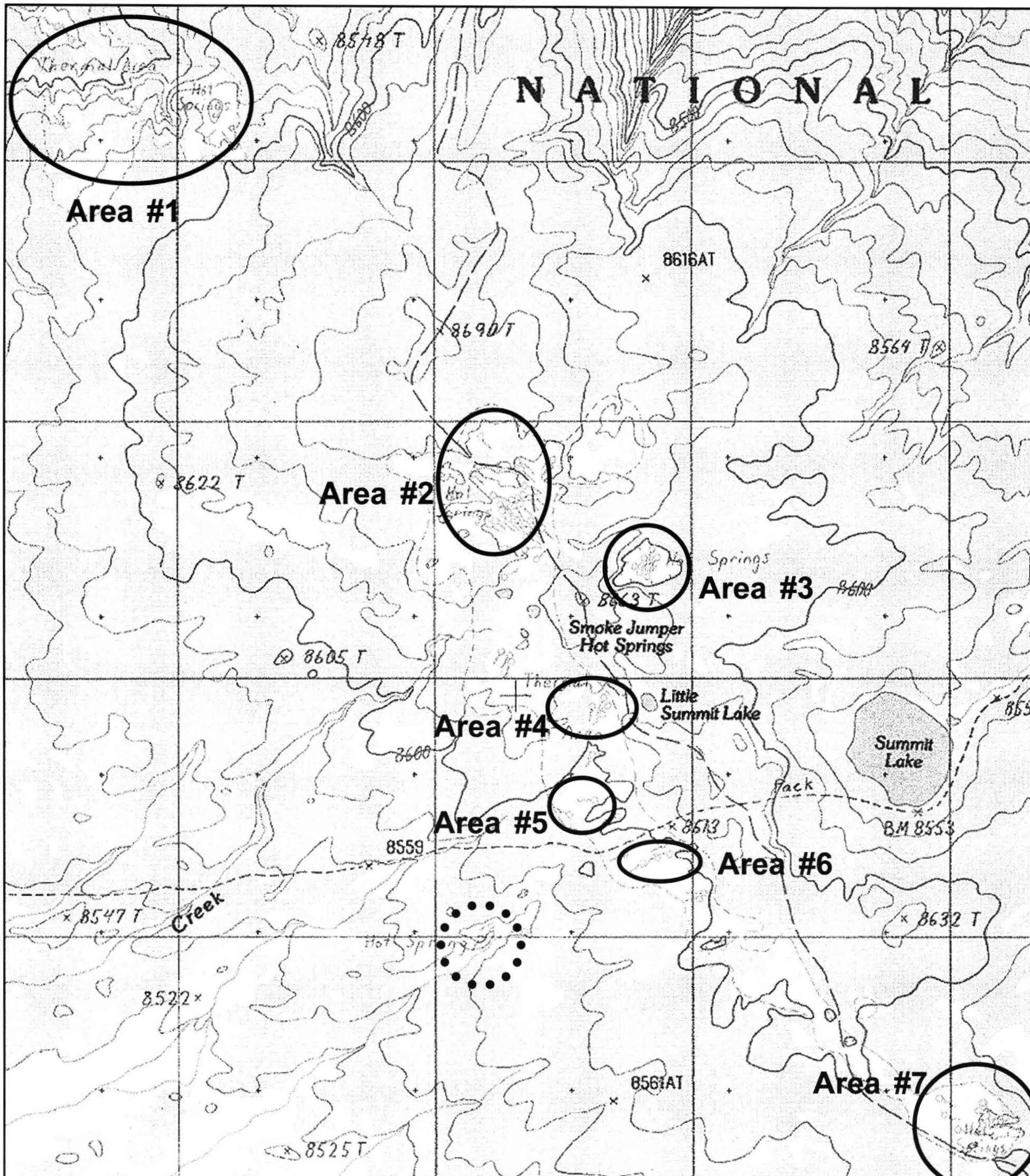
Smoke Jumper is an extremely acidic area with no hard sinter deposits. Most of the springs are large, lie within muddy basins, and contain yellow or brown water. Surrounding these springs are barren hillsides dotted with steam vents, small frying pan areas, and occasional sulphur–laden fumaroles. True geyser activity has never been documented in any of these springs. In 1991, three small perpetual spouters were found. In 2003, eight perpetual spouters were found in and around the main collection of springs. While six of them were muddy and appeared to be very acidic, two had clear water.



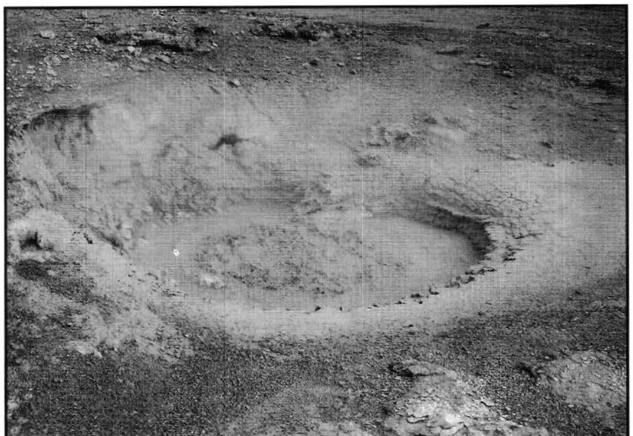
A view looking north across the expanse of **Area #2**. The greenish pool noted in the text is in the foreground.

Area #2:

This area constitutes the largest collection of springs in the area and could be considered the main portion of Smoke Jumper Hot Springs. Along a depression roughly 500 yards long by 150 yards wide are a number of features. The largest of these is a greenish pool on the southern side of the group. This feature is "L" shaped, about 60 feet wide and 40 feet long. Three other vents on the north and northwestern side of this area appeared to be superheated. All were perpetually erupting muddy water to a



Map B. Smoke Jumper Hot Springs and other thermal areas near Summit Lake. The individual hot spring groups are designated by numbers according to this article. The map indicates that an additional, unobserved group of springs lies within the dotted circle. Map from USGS "Summit Lake" quadrangle, scale 1:24,000, 1982; black squares represent 1,000 meter UTM gridlines.



Another feature of **Area #2**. This appeared to be superheated and bore a yellowish color.

height of one to two feet. Two large areas on the western side of this area contained numerous fumaroles and small frying pan–type vents. At no time did we find any vents with sinter or geyserite deposits around them.

Southwest and west of these springs is a region of long-extinct craters and features. At some time in the past there was a great amount of activity here, but there is nothing to indicate any recent action. One large circular spring in this area easily measures 80 feet across and has lukewarm water in its basin.

Area #3:

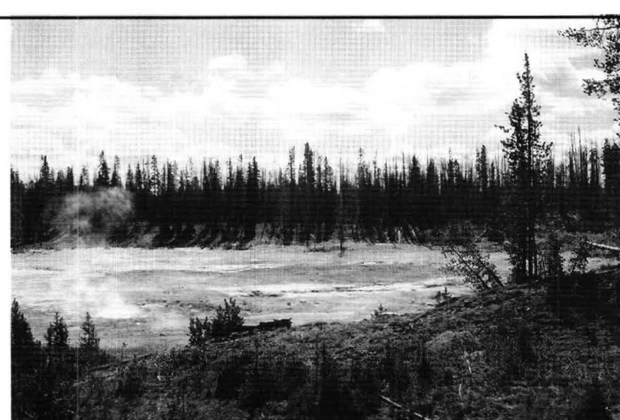
These features are about one–third of a mile southeast of the main group of springs (area #2). At the southern end of area #2 is a drainage channel. If you follow this drainage it will lead you to these springs. The author visited these springs in 1991 as well.

The activity of this area is located within an east–facing depression. While the forest grows thickly around the edges, no trees are found within this basin. In 1991, the water levels were very high and there appeared to be only 2 large springs. In 2003, the water levels had dropped several feet, resulting in about a dozen large, muddy craters being visible. Within one of these we found a perpetually erupting vent. The water was a dark chocolate color and was reaching about 2 feet above the ground. Several other springs were hot enough to appear dangerous, but they did not appear to be above boiling. All of the features had muddy brown– or yellow–colored water.

Area #4:

This group of springs lies perhaps 1,000 feet southeast of Area #2, and about one–third of a mile north of the Summit Lake Trail. It is about 100 yards west of Little Summit Lake and lies within a small depression in the plateau. This small collection of springs contained two perpetual spouters. Unlike the other features in the area, these spouters erupted clear water and appeared to be among the hottest in the area. The first of these spouters erupted from a pool at the base of some boulders. The pool was a few feet deep and in its bottom there was a steady "firecracker" sound caused by steam bubbles rising through the sandy base of the feature. Every few seconds one of the steam bubbles would make it to the surface and splash to about a foot. While the activity at the surface of

Area #3 viewed toward the northwest as it appeared, in 1991.



Area #3 viewed looking in the opposite direction, to the southeast, in 2003.

David Goldberg in the middle of **Area #6** provides some scale. This view is toward the southwest.

the pool was cyclic, there never was any true pause in the action at the bottom of the pool. The second spouting feature was about 50 yards south of the other and played 2 feet high. In this same area were a few other small springs and some frying pans.

Area #5:

This group lies immediately north of the main trail. While the ground for several hundred feet along this area is mixture of white, pink, and yellow, there was only one spring. This feature was very large, measuring 80 by 100 feet in dimensions. The water was a light green color and looked and smelled very acidic, but was not hot to the touch. The crater of this feature was reminiscent of an old explosion crater, this spring being the last remnant of the activity that formed it. Of all the groups in this area this one contained the least amount of activity and in our opinion was not worth the effort to visit.

A different view of **Area #6**, looking to the west.

Area #6:

Just south of the trail and maybe 300 yards south of area #5 is area #6. Like area #4, these springs lie in a depression surrounded by thick forest, but have no trees growing within the group of springs. On the opposite sides of this area were two large, muddy springs with yellow water. They smelled extremely acidic and, while being hot, did not appear to be superheated. In general there was more activity on the eastern and southeastern side of this group, with several smaller craters having hot, muddy water in them as well.

At the southeastern side of this group, about 30 yards into the trees were two more large craters. Each crater was about 40 feet across and 10 to 15 feet deep. In each of them we found more muddy springs.

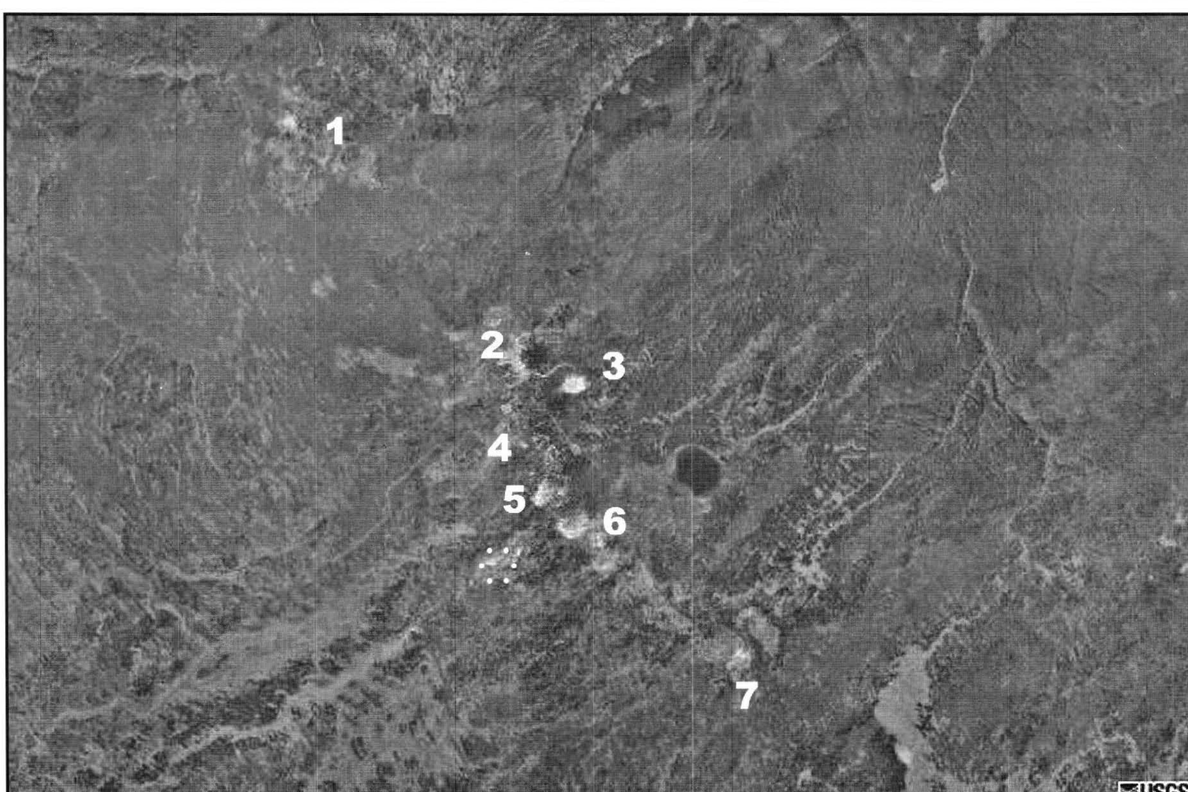
Area # 7:

These springs are the farthest south from the main group at Smoke Jumper, about three–quar-

A series of muddy springs that have developed along a fissure in **Area #7**.

ters of a mile from the trail and nearly two miles from the main group of springs. These springs lie along the southern edge of the plateau that covers most of this area of the Park. Between the trail and Area 7 is a large patch of very old whitebark pine trees, a species not commonly found in Yellowstone. As with the other springs, there is no vegetation growing within the area of thermal activity. The ground here is mainly white and pink. While this colored ground covers several hundred square feet, there are only two main features. The first consists of a fissure measuring about 20 feet in length, running roughly northeast to southwest. Along this fissure were three vents, the largest about five feet in diameter. White, muddy water was churning in two of them to a couple of feet and gave the appearance of being superheated. While there was a small cone of dried mud around the vent, we never saw the activity reach ground level. The second feature in the group was about 60 feet to the south of the fissure. This spring was a single pool, measuring about 10 feet in diameter. Within its basin was a muddy, red colored feature. While hot enough to be steaming, it didn't appear to be at or near the boiling point.

David Goldberg looking west across **Area #7**.



An aerial photograph of the Summit Lake (dark oval near center), Smoke Jumper Hot Springs (white spots), and vicinity. The thermal areas as described in this article are labelled; compare with Map B. [USGS photo, downloaded via terraserver.microsoft.com]

Southern California's "Soda Springs" — another possible mud pot locality near the Salton Sea

history compiled by T. Scott Bryan

Abstract

G.W. James in a 1907 publication described an area of "dead" mud pots near the west shore of the Salton Sea. The area involved is an intriguing one, but whether true mud pots have been active since the 1800s is questionable.

The Historic Description

In the late 1800s and early 1900s, G. W. James explored southern California's Colorado Desert region, providing some of the earliest available natural history descriptions of the area. Among these were accounts of the mud pot areas near the modern town of Niland, close to the southeastern limit of the Salton Sea. Some of those descriptions appeared in Volume VIII of *The GOSA Transactions*.

Here, from the same reference by James, is the description of another mud pot area:

> On the southwest side of the point below Fig Tree John's *[comment #1, see next section]*, about twelve or fifteen miles toward the mountains, is an area over half a mile square, covered with the cones of a mud volcanic region similar to the one I have just described *[comment #2]*. But these are all dead. The cessation of the activity left the cones to the forces of erosion. Wind storm, rain, and sand are playing havoc with them, and they are now rapidly succumbing and weathering away. In exploring the region, however, one must be exceedingly careful to avoid serious injury, or, perhaps, death, for the chemical and aqueous agencies long ago at work here have tunneled strangely into the crust of the earth. Great chambers, long galleries, far-reaching corridors, tall chimneys, sloping chutes, and yawning abysses lie in wait, merely covered by the calcareous and other deposits of the volcanoes. In treading one is liable to step on one of these covered pitfalls and drop to disaster or death below. *[comment #3]*. Being out of the line of any travel and in a region not at all alluring or suggestive even to a prospector, this "devil's half-mile" is practically unknown, save to a small handful of the adventurous spirits that love to penetrate even into the mysteries that seem to be profitless.

This article is an attempt to identify the location of these features.

Comments on the above

Although it did not appear in his text, James used the name "Soda Springs" on a map that accompanied the description. The name's words were quite large, though, so interpretation from the text is really needed to fix the location of James's Soda Springs. Comments #1 and #3 noted in the James extract (above) do this quite well.

Bryan Comment #1 — Fig Tree John was a famous Cahuilla Indian who lived near the modern settlement community of Oasis, not far from the northwest shore of the Salton Sea. A short distance south of Oasis is Travertine Point (also known as Travertine Rock), so called because of the tufa deposits left from the prehistoric highwater stand of Lake Cahuilla. From Travertine Point, which lies nearly astride the Riverside County–Imperial County boundary line, it is exactly 11.6 miles to Salton City and, therefore, a bit more than that to the presumed location of these springs (Map A).

Bryan Comment #2 — The "one I have just described" is the "Salton Buttes" area of mud pots and other hot springs lying near and underwater at the southeast shore of the Salton Sea. This includes the several mud pot localities described in Volume VIII of *The GOSA Transactions* [Bryan, 2003].

Bryan Comment #3 — The area here inferred to be the location of Soda Springs is a zone of alkaline springs, as shown on several maps (see both Map A and Map B).

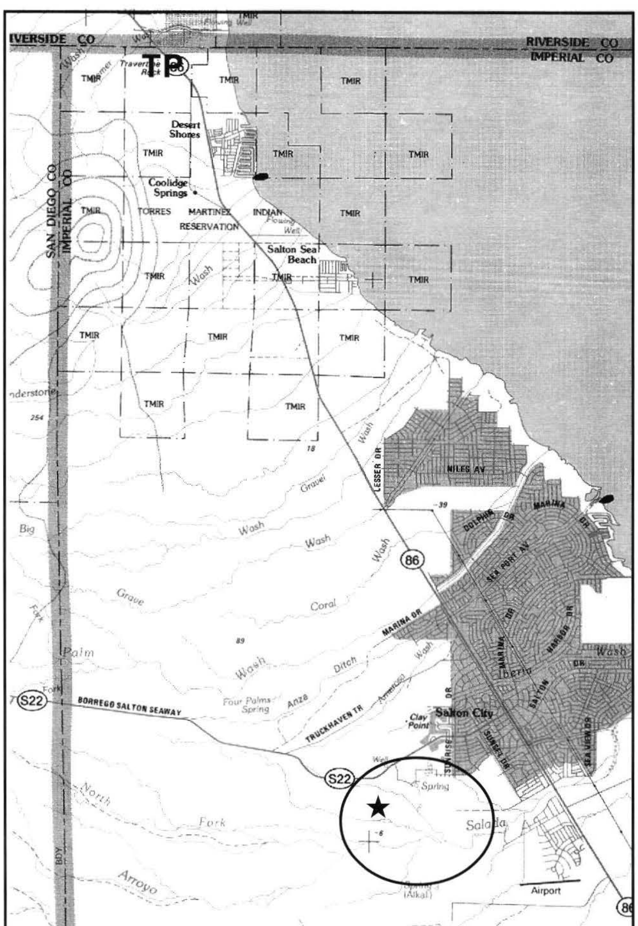
For persons familiar with the greater Anza–Borrego region, I must emphasize that these alkaline springs should *not* be confused with the "Gas Dome" area, which lies about 5½ miles south–southeast of Oh My God Hot Spring (described later in this paper). The Gas Dome is a broad mound of clay–rich sediment topped by a "spring" that may or may not be strictly natural. It is muddy, powered by warm carbon dioxide and occasionally erupts — and so perhaps can be taken as an infrequently active mud geyser. Not far from the Gas Dome is an artesian well (now capped) that struck near–boiling water at a depth of 4,000 feet; it was drilled near the same time as the Oh My God well.

Since James referred to an area of "over half a mile square," I infer that he was not speaking about any one distinct or closely spaced set of spring features. There is more on this interpretation in the following.

Inferred Location of James's "Soda Springs"

James's description apparently refers to now–dormant(?) mud volcanoes in the vicinity of "Oh My God Hot Spring," which itself bears an interesting story. This general area is a short distance southwest of Salton City and is accessible from the Borrego–Salton Seaway (Truckhaven Trail), the highway that leads west into Borrego Valley and the town of Borrego Springs.

Upon leaving State Highway 86 at Salton City, this road passes through the long–abandoned Salton City Golf Course area. I infer that some of the Soda Springs were/are just south of the southwestern–most extent of the golf course. In general, this is about 1 mile east of Oh My God Hot Spring.



Map A. General location of Soda Springs. Near the top of the map and just below the county line, "**TP**" indicates Travertine Point. The ellipse near the bottom shows the area of Oh My God Hot Spring (star) and Soda Springs. Map from *Southern and Central California Atlas & Gazetter*, ©DeLorme Mapping Co.

Oh My God Hot Spring

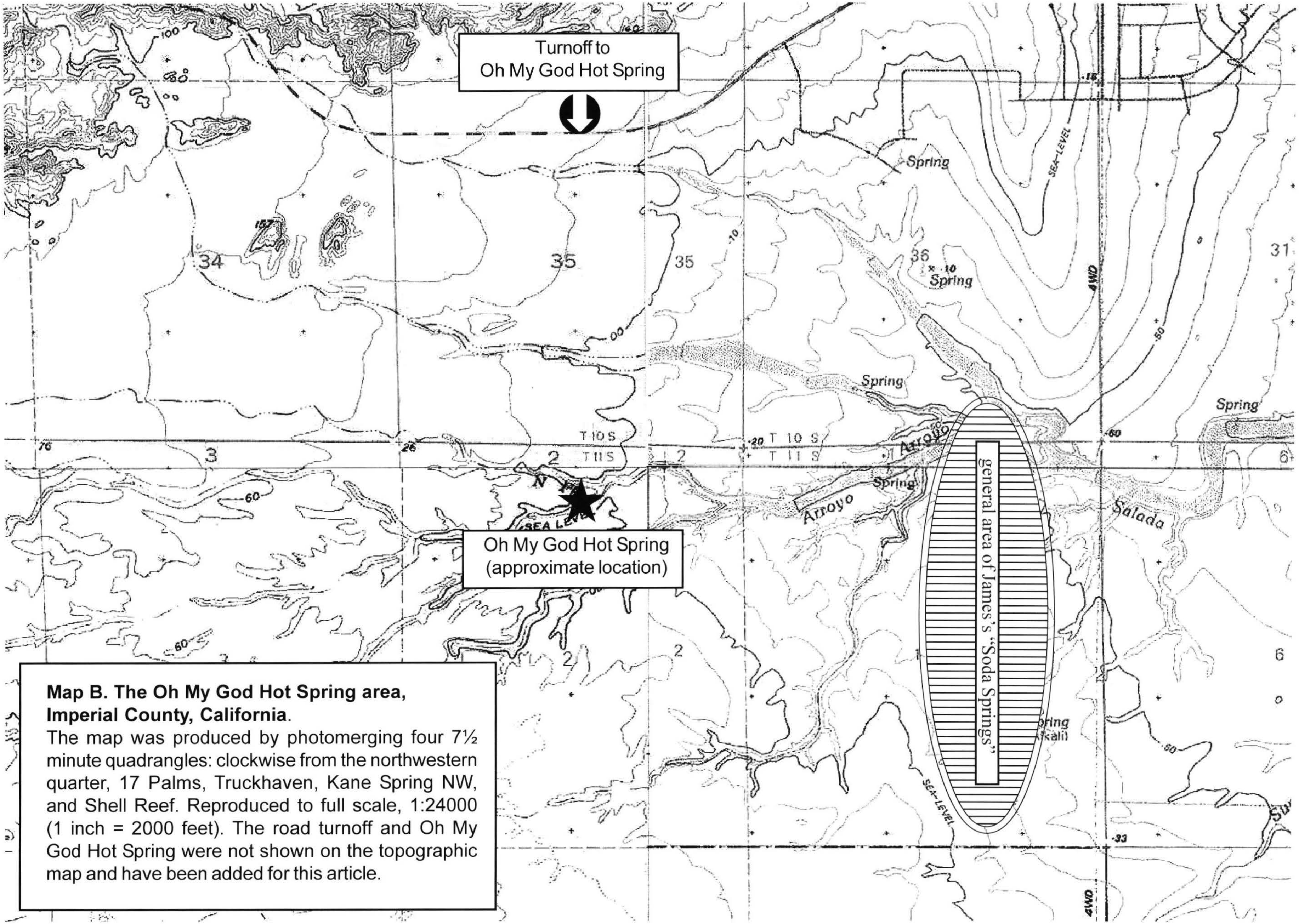
Oh My God Hot Spring was not a natural feature. In the early 1920s a number of wildcat oil wells were drilled throughout the Anza–Borrego region. None struck oil, but this one did encounter a flow of abundant hot water. The discharge was allowed to continue unabated and in time the "spring" was designated by the government as a protected water reserve.

Gradually, the place was discovered by campers, mostly of the free–spirit sort, who planted tamarisk tree windbreaks, erected pit toilets, built stone–walled hot tubs and so on. The name came about gradually, as in: "Oh, my god, this is nice."

There was never any fee for either camping or the use of the pools, and the place became too crowded. At holiday and school vacation times, the population of the campground could reach into the hundreds. Local people objected to the clothing–optional, sometimes–lawless party atmosphere. And so on June 6, 1993, Imperial County authorities, citing health concerns, bulldozed the site into oblivion. In doing so, the county referred to the place as "Soda Spring" (singular) and more recently Lindsey has used both "Soda Springs" (plural) and "Salt and Soda Springs" [Lindsey, 1998].

The turnoff from the Borrego Salton Seaway to the site of Oh My God Hot Spring is 2.9 miles west of Highway 86 at Salton City.

It is not clear whether or not there was any sort of natural water flow at or close to the site of the Oh My God Hot Spring prior to the drilling of the well. It is my feeling that there was not, and that this does *not* represent the Soda Springs of James.



Map B. The Oh My God Hot Spring area, Imperial County, California.
The map was produced by photomerging four 7½ minute quadrangles: clockwise from the northwestern quarter, 17 Palms, Truckhaven, Kane Spring NW, and Shell Reef. Reproduced to full scale, 1:24000 (1 inch = 2000 feet). The road turnoff and Oh My God Hot Spring were not shown on the topographic map and have been added for this article.

Soda Springs

What I infer to be James's Soda Springs is a relatively narrow north–south zone of alkaline springs, roughly 1.4 miles east of Oh My God Hot Spring. A scattering of these springs is shown on the "Truckhaven" and "Kane Spring NW" USGS topographic maps (as in Map B) and on other maps, but for each of those springs, there are several others. For the most part, these springs are nothing more than slight seeps of impalatable water.

Within this area are places where the ground appears to have collapsed, places that probably equate with James's "covered pitfalls."

BLM Geologist Steve Kupferman (Palm Springs Office) reported having seen an active mud pot somewhere in this area. That, however, was "several years ago" and Kupferman was unable to pinpoint the location on topographic maps. He ultimately admitted that he might have been remembering activity in the Gas Domes area.

During my one admittedly brief excursion to the area, I found no evidence of true spring activity. About 100 years ago, James described eroding cones. Kupferman might have seen a single mud pot here; but then again, maybe not. I saw a few seeps.

It is likely that these Soda Springs have had significant existences in the past. Perhaps this is one of those cases where earthquake tremors can stimulate thermal spring activity. The site certainly is geothermal in nature, and it lies within a region where numerous significant earthquakes took place during the latter half of the 1800s * — the right timing to have produced temporary activity not long before James's visit.

Acknowledgement

Thanks to Steve Kupferman for taking the time to sit down with topo maps and spend a few minutes discussing this area.

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Bryan, T. Scott, 2003, Mud pots and geysers near the Salton Sea, Imperial County, California: *The GOSA Transactions*, Volume VIII.

James, George Wharton, 1907, *The Wonders of the Colorado Desert*: Little, Brown, and Company, Boston, Volume I of II, page 191.

Lindsey, Lowell and Diana, 1998, *The Anza–Borrego Desert Region*: Wilderness Press, Berkeley.

* Geologists and historians have developed the record of strong southern California earthquakes during the second half of the 1800s as follows (date, magnitude): 1852, 6.5; 1858, 6.0; 1875, 7.0; 1891, 6.3; 1891, 7.0; 1892, 7.0; 1892, 7.1; 1894, 5.6; 1899, 6.5; and 1899, 6.8.

Geology of the Soda Dam Travertine Deposits, Sandoval County, New Mexico

by William P. Moats

Abstract

The thermal springs and travertine deposits of Soda Dam, in the Jemez Mountains of New Mexico, are associated with the nearby Valles Caldera, which bears a high–temperature geothermal system. This paper presents the results of a mapping project that defines the relationship between the springs and the local geologic setting.

Introduction

Soda Dam is an active travertine mound situated on the floor of Cañon de San Diego in the Jemez Mountains, Sandoval County, New Mexico (Figure 1). It is located within the Santa Fe National Forest along New Mexico Highway 4 about 0.8 kilometers (km) north of the entrance to the U.S. Forest Service Ranger Station at the village of Jemez Springs. The highway crosses Soda Dam through a road cut which dissects the western end of the travertine mound. Because of its easy access along the highway, it is a popular stop for tourists traveling through the Jemez Mountains.

Associated with Soda Dam are several active thermal springs and a number of other travertine deposits of various ages and sizes. Soda Dam spans the entire width of the canyon floor and diverts the Jemez River from the west to the east side of the canyon. The Jemez River flows over a waterfall and beneath the eastern end of Soda Dam through a natural tunnel that has been eroded between the travertine deposit and the underlying bedrock. The waterfall forms a deep plunge pool on the downstream side of Soda Dam which is popular as a swimming hole in the summer months. Elevation of the bottom of the canyon near Soda Dam is about 1980 meters (m).

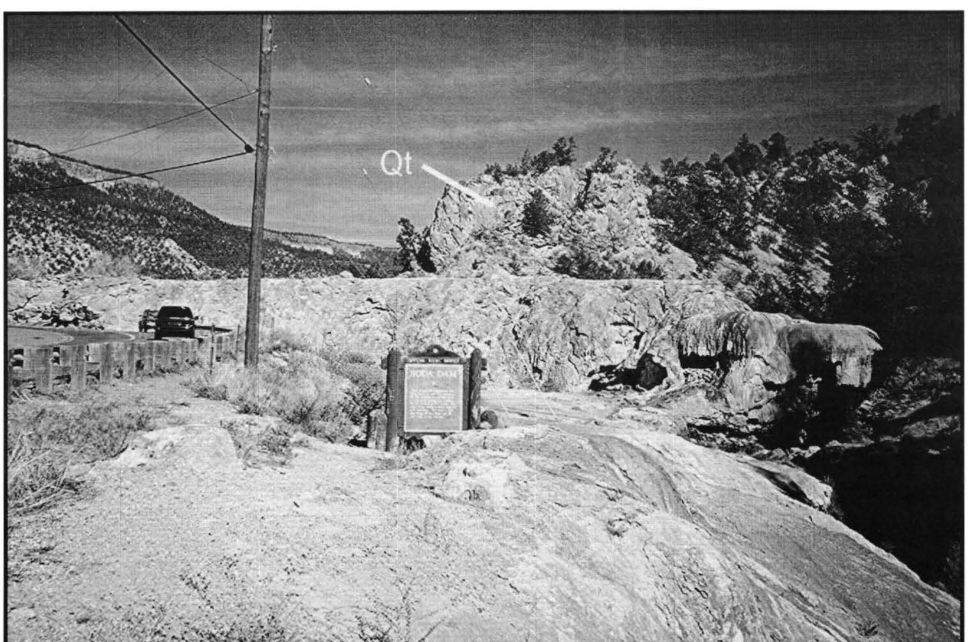

Figure 1. Photograph of Soda Dam looking northeast. The white rocky outcrop in the center of the photograph and visible above the crest of Soda Dam is Travertine B (labeled Qt). The ridge to the right of Travertine B is composed of limestone beds of the Osha Canyon Formation. Two small highly-eroded deposits of travertine occur on top of this ridge and are considered to be a part of Travertine B. In the center foreground, in front of the sign, is a group of inactive cones (Cone Group G).

A few years ago, the author began a mapping project to document the geometry and structure of the younger travertine deposits at Soda Dam. Subsequent research indicated that the travertine deposits and their relationship to the local geologic setting were not well understood. This finding was surprising given that the thermal springs at Soda Dam have been otherwise well studied because of their association with the high-temperature geothermal reservoir in the nearby Valles Caldera (for example see Goff and others, 1981; Trainer, 1974; Dondanville, 1971). Thus, the scope of the original mapping project was expanded in an effort to better determine the origin of the travertine deposits. The results of this mapping project are discussed in this paper.

Geology of the Jemez Mountains

The Jemez Mountains are made up of Tertiary and Quaternary volcanic rocks that overlie a variety of older sedimentary rocks and Precambrian crystalline and metamorphic rocks (Smith and others, 1970; Goff and Kron, 1980; Kelley and others, 2003). The volcanic pile comprises the Jemez Volcanic Field, which is situated at the intersection of the Jemez Lineament and the western margin of the Rio Grande Rift (Figure 2). The Jemez Fault Zone, along which Canon de San Diego follows, makes up a part of the Jemez Lineament (Goff and Shevenell, 1987).

Voluminous eruptions of the Tshirege Member, Bandelier Tuff created the 1.12 million year old (Ma) Valles Caldera and represent the most important volcanic event in the Jemez Mountains. The Valles Caldera has a circular topographic rim 23 to 29 km in diameter, enclosing a ring fracture zone 13 to 16 km across. The southwestern edge of the caldera is breached by the Jemez Fault Zone. A geothermal reservoir lies within the caldera at depths ranging up to 2 km below ground surface. Fluid temperatures within the reservoir reach as much as 330°C (Trainer and others, 2000).

Analysis of stable isotopes indicates the majority of the thermal water contained in the reservoir is of meteoric origin (Trainer and others, 2000). Ground-water recharge within the caldera is heated conductively by hot rocks at depth. Once heated, the thermal waters rise convectively to depths of about 0.6 km or less, and then flow out of the caldera to the west and southwest along the Jemez Fault Zone and under the Jemez Plateau (Trainer and others, 2000). Soda Dam lies outside the Valles Caldera, but within the Jemez Fault Zone.

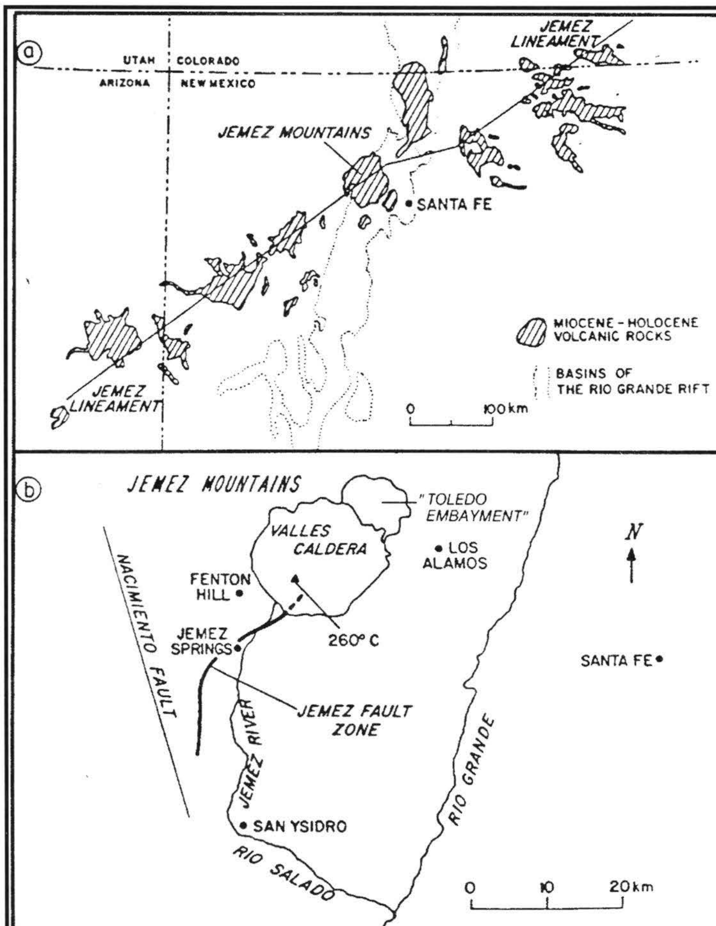

Figure 2. (a) Map showing the location of the Jemez Mountains, the Jemez Volcanic Field, the Jemez Lineament, and basins of the Rio Grande Rift. (b) Map showing the location of Jemez Springs, the Valles Caldera, and the Jemez Fault Zone (from Goff and Shevenell, 1987). The Jemez Fault Zone, a part of the Jemez Lineament, is considered to be the western margin of the Rio Grande Rift in this part of New Mexico.

Geology of the Soda Dam Area

In the Soda Dam area, Precambrian gneiss is overlain by Paleozoic sedimentary rocks and by Quaternary travertine (Figure 3). Precambrian gneiss makes up the cliffs along the bottom of the canyon extending south from Soda Dam to the ranger station. From oldest to youngest, the Paleozoic rocks include the Mississippian Arroyo Peñasco and Log Springs Formations, and the Pennsylvanian Osha

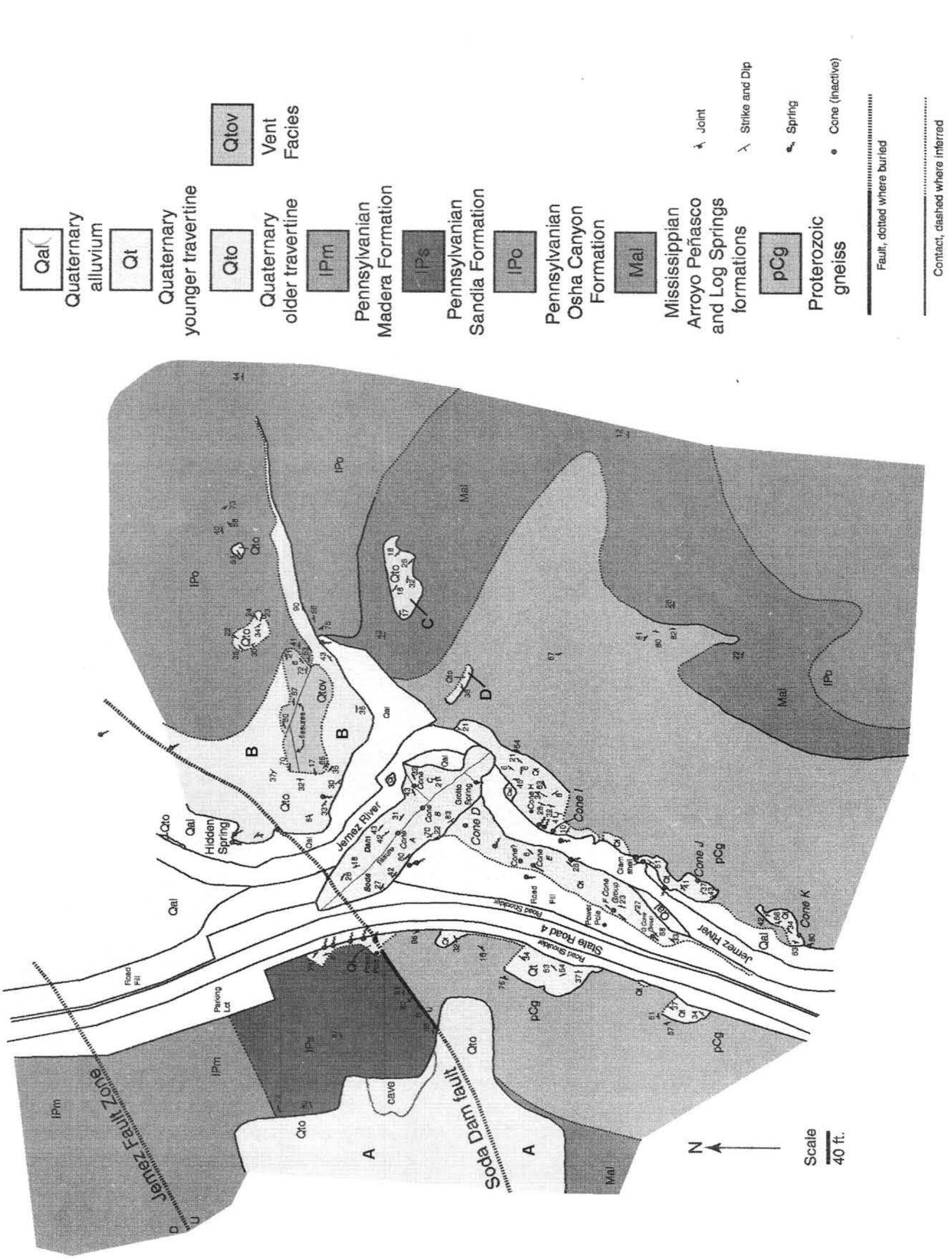

Figure 3. Geologic map of the Soda Dam area. Unit shown as Vent Facies, Qtov, denotes the portion of Travertine B that is characterized by steeply dipping layers of travertine that have been deposited along the two medial fissures. Lines shown near Cone E and Cone Groups F and G denote possible remnants of a medial fissure.

Canyon, Sandia, and Madera Formations. The Arroyo Penasco and Log Springs Formations were mapped together in this study because of poor exposures of these rock units in the Soda Dam area. These latter rocks and the Osha Canyon Formation have a very limited distribution in the Jemez Mountains, being preserved in only a few fault blocks (Woodard, 1996).

The Paleozoic rocks in the Soda Dam area generally strike near east–west and dip from about 20 to 50° north. The overall sedimentary sequence represents several cycles of transgression and regression, and other than the Sandia and Madera Formations, contacts between the rock units are unconformable (Woodard, 1996). Although located to the south and outside the area of this study, rocks of the Permian Abo Formation (red beds) make up part of the lower west canyon wall along the highway between Soda Dam and the ranger station and are in fault contact with Precambrian gneiss and older Paleozoic rocks. Part of one of the older travertine deposits in the Soda Dam area overlies rocks of the Abo Formation based on mapping done by Goff and Shevenell (1987).

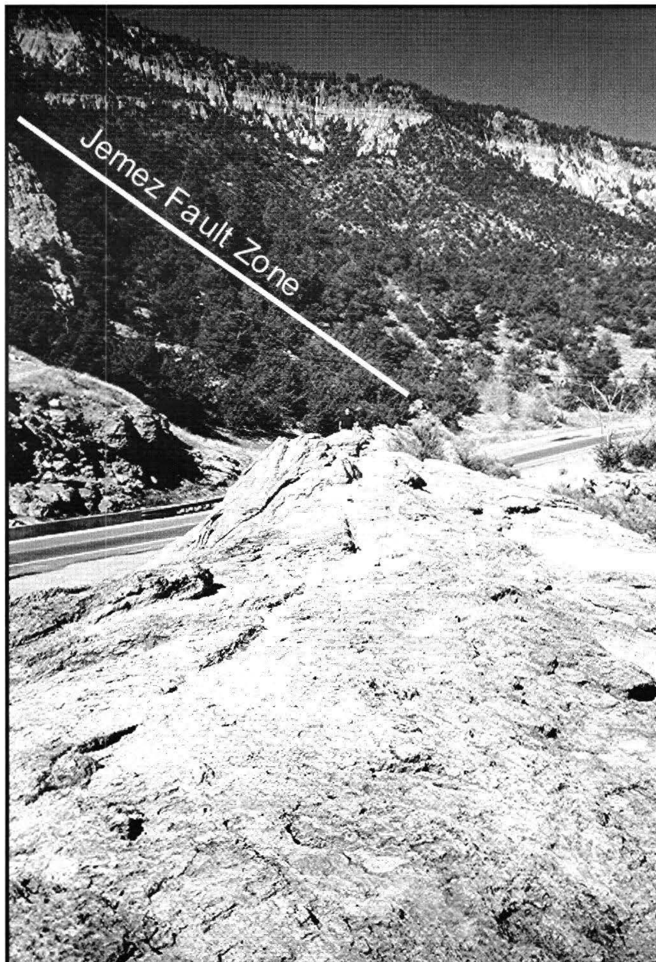

Figure 4. Photograph looking northwest along the crest of Soda Dam. Note the central fissure shown extending from the cone in the center of the photograph towards the lower left. The trace of the west strand of the Jemez Fault Zone is shown as a line on the photograph. Younger Madera Formation strata to right (north) of the fault have moved down relative to older Madera rocks on the left (south).

Steeply dipping rocks of the Sandia and lower Madera Formations crop out west of the highway next to Soda Dam. These rocks were mapped previously by Goff and Kron (1980) as Sandia Formation and older Mississippian rocks, but thick limestone beds near the top of the sequence are characteristic of the Madera Formation and the stratigraphy does not correspond to that of the Mississippian units east of the river. To the north these rocks are faulted against younger shallow–dipping beds of limestone and shale of the Madera Formation (Figures 3 and 4). These younger rocks strike N 25°W and dip 16° northeast. This particular fault is considered to be the main western strand of the Jemez Fault Zone and has an estimated displacement in the Paleozoic rocks of about "650 to 825 feet" (Rogers and others, 1996).

The travertine deposits rest mainly on Precambrian gneiss and to a lesser extent on the Paleozoic rocks (Figure 3). Until recently, the most comprehensive work completed on the travertine deposits was that by Goff and Shevenell (1987). In addition to Soda Dam, they dated and described three of the older travertine deposits in the Soda Dam area, designating them as Travertines A, B, and C; for convenience these same designations are retained by this work.

West of the road, a normal fault striking N 53° E, dipping 80° northwest, intersects the west end of Soda Dam (Figures 3, 5 and 6). Herein referred to as the Soda Dam Fault, it separates arenites of the Sandia Formation from Precambrian gneiss and is exposed on the surface for only about 40 meters (m). To the west, the fault is buried by a large deposit of older travertine (Travertine A); to the east, it is concealed by alluvium and travertine on the valley floor. The Soda Dam Fault aligns with the most significant of the active hot springs located in the road cut.

Goff and Kron (1980) mapped a north–north-west-trending fault separating Precambrian gneiss from Paleozoic rocks at a location about 24 m east of the eastern end of Soda Dam. The northern extent of this fault presumably intersects Travertine B. Although this fault likely exists to the south near the ranger station, it does not actually extend into the Soda Dam area.

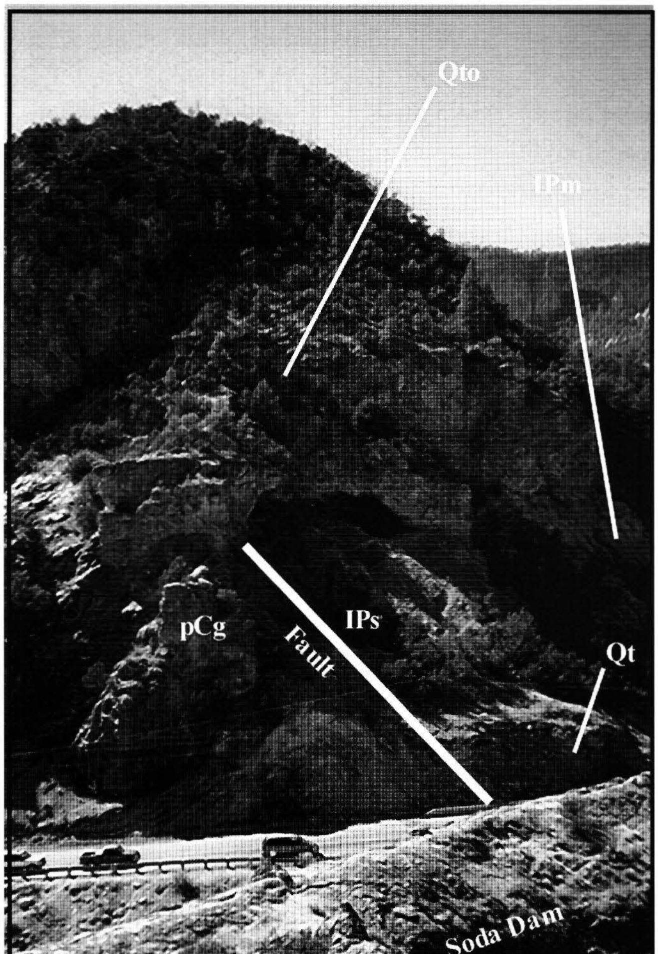

Figure 5. Photograph looking west from Travertine C. The trace of the Soda Dam Fault is shown as a line. The Precambrian gneiss (pCg) forms the footwall left of the fault contact, the Sandia Formation (IPs) forms the hanging wall to the right. The gneiss, normally red or pink in color, has been bleached gray in the vicinity of the fault by hydrothermal alteration. Steeply-dipping limestone beds of the Madera Formation are denoted by the symbol IPm (these beds make up the base of the unit). Travertine A (denoted by the symbol Qto) forms the cliffs above the Sandia and Madera Formations. Note the cave at the base of Travertine A. The symbol Qt denotes the exposed travertine located west of the road cut that represents where Soda Dam once was connected to the hill slope.

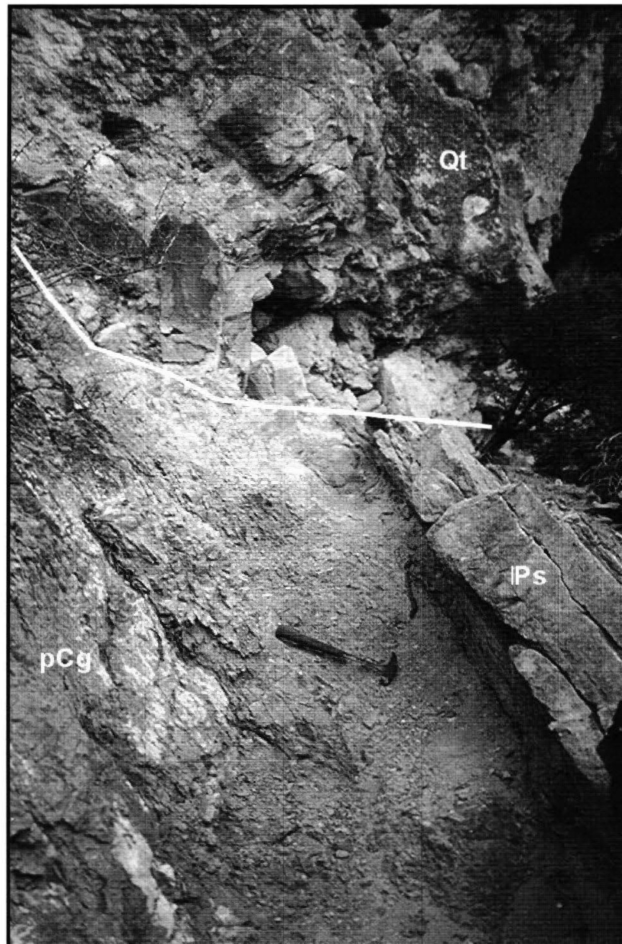

Figure 6. View along the Soda Dam Fault. To the right of the hammer are beds of sandstone (arenite) assigned to the Sandia Formation (IPs). As shown in the upper half of the photograph above the line, the western extent of the fault is buried by Travertine A (Qt). The hammer rests on brecciated and hydrothermally altered Precambrian gneiss (pCg).

Younger Travertine Deposits

Aside from Soda Dam, younger travertine deposits also occur along the east and west banks of the Jemez River and along both walls of the canyon. Small bodies of travertine–cemented colluvium and river gravels occur locally adjacent to some of the younger travertine deposits, and are

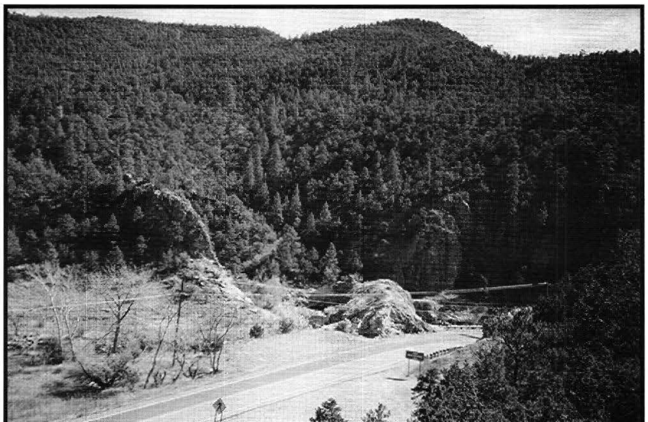

Figure 7. Photograph of the Soda Dam area looking southeast. Soda Dam is to the right and below the center of the photograph. Travertine B forms the white rocky outcrop left of center. Travertine C is visible just behind Travertine B and dips down to the right. Travertine D (not visible in the photograph) lies along the drainage shown in the center of the photograph. Cliffs of Precambrian gneiss (pCg) are visible right of center. Note fractures in pCg with orientations similar to the trend of the central fissure of Soda Dam.

mapped undifferentiated with the latter units. The younger travertine deposits in the Soda Dam area are briefly described in the following paragraphs.

Soda Dam

Being the largest of the travertine mounds on the floor of the canyon, Soda Dam is approximately 12 m high, 18 m wide at its base, and 84 m long (Figures 1, 4, and 7). The crest of Soda Dam is typically only a few meters wide. An active travertine mound, Soda Dam has an estimated age ranging from 0 to about 7 thousand years (7 Ka) (Goff and Shevenell, 1987; Rogers and others, 1996). A central (or medial) fissure trending N 43° W runs along nearly the entire length of the mound (Figures 3 and 4). Scalloped-surfaced layers of dense and porous travertine dip away from both sides of the central fissure. Three inactive cones (Figure 3, Cones A, B, and C [Figure 8]), 0.7 to 1.4 m in height, sit on the crest of Soda Dam. Additionally, several solution caves occur on the downstream side of Soda Dam next to the river (Figure 9).

Travertine layers at the base of and on the upstream side of the deposit are locally truncated because of erosion by the river, and in places incorporate boulders and alluvial gravels. The crest of Soda Dam is remarkably horizontal for most of its length, but drops abruptly about 2.4 m in elevation (Figure 1) at the east end of the mound. Furthermore, the east end of Soda Dam has a round shape that is dissimilar to the linear form of most of the rest of the mound (Figure 3). The central fissure continues uninterrupted through this part of Soda Dam and at this location dips 88° northeast.

The travertine strata that make up Soda Dam are composed of dense, porous, or alternating zones of dense and porous travertine separated by well-defined bedding planes. Contacts between zones

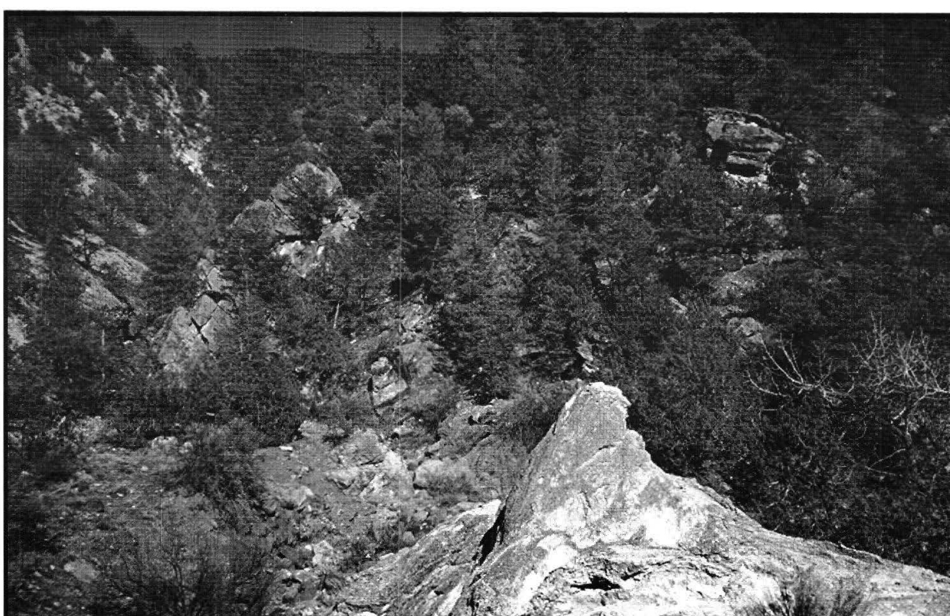

Figure 8. Photograph looking northeast from the crest of Soda Dam. Cone "C", located on a subsidiary fissure of Soda Dam, is visible in the lower center of the photograph. A thick sandstone bed forming the base of the Osha Canyon Formation is visible left of center. Travertine C is visible in the upper right of the photograph. Dips of the Paleozoic rocks increase towards the Soda Dam Fault, probably a result of drag folding along the fault.

Figure 9. Close up view of the solution caves at the east end of Soda Dam. Grotto Spring is located in the cave to the right with the column at the entrance. Discharge from the cave entrance comes from this spring.

of dense and porous travertine may be sharp or gradational. Scalloped surfaces are preserved on the bedding planes which occur at intervals ranging from as little as one centimeter (cm) to about one meter.

Within individual travertine layers, vugs (open spaces) in the porous travertine can vary from a few millimeters to several tens of centimeters in maximum dimension. Perpendicular to the bedding, the vugs are usually no more than a few millimeters to a centimeter in height. Botryoidal masses of white microcrystalline calcite occur ubiquitously in the vugs.

There is no evidence of vertical displacement on either side of the central fissure. Thermal water once flowed from the central fissure of Soda Dam during modern times, however, by the late 1960's road construction damaged part of the natural plumbing system (Goff and Shevenell, 1987). The walls of the central fissure are typically separated by 0.6 to 10 cm of open space. Along the top of Soda Dam much of the open space is now filled with sediment derived chiefly from weathered travertine.

Where exposed at the east side of the road cut, both walls of the central fissure are lined with dense vertically–banded white to gray massive calcite that is 10 cm or more thick. Small crystals of calcite occur as drusy coatings on the outer surfaces of the calcite lining and project into open spaces between the fissure walls. Here also the north wall of the fissure has been exposed over an area of 3 x 10 m and is somewhat curvilinear, dipping on average about 83° northeast. The core of the mound is traversed by a number of fractures that are oriented both concordant and discordant to the travertine strata. Some of these fractures have been enlarged into solution channels (water courses), and a few are filled with veins of crystalline calcite. Travertine in the core of the mound appears to consist more of the denser variety, with less dense, porous travertine becoming more prevalent in the outermost portion of the mound. On the west side of the road cut where Soda Dam was once connected to the hill slope, crude concentric layering of the travertine is evident, but the central fissure is not present. Part of the travertine exposed on the west side of the highway is stained by iron oxides.

A spur approximately 10 m in length branches off from the main trend of Soda Dam (Figure 3), forming along a subsidiary medial fissure trending about N 58° E. The Jemez River has undercut the tip of the spur, causing a portion of it to collapse and fall into the river channel. The subsidiary fissure along which the spur has formed aligns with several hot spring vents located on the west bank of the river.

East Bank Mound

The travertine deposits on the east bank of the river next to Soda Dam lie chiefly at two different elevations and form a composite mound about 15

Figure 10. View of inactive Cone "H" in the center of the photograph. Inactive Cone "I" lies behind Cone "H" to the right of the small natural arch. Inactive Cone Groups "F" and "G" are visible in the upper right of the photograph by the sign on the opposite side of the river.

m wide by 67 m long. The lower part of the mound rises 1 to 2 meters above river level; whereas, the top of the upper part of the mound is an additional 4 m or so higher. The upper part of the mound forms a narrow bench and is bounded on its east side by a prominent fracture in the Precambrian gneiss. The lower part of the mound contains at least two inactive cones situated just above river level, and one active cone in the river, trending N 41° E (Figure 3, Cones H and I; and Figure 10). A pool (or vent) may have once existed adjacent to Cone I based on the presence of an oval-shaped depression in the travertine, 1.5 m wide by 2 m long by 0.15 m deep. Smaller, nearly contiguous travertine deposits extend to the south along the base of the east canyon wall and are discussed later in this paper.

West Bank Mound

The travertine mound on the west bank of the Jemez River is about 12 m wide by 91 m long. The west contact of the mound is obscured by road fill. The mound contains one unnamed active spring (of very low discharge) and at least four inactive cones or cone groups aligned along a trend of approximately N 30° E (Figure 3, Cones D, E, and Cone Groups F and G). In close proximity to some of the cones are possible remnants of a medial fissure that include several fractures, 3 to 4 m long, and a 5.5 cm thick banded calcite vein that is 4.4 m long. Each of the fractures and the calcite vein are oriented similar to the general trend of the cones.

A solution cave, 2.3 m wide by 11 m long by 0.3 to 1 m high, occurs just above river level at a distance of 13 m southeast of Cone E. The cave contains abundant seeps and a spring with small discharge. At the north end of the cave is a pool of water about 1 m wide by 3 m long x 5 cm deep. Stalactites, 3 to 7 cm in length, are present above the pool and are actively forming from continual drips of water.

Travertine Deposits along the Base of the Canyon Walls

A number of small travertine deposits occur along the canyon walls downstream of Soda Dam. A few inactive cones (Figure 3, Cones J, K, and the "Clamshell") occur on the crests of the deposits that are located on the east side of the Jemez River. Small seeps are occasionally observed as much as 3 to 4 m above the river on the travertine deposit that includes Cone J, and two small active cones lie in the river next to this same travertine deposit. In contrast, there are no active seeps or springs associated with the travertine deposits on the west canyon wall.

As they formed on the canyon walls, the dip angles of these deposits tend to be moderately steep (35 to 50°) and toward the river. Travertine deposits on the west wall of the canyon are aligned in a direction of about N 20° E (Figure 11); whereas, those on the east wall trend about N 30° E (Figure 12).

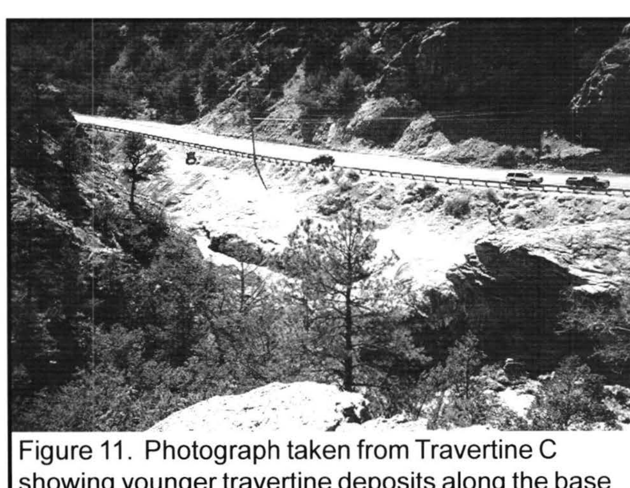

Figure 11. Photograph taken from Travertine C showing younger travertine deposits along the base of the cliffs on the west side of the Jemez River.

Figure 12. Photograph showing younger travertine deposits along the base of the cliffs on the east side of the Jemez River. Just below and left of center is a highly eroded cone referred to in this study as the "Clamshell" because of its shape. Inactive Cone J is visible on the right side of the photograph.

Older Travertine Deposits

Older travertine deposits (Travertines A–D) lie at higher elevations than the younger deposits on both sides of the canyon. As mentioned before, three of these older deposits have been described and dated by Goff and Shevenell (1987), and range in age from about 58 Ka to 1 Ma. Except for Travertine D, river gravels deposited by an ancestral Jemez River occur locally at the base of each of the deposits.

Travertine A

Travertine A is the oldest (0.48 to 1.14 Ma) and largest of all of the travertine deposits in the area and caps the hill west of Soda Dam. It is 30 m or more thick (Figure 5). Only a small portion of the deposit is shown on the geologic map in Figure 3. The northern portion of the deposit overlies the Soda Dam Fault. As can be seen from the highway, a cave 13 m deep by 20 m long has developed at the base of the deposit. Beds of medium to coarse grained sandstone (Sandia Formation) with an exposed total thickness of about 3 m crop out at the back of the cave.

Although located outside of the area of this study, cursory observations suggest that the southern half of Travertine A (as shown on the map of Goff and Kron, 1980) is actually made of slump blocks of travertine that are sliding down the steep hill slope in this area (the hill slope is composed of mudstones of the Abo Formation). Thus, the aerial extent of Travertine A is probably about half the size as was previously thought.

Travertine B

Travertine B (58 to 98 Ka) has a maximum thickness of 18 m and is unusual in that it is traversed by two medial fissures; one trending N 80° E, the other N 69° W (Figure 1). Two smaller bodies of travertine, which are considered to be a part of Travertine B, lie on the ridge to the east and overlie limestone strata of the Osha Canyon Formation. A few active seeps and springs lie at the base of the deposit. Part of Travertine B appears to extend north onto private land, for this reason, that part of the deposit is not shown on the geologic map (Figure 3). However, the part not shown is believed to be only a small portion of the deposit.

Based on the degree of erosion, some of the travertine at the base of Travertine B is probably younger than that making up the main part of the mound. Active springs and seeps at the base of the deposit would seem to support this assertion, but they currently deposit little travertine.

Travertine C

Travertine C (107 Ka) is located about 60 m south of Travertine B on the other side of the drainage (Figure 7). Eroded significantly, it overlies ancient Jemez River gravels and the Arroyo Penasco and Log Springs Formations. The travertine layers making up the deposit dip from 17 to 32° to the southwest.

Travertine D

Travertine D is the smallest of the older travertine deposits and rests on Precambrian gneiss (Figure 13). It lies about 30 m southwest of Travertine C. Although samples from Travertine D have not been dated, the high degree of erosion suggests that it is older than Soda Dam. The deposit dips 36° northwest.

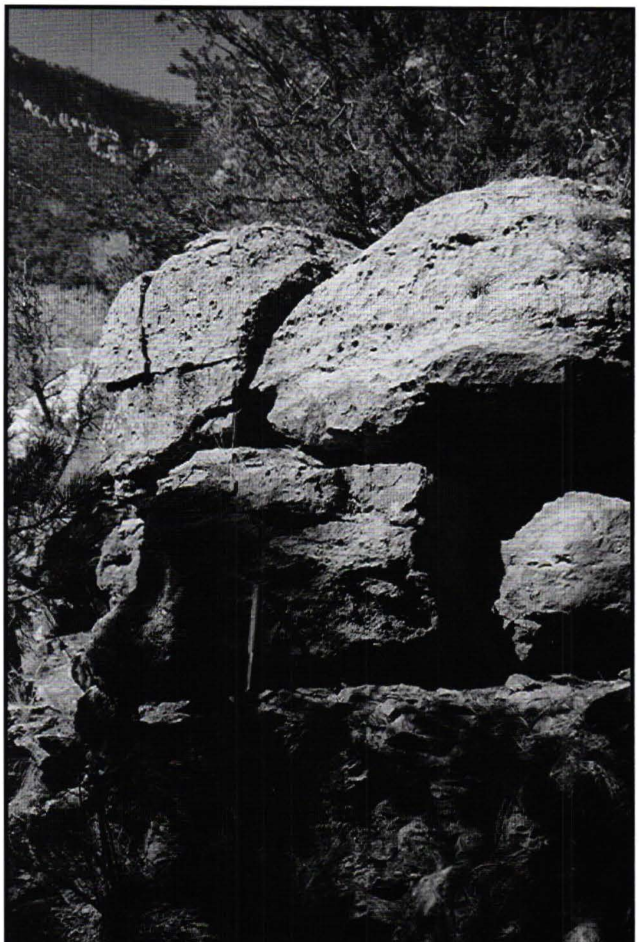

Figure 13. Photograph showing a close up view of the highly eroded Travertine D, which overlies Precambrian gneiss (hammer head rests at contact).

Active Springs

The thermal springs at Soda Dam have been known as the "Upper Group of the Jemez Hot Springs" (Loew, 1875; Peale, 1886; Crook, 1899) and "The Sulphurs" (Jones, 1904). According to Summers (1976), Reagan (1903) was first to apply the name "Soda Dam" in the literature. The number of active springs at Soda Dam has been greater in the past compared to more recent times. Loew (1875) observed 42 springs in the Soda Dam area with temperatures ranging from 21.1°C to 40.6°C; twenty of these springs were located on Soda Dam proper. Reagan (1903) reported 22 springs on Soda Dam, stating that they represented about half of the springs in the Soda Dam group. Based on observations made in 1912, Kelly and Anspach (1913) noted that they were unable to find more than half of the springs on Soda Dam that were reported by Reagan. Some of the springs shown by Summers (1976) along the west side of the highway are now dormant.

The thermal waters that issue at Soda Dam are sodium-chloride waters containing considerable calcium and bicarbonate (Table 1; Trainer and others, 2000). Chemical and isotopic compositions of water samples from the springs suggest that the thermal springs at Soda Dam discharge mixtures of thermal water from the Valles Caldera and colder ground water from mountain recharge (Trainer and others, 2000; Goff and Shevenell, 1987; Rogers and others, 1996). Most of the springs at Soda Dam discharge directly into the Jemez River from the river bed (Trainer and others, 2000). Gas bubbles rising to the surface of the river mark the locations of many of these underwater vents; the plunge pool below the waterfall is a good place to observe such phenomenon when the river flow is low. Trainer and others (2000) used the chloride-load method

Figure 14. View of Main Spring. The Soda Dam Fault aligns with this spring.

Table 1. Hydrochemistry, pH, and temperature of selected springs at Soda Dam. Concentrations in mg/L, except temperature (in °C) and pH (in pH units).

Constituent	Main Spring			Grotto Spring	Hidden Spring	
Sample Date	5/1979	*12/1972	10/1981	7/1978	5/1979	1/1983
SiO_2	46	50	48	38	44	43
Ca	429	330	346	324	376	226
Mg	21.4	24	24.6	27	18.8	15.3
Na	920	990	840	1000	720	817
K	177	200	186	174	141	130
HCO_3	1490	1578	1500	834	1400	1324
SO_4	49.4	52	36.7	41	69.1	53
Cl	1460	1500	1570	1480	1195	1294
TDS	4630	3740	4539	3950	3990	3930
Temperature	47	48	47	38	29	32.3
pH (pH units)	6.52	--	6.3	6.8	6.28	6.13

Note: (*) means data from Trainer and others (2000), all other data are from Shevenell and others (1987).

to estimate the median total discharge of the thermal springs in the Soda Dam area and found it to be about 1400 liters per minute. Only a small fraction of this discharge is from overland flow.

Algae–covered seeps are not uncommon and typically issue from bedding planes exposed in the eroded travertine deposits along the river banks. Seeps coated with algae are also common on the walls and ceilings of the solution caves, and some of the seeps occur at elevations of more than 4 m above river level. These seeps suggest that the bedding planes between travertine layers can serve as important zones of secondary porosity.

About a dozen springs flowing onto the ground surface remain active at Soda Dam. None of the active springs at Soda Dam has a high rate of discharge, and most have very low rates of discharge (less than 1 liter per minute). A few springs and seeps discharge from small cones that are located in the river.

Several springs issue along the west side of the road cut with an estimated combined flow of 40 to 80 liters per minute. Additional runoff also collects under the road and accumulates beneath a cattle guard before exiting to the ditch along the highway. These are all unnatural springs created by the excavation of the road cut. Others have given the name "Main Spring" to this group (Figure 14). In general, springs issuing from the road cut have higher temperatures than those located closer to the river.

Grotto is perhaps the most striking spring at Soda Dam (Figure 15). It is located in a solution cave on the east end of Soda Dam (Figure 9) and discharges thermal water at an estimated rate of 8 to 12 liters per minute. The solution cave is approximately 3 to 4 m wide by 9 m long by 1.2 m high. Water constantly drips from the walls and ceiling of the cave in the area adjacent to Grotto Spring. Runoff from Grotto Spring overflows from a shallow rimmed pool that is approximately 0.9 m wide by 1.2 m long by 15 cm deep (Figure 15).

Aside from Main and Grotto Springs, Hidden Spring is the only other named spring at Soda Dam. Hidden Spring (Figure 16) lies at the base of Travertine B and is "hidden" by grass surrounding its vent. The spring is situated in a marshy area created by spring runoff. The spring lies near the projected trace of the Soda Dam Fault.

Two unnamed springs lie together just east of the road at the downstream toe of Soda Dam; each discharges warm water at a rate of perhaps 8 liters per minute. Because the springs issue from what appears to be disturbed ground (road fill), it is unclear whether they are natural features, or simply represent underflow from beneath the highway.

Figure 16. View of Hidden Spring, which is located at the base of Travertine B. Bubbles rising to the surface are probably chiefly carbon dioxide gas. This spring and others near it are located along or close to the projected trace of the Soda Dam Fault on the east side of the river.

Discussion

Soda Dam is a classic example of a fissure ridge, which is a linear mound of travertine deposited from a series of springs that issue along a fracture or fault. A medial fissure is usually present along the crest of a fissure ridge, as at Soda Dam, but it may be covered in part or in whole with deposits of travertine or sediment. Other travertine deposits associated with Soda Dam are also fissure ridges. Although not as spectacular as Soda Dam, the alignment of hot spring vents suggests that the travertine deposits along both the (lower) east and west banks of the Jemez River are also fissure ridges (Figure 3). Additionally, with its two deep medial fissures, Travertine B is unquestionably a fissure ridge. Each of these deposits is comparable in size, structure, and geometry to the fissure ridges that occur at Mammoth Hot Springs in Yellowstone National Park (Bargar, 1978).

A number of inactive and a few active cones are associated with the travertine deposits in the Soda Dam area. Cones are conical–shaped deposits of travertine that have developed from persistent, isolated points of ground–water discharge. Vents at the top of the cones are usually round or oval in shape and usually range from about 3 to 15 cm across. Most of the inactive cones present in the Soda Dam area today likely formed during the waning stages of spring activity, and are commonly located on the crests of the younger travertine deposits.

Figure 15. View of Grotto Spring. Travertine deposition from water in the pool has formed a small terracette. The scalloped surface texture of the travertine is clearly evident in the photograph.

The upper part of the travertine mound along the east bank of the river would surely have formed in the shape of a classic fissure ridge if it had not formed along a fracture intersecting a cliff face, which allowed travertine deposition to occur only on the downhill side of the fracture. This mode of formation obviously applies to the many smaller travertine deposits located at the base of the canyon walls (Figures 11 and 12).

Although cropping out for only 40 meters, the significance of the Soda Dam Fault cannot be overemphasized as it is the primary conduit for the thermal waters that have formed and continue to form the travertine deposits. Previously, the existence of the Soda Dam Fault has not been properly understood. For example, a "fault zone" between the Precambrian gneiss and Paleozoic rocks was mapped by Summers (1976, referred to by him as granite and limestone). However, it was incorrectly shown as trending northwest in his sketch map of the thermal springs, and he did not show correctly its position relative to Soda Dam. Goff and Shevenell (1987) state that the thermal springs issue from a shear zone between Precambrian gneiss and vertically standing Paleozoic rock, but they did not map a structure that would correspond to the Soda Dam Fault. Furthermore, they may have believed that the contact between the gneiss and the Paleozoic rocks is depositional, as suggested by Rogers and others (1996). Finally, Trainer and others (2000) simply state that the thermal springs at Soda Dam discharge from fractured gneiss and limestone cropping out within the Jemez Fault Zone.

Travertine A probably owes at least part of its origin to thermal waters rising along the Soda Dam Fault given that it overlies and is partly elongated along the projected trace of the fault. Goff and Shevenell (1987) report a probable hot spring vent at the summit of Travertine A (at sample site 6 on their sketch map of sampling locations). The location of this vent as shown on their map suggests that the vent overlies the Soda Dam fault. It is suggested here that careful mapping of the dip directions of the travertine layers may be useful to constrain possible vent locations for this large travertine deposit.

Most of the hot spring deposits in the Soda Dam area overlie the Precambrian gneiss. Compared to that of the sedimentary rocks, the hard brittle character of the gneiss allowed for the formation of more laterally extensive and open fractures in response to tectonic stresses. Evidence supporting this conclusion is found along the Soda Dam Fault, where sheeting, brecciation, and hydrothermal alteration are more extensive in the Precambrian gneiss compared to the dominantly clastic rocks of the adjacent Sandia Formation. Fractures within the Precambrian gneiss have served as important pathways for the migration of the thermal waters.

The overall distribution of the spring deposits suggests that the thermal waters migrating along the Soda Dam Fault are further dispersed by two dominant fracture sets cutting the Precambrian gneiss at trends of N 20° E to N 41° E, and N 43° W to N 56° W (Figure 3). Although cones tend to occur mostly at the intersection of the two fracture sets, nearly all of the spring deposits are elongated with their maximum dimensions oriented northeast–southwest. This suggests that of the two fracture sets, the northeast–trending fractures played the most important role in the genesis of the hot spring deposits.

In contrast to the latter, Soda Dam has formed from the deposition of travertine along a northwest-trending fracture (N 43° W). That it is one of the larger and currently the most active of the travertine deposits is likely a consequence of it being connected directly to the Soda Dam Fault, which as mentioned previously, is the main conduit for the thermal waters forming the travertine deposits.

Travertine C and at least the eastern portion of Travertine B rest on Paleozoic rocks instead of the Precambrian gneiss. The geometry of each of these deposits suggests that they formed along a fracture pattern that is different from that occurring in the Precambrian gneiss. More specifically, the deposits must have formed from springs that issued along a fracture set that trended similar to the strike of the Paleozoic rocks on which the deposits rest.

The round shape, flat top, and lower elevation of the eastern end of Soda Dam (Figure 3) suggests that this part of Soda Dam was once a separate and smaller travertine mound, which has since coalesced with the main fissure ridge. Horizontal strata and remnants of low rimstone dams mark the locations of shallow pools that once existed on the crest of this part of Soda Dam. Overflow of water from these pools deposited travertine forming two terracettes. The stalactite-like masses of travertine that in part overhang the river have developed on the sides of these terracettes. One of the terracettes, about 7.6 m in diameter, forms the eastern terminus of Soda Dam and is split into two halves by the main medial fissure. The other terracette is semicircular in shape (radius of about 6.5 m), about 1 m higher in elevation, and has formed along a subsidiary fissure that is 5.5 m long, trending S 40° W (Figure 3). Grotto Spring apparently discharges underground from this same subsidiary fissure.

Conclusions

The Soda Dam Fault is the primary conduit for the thermal waters that have formed and continue to form the travertine deposits at Soda Dam. Thermal waters migrating along this fault are further distributed by two dominant fracture sets within the Precambrian gneiss that trend N 20 to 41° E and N 43 to 56° W. Most of the spring deposits overlie the Precambrian gneiss and are elongated in a northeast-southwest direction, indicating that the northeast-trending fractures were the most important with respect to the genesis of the travertine deposits. Unlike most of the other travertine deposits in the area, Soda Dam has formed along a northwest-trending fracture that is connected directly to the Soda Dam Fault.

Acknowledgement

The author thanks Dr. Shari Kelley for helpful discussions on the lithology of the Sandia and Madera Formations and for drafting the geologic map used for this publication.

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A first day cover of Russian postage stamps, showing the Vitrazh in the Valley of Geysers (left) and muddy springs in Uzon Caldera (right), cancelled on June 20, 2002. The image to the far left is a drawing of Volcano Ayvachinsky. The envelope, a gift from Bill Warnock, is in the collection of Scott Bryan.

Geysers in Bolivia —
a summary of possibilities

compiled by T. Scott Bryan

Abstract

That geysers might exist within Bolivia should be no surprise, given their certain existence at no fewer than three localities not far across the border within Chile. However, although geysers have been reported to occur at six Bolivian locations, at none of those places have *true* geysers been confirmed to exist. This paper summarizes the bare knowledge available about these localities.

Introduction

The primary source of information for this paper was written by Raúl Carrasco [1977]. It is a very brief summary, with most of the information presented in a tabulated format. A little additional knowledge came from Swaney [1996], from an on–line brochure from Toñito Tours [undated] of Uyuni, Bolivia, and a published booklet from Servicio Colibri [1993]. Last was the first–hand knowledge of American geyser gazers who visited Sol de Mañana in 2002 [Glennon and Pfaff, 2003].

During past searches for information via the World Wide Web, I have occasionally encountered additional Bolivian hot spring areas described as including "geysers," but beyond any future confirmation about those places, I conclude that they contain no true geysers.

The six cited localities are briefly described in the following text (quotations from Carrasco are translated from the Spanish) and their locations are plotted on the map of Figure 1. Please understand that I have not been to Bolivia, and that here I simply report from published sources.

1. Rio Junthuma, Parque Nacional Sajama — 18.08°S, 69.05°W

This rather extensive thermal area is located at an altitude of nearly 14,700 feet (4,480m) in western Bolivia. Carrasco did not state the existence of actual geysers, but with a temperature of 179°F (82°C) he did note "steam vents, pools of hot water and the deposition of siliceous sinter."

In Swaney is the following: "About 1½ hours on foot due west of Sajama [village] is a geyser field with some nice spouting hot springs. Given the temperature and the obvious risks, don't get too close…"

A Web page noted a geyser field within the national park but described the pools as only tepid. That author may have been confused, however, as another set of hot springs lies near the road only 5 km from Sajama village. These springs, advertised as "swimmable," might be those of **Rio Kasilla**, described by Carrasco as being "lukewarm [temperature only 93°F], on and within a terrace of sinter."

2. Towa — 20.55°S, 68.43°W

I have been unable to learn anything about this locality beyond the small bit published in Carrasco. At an altitude of 12,400 feet (3,780m), water as hot as 185°F (85°C) supports "hot pools and geysers among small deposits of siliceous sinter."

Perhaps notable is that Towa lies within four miles of the Mina Concepcion, an active sulfur mine among steam vents with a high content of hydrogen sulfide.

3. Rio Quetena — approximately 22°S, 67.7°W

It is commonly said that Yellowstone's Norris is the world's only acidic geyser basin. That is not so, if geysers truly exist at Rio Quetena — the pH of the water is about 5 and the springs are described as "extremely muddy."

The Rio Quetena springs are located along the river that drains northeast from Laguna Colorada, near its confluence with Rio Lipez. Here the water temperature reaches 176°F (80°C) where the elevation is 13,546 feet (4,130m) above sea level. Carrasco's description is of: "Steam vents and small geysers, on alluvial terraces. Ferric alteration."

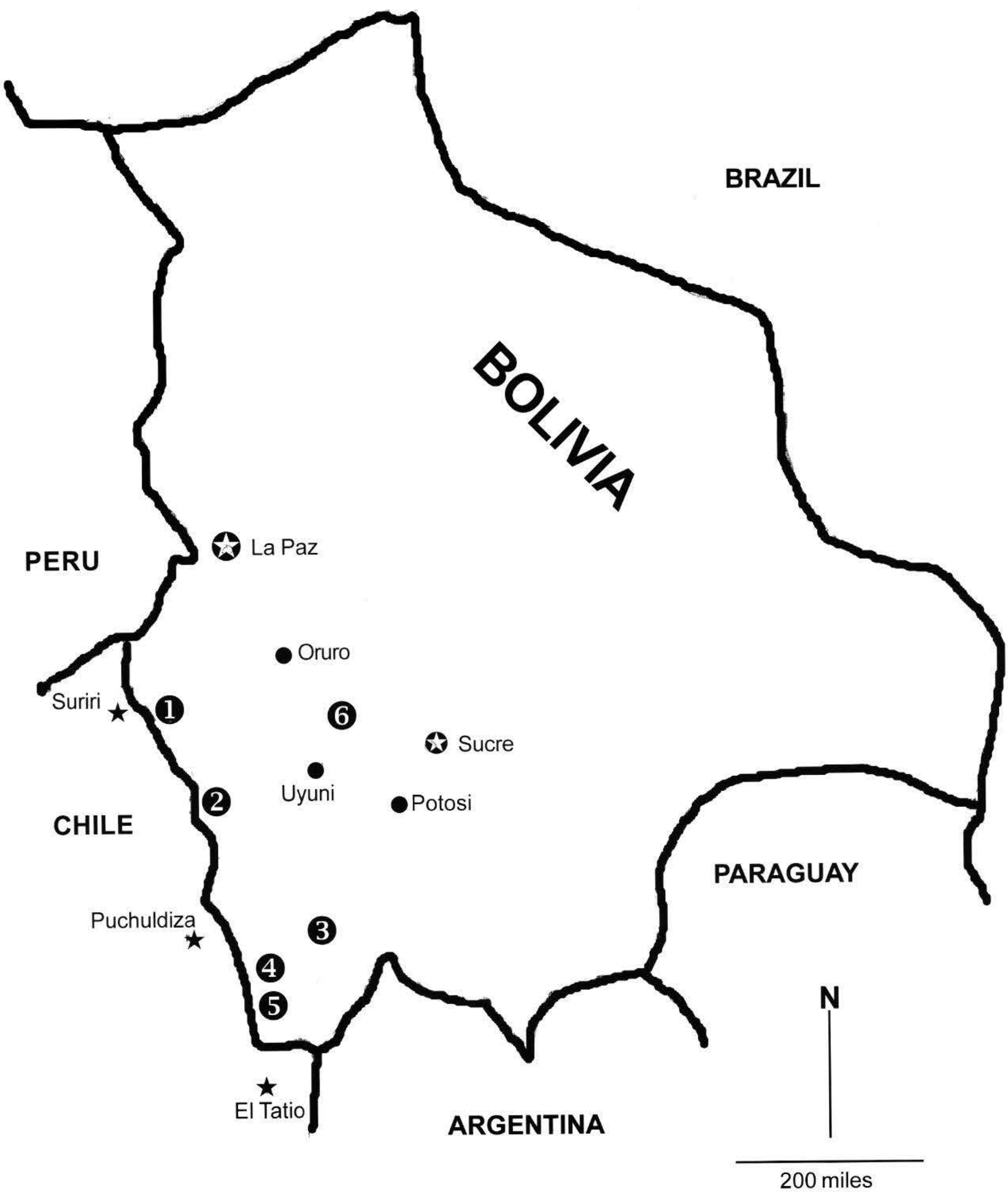

Figure 1. The Geysers of Bolivia — possible localities as described in this paper

The described localities are by number:
1 — Rio Junthuma; 2 — Towa; 3 — Rio Quetena; 4 — Rio Huayllajara; 5 — Rio Agüita Brava; 6 — Luluni.
Note the relative positions of the three known geyser fields of Chile (stars with names).
Map scale 1:10,700,000.

4. Rio Huayllajara — geographic coordinates not cited

This area combined with #5 below corresponds to Sol de Mañana, a prime tourist destination that *might* include true geysers. Carrasco said that Rio Huayllajara is at an altitude of 15,678 feet (4,780m) and has a maximum water temperature of 177°F (81°C). Carrasco said: "Steam vents, pools and geysers of hot water, fumaroles and small volcanoes of hot mud, alteration and deposits of sinter."

5. Rio Agüita Brava — geographic coordinates not cited

This is likely the area most specifically known as Sol de Mañana, and if so it is located at 22.45°S, 67.76°W. The elevation is 16,000 feet (4,880m) and higher; the water temperature reaches as high as 186°F (85°C), superheated at that altitude. Carrasco's description was identical to that for Rio Huayllajara (#4 above).

Presuming that this is Sol de Mañana (which covers an area of at least 10 square kilometers), it was briefly visited by Rhonda Pfaff, Shane Fryer and Wendon Hawkins in 2002. Part of their description [Glennon and Pfaff, 2003] says: "...we saw one perpetual spouter sputtering a fine spray a meter high within its crater. Because other features in the area appeared to be watery, it is likely that there are other perpetual spouters and possibly geysers." Indeed, this is the only place in Bolivia that is nearly always listed as including geysers — for example, "fumaroles and geysers" by Servicio Colibri and "exploding geisers [*sic*]" by Toñito Tours.

6. Luluni — 18.67°S, 66.38°W

This locality is in a very different part of Bolivia from the above, lying in the Eastern Cordillera at an altitude of 11,150 feet (3,400m). The water temperature was given as 183°F (84°C) and the activity as: "Vents of hot water and geysers in a zone of rugged outcrops and deposition of travertine."

Acknowledgements

Thanks are due to Bill Warnock who, via a friend of his in World Vision International's Bolivian office, provided the Carrasco paper, and Alan Glennon who clarified the locality description for Sol de Mañana.

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The Operation and Geography of Carbon Dioxide-Driven, Cold-Water "Geysers"

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Abstract

Eruptive activity of carbon-dioxide-driven, cold-water geysers is similar to hot-water geysers, except that CO_2 bubbles cause the eruption instead of steam. CO_2-driven eruptions occur as CO_2 degasses and expands, displacing overlying water. Many, if not most, cold-water geysers are actually manmade boreholes. Several such erupting wells, including Crystal and Woodside Geysers, are located near Green River, Utah. Similar to their naturally occurring counterparts, their exact eruptive activity may be erratic and change through time. Generally, however, frequency and power of Crystal and Woodside Geysers' eruptions have been observed to be fairly consistent over the past decade. Cold-water geysers are known in France, Germany, New Zealand, Serbia, Slovakia, and the United States.

The Operation of CO_2-driven Cold-Water Geysers

The activity of cold-water geysers is similar to their hot water counterparts, except that CO_2 bubbles drive the eruption instead of steam. In cold-water geysers, CO_2-laden water lies in a confined aquifer, in which water and CO_2 are trapped by less permeable overlying strata. Only in a handful of places, such as at faults, joints, or drilled wells, can the water and CO_2 readily escape the underlying aquifer. If a well is drilled through a confining layer into a CO_2-laden aquifer, the borehole provides a path for the pressurized water and CO_2 to reach the surface. Faults and joints also may provide routes for gas-laden water to penetrate an overlying confining layer. Aquifer and plumbing attributes, including plumbing depth, CO_2 concentrations, aquifer yield, and so on, combine to provide the differing scales and frequencies of eruptions.

Analogous to steam bubbles expanding to displace water in a hot water geyser, the column of water in a cold-water geyser's plumbing exerts enough pressure to keep the CO_2 in solution and in small bubbles. A decrease in pressure of the water column allows CO_2 to outgas and any existing CO_2 bubbles to expand. This "boiling" deep in the system is comparable to water flashing to steam in a hot water geyser. As the CO_2 outgasses, it displaces water and starts the eruption.

Activity at Crystal Geyser, Utah

Crystal Geyser is a CO_2-driven erupting well located eight kilometers south of Green River, Utah. The geyser itself is situated on a broad and colorful travertine terrace developed along the eastern bank of the Green River. While the borehole is manmade, the periodic eruptions occur naturally. A 1.5-by-1-meter pool is located 15 meters east-southeast of Crystal Geyser. Closely related to Crystal Geyser, this small pool periodically sputters and splashes.

Note: A *geyser* is defined as a hot spring in which eruptive activity is induced by boiling at depth within a plumbing system that forcibly ejects water out of the vent in an intermittent fashion (White 1968, Bryan 2001). Because Crystal Geyser and the other known cold-water geysers are neither hot springs nor are their vents naturally occurring, these features are not *true* geysers. However, for this report, these cold-water, CO_2-driven, periodically-erupting features will be described informally as geysers. In addition, in this report, *boiling* refers to periods of effervescent bubbling of CO_2.

Table 1 — Known Cold-Water Geysers of the World

Name	Location	Height	Interval	Duration
Crystal Geyser	Green River, Utah, USA	15–20 meters	11–18 hours	15–45 minutes
Woodside Geyser (Roadside Geyser)	Woodside, Utah, USA	6–10 meters	28 minutes	1.0–1.5 hours
Champagne Geyser (Chaffin Ranch Geyser)[1]	Green River, Utah, USA	7–8 meters	2 hours	5 minutes
Ten Mile Geyser[2]	Green River, Utah, USA	2.5–3.5 meters	6 hours 42 minutes	51 seconds
Tumbleweed Geyser[2]	Green River, Utah, USA	0.3–1.5 meters	2–8.5 minutes	46–94 minutes
Unnamed geyser[3,*]	Salton Sea, California, USA	0.1–0.5 meters	10–60 seconds	seconds
Jones Fountain of Life[4]	Clearlake, California, USA	< 1.0 meter	60 minutes	22 minutes
Cold Water Geyser[5,*]	Yellowstone, Wyoming, USA	0.5 meters	unknown	10 minutes
Source Intermittente de Vesse[6]	Bellerive, France	1–6 meters	230–270 minutes	45–50 minutes
Andernach Geyser[*]	Andernach, Germany	40–60 meters	1.5–4 hours	7–8 minutes
Boiling Fount local name: Brubbel	Wallenborn, Germany	2–3 meters	30 minutes	"a few minutes"
Mokena Geyser[7]	North Island, New Zealand	0.5–5 meters	minutes–hours	seconds–minutes
Povremeni Geyser[8]	Sijarinska, Serbia	20 meters	9 minutes	2 minutes
Herlany Geyser	Herlany, Slovakia	20–30 meters	32–34 hours	30 minutes
Perši Geyser[9]	Perši, Slovakia	"smaller than Herlany Geyser"	hours ("shorter than Herlany Geyser")	minutes (probably < 30)

[1] Murray, unpublished manuscript.; [2] Ross (1997); [3] Bryan (2003); [4] Galloway *et al.* (1997); [5] Whittlesey (1988); [6] Bellerive-sur-Alleir (2004); [7] Environment Waikato (2004); [8] Serbia Tourism (2004); [9] Rinehart (1980).

[*] when active

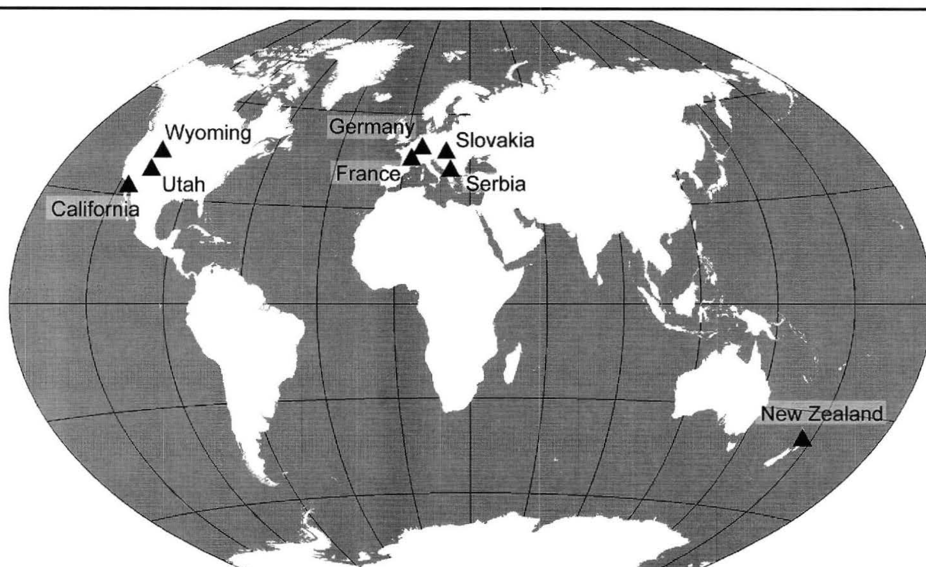

Figure 1. World map showing the known locations of cold-water geysers.

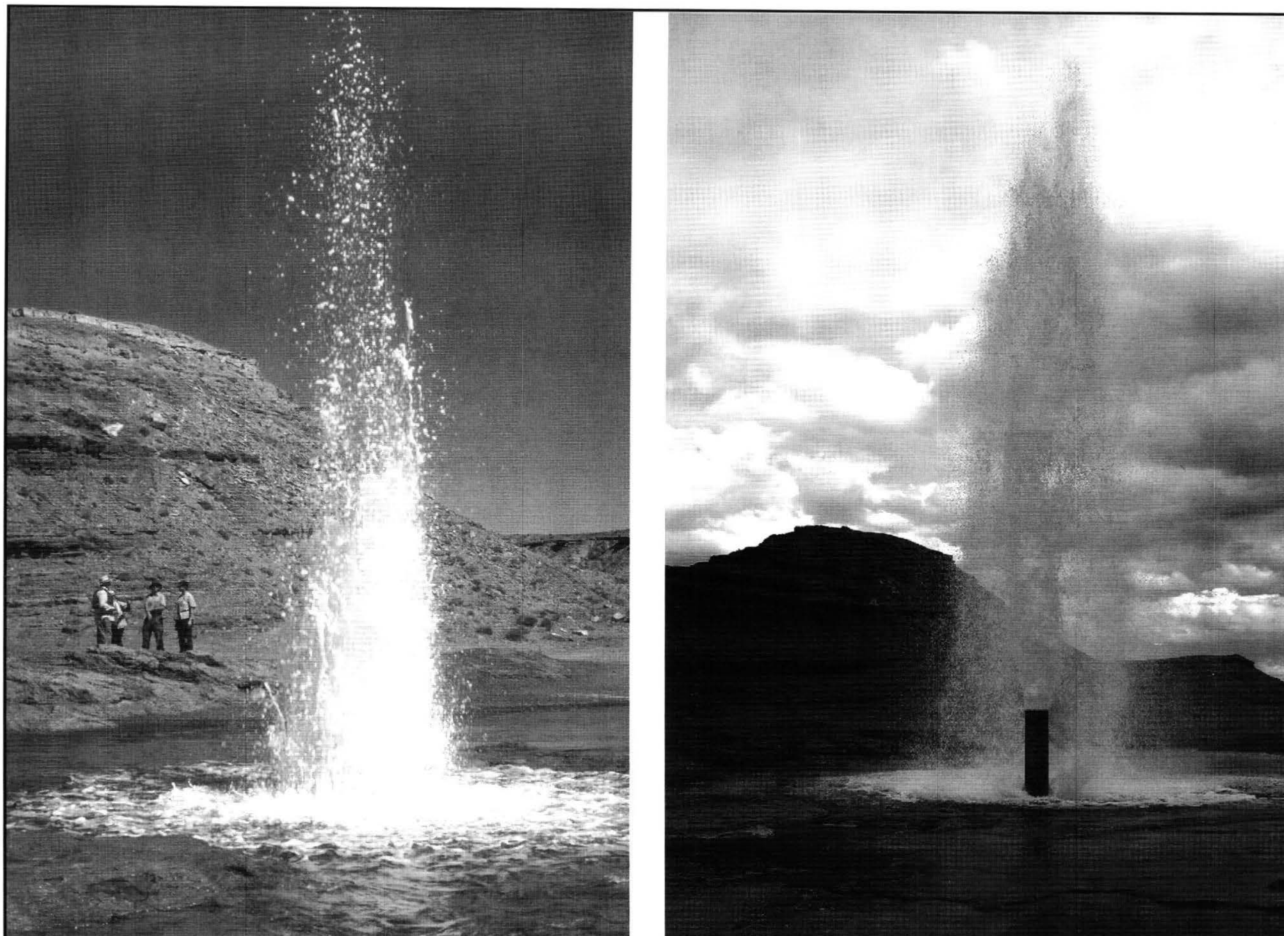

Figure 2. Crystal Geyser, Utah, comparing an eruption in 1995 (left photo) with another on June 10, 2004 (right). [Photos by Alan Glennon]

Murray and others have described the geyser and setting (Murray, 1989a; Baer and Rigby, 1978; Waltham, 2001). Research on the area's CO_2-laden groundwater reservoirs is being conducted by Utah State University (Heath *et al.*, 2003). Since Murray's article in GOSA Transactions II (1989a), a taller and somewhat wider-diameter, casing has been installed on the well. Before October 2000, a rusted metal casing rose approximately 0.3 meters above the ground surface. The well's current casing stands 1.2 meters or more above ground. Additionally, a metal screen at the ground surface allows limited inflow and outflow of water.

Crystal Geyser's well penetrates a confined aquifer with a hydraulic head above the level of the ground surface. If not for the geyser-like behavior, the well likely would possess artesian discharge. When CO_2 and water reach the surface, CO_2 outgassing creates effervescent boiling at the vent. This agitation causes a pressure release for the CO_2 in the aquifer plumbing. Eventually, one of the boiling episodes is large enough to create a chain reaction of CO_2 degassing and expanding down the well: an eruption.

During a trip to the site in 1995, the nearby erupting pool splashed up to a meter in concert with Crystal's eruptions. Between that trip and 2000, someone had attempted to seal the pool's eruptions. During visits in 2000 and 2004, the pool had fresh debris—mostly mud and gravel—filling its crater. A local gas station owner said that the pool was filled in, the upper reaches of the well re-drilled, and the new casing installed in an effort to increase Crystal Geyser's frequency. The fill's effect on Crystal Geyser is unclear: although the larger-diameter casing mutes the height of the eruption, the power of activity and major eruption timing appears to be quite similar to observations in

1995 and 2000.

Alan Glennon visited Crystal Geyser on 10 June 2004; it erupted at 16:29 (Mountain Daylight Time). Upon arrival at 08:00, the terrace was dry except for a single area dampened by light overflow. At 08:04, the vent became agitated and discharge increased, wetting a larger area of the terrace. After a few minutes, the activity subsided and the vent's overflow stopped. Cycles of increased bubbling and agitation occurred approximately every 30 minutes. During these active periods, the well vent surged with frothy boiling for five to 10 minutes. At that point, overflow ceased, the water flow reversed, and water drained into the well. While the well was "taking" water, the small muddy pool nearby filled, sputtered, and boiled from CO_2 gas. The pool splashed for about five minutes to heights of several centimeters to a decimeter. When the well stopped taking water, the pool drained. Next, over a period of 15–20 minutes, the basin around the well slowly filled with water. The cycle maintained approximately the same pattern throughout the day, but the runoff from the well increased and the muddy pool's eruptions strengthened with each cycle.

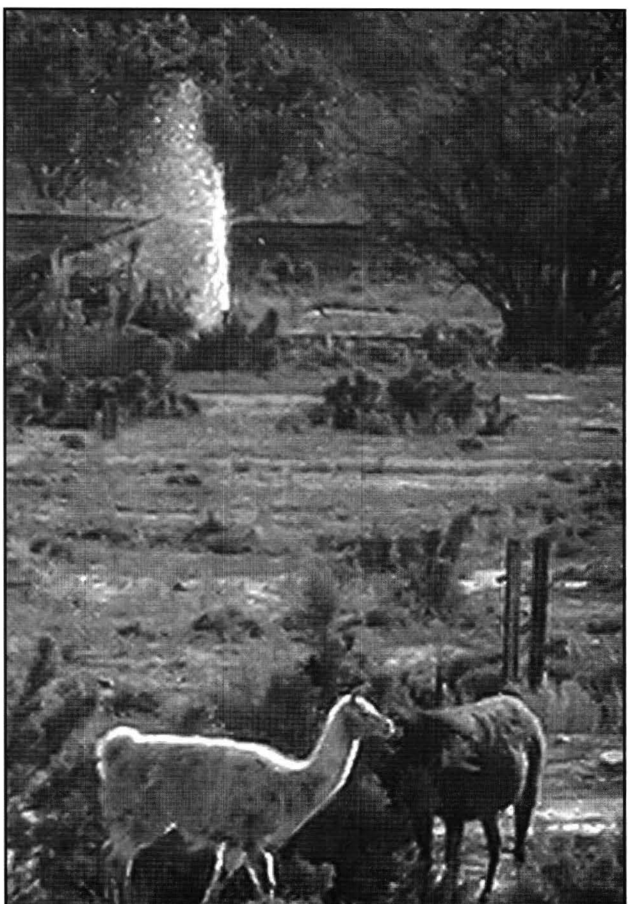

Figure 3. A 2004 eruption of Woodside Geyser, Utah, as viewed from the nearby highway. [Photo by Alan Glennon]

The major eruption began during an episode of agitation in the main well. Instead of reversing flow and triggering agitation in the nearby pool as the effervescence waned, the mild boiling behavior continued in the main well. Over the next two minutes, agitation of both the pool and well increased—triggering the major eruption. The burst-and-pause major eruption lasted approximately 20 minutes with a maximum height of approximately 10 meters, which was achieved for only the first two to three minutes. The remaining play consisted of progressively weakening bursts of two to three meters. By 30 minutes after the initial eruption burst, the water column in the well had lowered to a few meters below the surface.

Unlike the observations in 1995 and 2000, no afterbursts or secondary eruptions occurred. A closed interval was not observed but the interval is estimated to be 11–18 hours based on local accounts and previous activity.

Woodside Geyser, Utah

After visiting Crystal Geyser, Glennon drove to Woodside Geyser. Woodside Geyser is located approximately 30 kilometers northwest of Green River, Utah. The geyser, an erupting drilled well, lies behind an out-of-business gas station along Highway 6/191. Glennon was unable to observe the geyser closely, but saw it in eruption from a distance of several hundred meters. A one-meter or taller casing also has been installed at Woodside Geyser. During Glennon's trip to Woodside in 1995, the geyser erupted from the middle of a shallow pool and little or no casing was visible. Murray describes the geyser in GOSA Transactions II (1989b).

The landowner reported on 10 June 2004 that the geyser erupts for periods of 1.0–1.5 hours followed by a quiet interval of 28 minutes. The play is comprised of bursts and pauses. At the start of the eruption, bursts may reach 10 meters or more, but they quickly weaken. For the rest of the eruption, bursts reach between two and three meters.

Cold-Water Geyser Locations

Given that many, if not most, cold-water geysers are drilled wells, they rarely reside in pristine natural settings. At Source Intermittente de Vesse, France, Boiling Fount, Germany, and Herlany Geyser, Slovakia, concrete and stonework basins have been constructed around the wellheads; the geysers look like city park fountains. Only two CO_2-driven, cold-water geysers — a small unnamed spouter at Salton Sea, California, and Cold Water Geyser, Yellowstone — possess both natural vents and lie in relatively undisturbed settings. The appearance of cold-water geysers may be quite similar to their steam-driven counterparts; however, often CO_2-laden water is more white and frothy. Cold-water geysers are known in France, Germany, New Zealand, Serbia, Slovakia, and the United States (Table 1).

Several effervescent springs exist near the town of Vichy in central France. At least one of these, at the village Bellerive, the Source Intermittente de Vesse, has periodic eruptions. The geyser typically erupts one meter high for 45–50 minutes followed by a quiet period of 230–270 minutes (Bellerive-sur-Alleir, 2004). Thus, the period from the start of an eruption to the subsequent eruption start is 4.5–5.5 hours.

The Rheinland-Pfalz Region of Germany, south of Bonn, has at least two cold-water geysers. Badly damaged during the First and Second World Wars, a cold-water geyser at Andernach was redrilled and restored in 2001 (Schmitt, 2004). However, due to its location within a restricted nature preserve, the erupting well currently is capped and closed to the public. The geyser reportedly is capable of eruption heights to 40–60 meters for 7–8 minutes every 1.5 hours. A small cold-water geyser is found in a city park in the town of Wallenborn. Locally known as the Brubbel, a renovation of its well basin was completed in 2001. In the same region, eruptive activity has been reported at Bad Neuenahr (Rinehart, 1980). Postcards from the 1950s show Bad Neuenahr's Großer Sprudel erupting to 20 meters; whether eruptions still occur is unknown.

Figure 4. Mokena Geyser at Te Aroha, North Island, New Zealand. [Photo copyright Waikato Regional Council, also appeared in *The GOSA Transactions*, Volume VII]

On New Zealand's North Island, Mokena Geyser erupts to heights of less than a meter to five meters (Katherine Luketina, pers. comm.). The geyser — a well drilled in 1936 — is located at the base of an extinct volcano in the Te Aroha Domain. Mokena's eruptions produce a thin, vertical stream of 70°C water several times a day. The well's water is used for a nearby swimming pool and sometimes the well is capped to prevent eruptions (Environment Waikato, 2004). The geyser has deposited a thin coating of travertine around its opening.

Of three spouters known in Serbia, one appears to possess geyser-like periodic eruptions. In central Serbia, the spouter at Kopaonik National Park is probably a perpetually erupting well. The play commonly reaches five meters, but park visitors often modify the vent with rocks to change the water column's appearance. Sijarinska Banja, in southeastern Serbia, has two warm-water spouters:

Veliki and Povremeni Geysers (Serbia Tourism, 2004). Veliki, or Giant Geyser, perpetually erupts 70°C water to eight meters. Povremeni, or Occasional Geyser, erupts for two minutes every nine minutes. Its 55°C water plays to 20 meters.

In Slovakia, a well known cold-water geyser erupts in the village of Herlany. The geyser, a well drilled in 1870, plays to heights of 20–30 meters for approximately 30 minutes every 32–34 hours. Rinehart (1980) reported a cold-water geyser at Perši, Slovakia. The geyser has a shorter eruptive height, duration, and interval than Herlany.

Within the United States, cold-water geysers are found in California, Utah, and Wyoming.

A small, ephemeral CO_2-driven geyser has been observed along the southeastern shore of California's Salton Sea (Bryan, 2003; photos p. 173). Erupting less than a meter high, it is a rare example of a natural cold-water geyser. In northern California, near Clearlake, Jones Fountain of Life erupts 62°C water. Driven by CO_2 and methane, the geyser's eruptions occur approximately every hour and last about 20 minutes (Galloway *et al.*, 1997).

In Utah, near Crystal and Woodside Geysers, at least four additional erupting wells — Champagne Geyser, Ten Mile Geyser, Tumbleweed Geyser, and a capped test well near Green River — have been reported. Champagne Geyser, also known as Chaffin Ranch Geyser, is located approximately 40 kilometers south of Crystal Geyser and erupts from a well drilled in the early 1930s. Although the diameter of the pipe is only a few centimeters, water spurts 7–8 meters for five minutes from it every two hours (Clark Murray, pers. comm.; Mutschler, 1977). Several kilometers north of Champagne Geyser, Tumbleweed Geyser is small geyser that is in eruption more than quiet; Ross (1997) observed the geyser in eruption more than 70 percent of the time. The activity consists of short eruptions of 1–4 minutes, followed by a pause of several minutes. Eventually, the geyser has a long eruption of 46–94 minutes. The play is between 0.3 and 1.5 meters high. Ross (1997) also reported a cold-water geyser, Ten Mile Geyser, lying approximately 8 kilometers south of Crystal Geyser. Unlike Tumbleweed, Ten Mile Geyser's activity is marked by long quiet intervals and short durations. From 21 hours of continuous observation, Ross (1997) witnessed only four eruptions. The average interval was six hours and 42 minutes with a duration of 51 seconds. Play reached 2.5–3.5 meters. In 1991, near the City of Green River's eastern I-70 off-ramp, a test well sent water spouting 10 to 12 meters in the air; the well was capped two days after it was drilled (Murray, unpublished manuscript).

In Yellowstone National Park, Wyoming, a small cold-water geyser is located along the bank of the Yellowstone River below Nez Perce Ford (Whittlesey, 1988). Cold Water Geyser's 10-minute eruptions were regular from the 1930s until 1983 when its activity became erratic. Long dormancies are now common, although the spring does cycle between filling and draining (Taylor, 1997). When active, the CO_2-laden play reaches heights of about half a meter.

Other features displaying spouting or intermittent discharge are sometimes described as cold-water geysers. Examples include artesian springs, flowing wells, ocean blowholes, periodic springs, and sand volcanoes. Below, several features that either have been labeled by others as cold-water geysers or have eruptive activity driven by CO_2 are described.

Near Orlando, Florida, a drainage well drilled into the karst Floridan Aquifer can produce eruptions to nearly 20 meters every seven to 30 minutes (Steinman, 2002). The geyser only operates during and immediately after heavy rains. The activity apparently is driven by escaping air bubbles, which accompany the heavy volumes of water draining into the well. Short-lived spouting has been observed and described in other karst landscapes, as well as on glaciers (Veni and Crawford, 1986).

A CO_2-driven well at Soda Springs, Idaho, would spout perpetually if left uncapped. Advertised as "The World's Only Captive Geyser", once an hour the city uses a timer to allow 1–2 minute eruptions. The play reaches 20–30 meters.

Boiling Springs at Savage, Minnesota, is a periodic spring that displays intermittent surging. Usually rising a few decimeters above the spring's pool surface, surges occur every few minutes

(MPCA, 2001). Occasionally, the activity is more vigorous, and the surges reach a meter. Groundwater pumping has threatened the springs, and current behavior is unknown.

A warm-water, gas-driven geyser produced modest eruptions less than 0.3 meters high among the steam-driven geysers at Steamboat Hot Springs, Nevada (White, 1968). Labeled Spring #10, its activity ceased in the late 1980s when a geothermal power plant was constructed near the site.

Effervescing springs and erupting wells are found in Saratoga Spa State Park near Saratoga Springs, New York. One of these features, Island Spouter, sends a constant, thin stream of CO_2-laden water approximately three meters above its travertine mound.

Often described as a cold-water geyser, Periodic Spring near Afton, Wyoming, possesses behavior that alternates between discharge and quiescence. When running, the water is not ejected into the air, but flows like a typical spring. The periods of flow and calm change based on seasonal precipitation, and have been timed between four and 25 minutes. The spring, developed in a karst aquifer, likely possesses an internal conduit geometry that creates a siphon. The periodic activity is an effect of the siphon filling and draining.

Occasionally, springs at Mammoth Hot Springs, Yellowstone National Park, exhibit geyser-like behavior. At 50–70°C, the water at Mammoth Hot Springs is cooler than boiling, and such eruptive activity tends to be driven by rapid CO_2 degassing. Recent activity at the western extension of Narrow Gauge Springs, part of the upper terrace of the Mammoth Hot Springs complex, has included weak splashing at various spring orifices. These splashes, typically less than 0.3 meters, have been observed on occasion to send droplets 2 meters high.

Levels of dissolved CO_2 are so high in some volcanic lakes that geysering pipe installations are used to reduce the possibility of catastrophic, large-scale gas release (Halbwachs, 2001). In 1984, a gas cloud emerging from Lake Monoun, Cameroon, killed 37 people. Two years later, catastrophic CO_2 degassing at nearby Lake Nyos killed over 1,700 people, some as far away as 25 kilometers. To reduce the recurrence of such events, a system has been devised to extract the CO_2 in a controlled manner. At Lake Nyos, pipes have been installed that reach from the lake surface to the bottom of the CO_2-laden lake. By artificially reducing the pressure near the bottom of the pipe, a CO_2-driven, geyser-like eruption is induced. Five installations in Lake Nyos now erupt perpetually to 50 meters high.

CO_2 also may exacerbate eruptions of steam-driven geysers. Though the geysers at El Tatio, Chile are steam-driven, the frothy, erratic eruptions of the Middle Geyser Basin appear to be caused by both steam and vigorous CO_2 degassing (Waltham 2004, Glennon and Pfaff 2003). Similarly, at Yellowstone National Park, Crater Hills Geyser and an unnamed geyser a few kilometeres west of Norris Geyser Basin appear to be at least partially gas-driven (Rocco Paperiello, pers. comm.).

In Karlovy Vary, Czech Republic, Vridlo Geyser is a warm-water perpetual spouter that plays to 12 meters. An unusual characteristic of the 73°C spouter is that a glass and column colonnade has been built around it; thus, the geyser is indoors.

In central Madagascar, near the village of Analavory, geyser-like eruptions occur from an area of travertine mounds (Eric Sibert, pers. comm.). The travertine has deposited at the warm-water outflow of pipelines from a nearby mine. When the vents are blocked, the build up of pressure produces spouting to several meters once uncovered. Otherwise, spouting perpetually plays to 20–30 centimeters.

Historic accounts from the mining village of Marmol, Mexico, state that a nearby spring, El Volcan, erupts gasses and water once a month as high as 16 meters (Petersen 1999, page 135). Photographs of the vicinity show effervescing springs and large travertine mounds. Whether El Volcan continues to have eruptive activity is unknown.

Undoubtedly, other CO_2-driven cold-water geysers and spouters exist. Readers are encouraged to document any other known spouters, either by publishing in this journal or contacting the authors.

Acknowledgements

The authors wish to recognize the personal communication, comments, and information provided by Scott Bryan, Tom and Genean Dunn, Hugo Loaiciga, Katherine Luketina, Clark Murray, Rocco Paperiello, Kyle Ross, Eric Sibert, and Lee Whittlesey.

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An overview of the setting at Crystal Geyser, Utah. The new casing is visible at the left–center of the image, and extensive travertine terraces extend from there to the Green River. [Photo by Alan Glennon]

The beginning of an eruption by Crystal Geyser, Utah, on June 10, 2004. A muddy eruption in a small pool can be seen at the lower left. [Photo by Alan Glennon]

A Guide to Making Proposals for Place Names of Thermal Features in Yellowstone National Park, Wyoming–Montana–Idaho

by Lee Whittlesey and Hank Heasler
Park Historian Park Geologist

Editorial Note
The following document, dated March 4, 2004, is presented without further comment for the information of the readers.

There are over ten thousand individual thermal features in Yellowstone National Park—hot springs, geysers, mudpots, and steam vents (fumaroles). Because thermal features can change their appearance (sometimes dramatically), dry up completely, or change their location, being sure of which historic place name applied/applies to which physical feature is not and has not always been an easy task for park officials and researchers. Because thermal features change so quickly, their names, when newly applied, are sometimes fleeting things in local usage. Another scenario is that the latest thermal feature that the park historian or geologist refers to as, say, Cradle Mud Spring may dry up tomorrow and leave a place name on a map or in literature for a feature that no longer exists. Or the feature may change from a quiet hot spring to a spouting geyser, in which case its name may be locally changed from such-and-such "spring" to such-and-such "geyser." The use of the term *pool* (i.e. *Morning Glory Pool*) in a place name has been random and arbitrary, since both hot springs and geysers can be pools. In addition, all geysers are hot springs but not all hot springs are necessarily geysers, so a geyser can be properly named *Big Alcove Spring* but a non-erupting hot spring cannot be properly named "so-and-so Geyser." When mudpots and steamvents are thrown into the naming mix and multiplied across thousands of individual features that pockmark large basins, the situation quickly becomes complex and confusing.

For lack of a name, park personnel often refer to smaller, newer, or otherwise unnamed thermal features with a number. This has the advantage of not cluttering maps with printed names for hundreds of minor features that may exhibit little or no activity. It also has the advantage of preventing names from becoming invalid or confusing when "Crystal Blue Spring" suddenly turns into "White Mudpot" or "Dry Steamvent."

But it has definite disadvantages, as evidenced by this conversation that has been actually heard among park interpreters, concessioner tour guides, GOSA geyser gazers, and scientific or historic researchers (all of whom use thermal place names constantly):

"I saw pool #9 erupt today."
"Oh, is that anywhere near spring #10?"
"No, it's over by unnamed geyser #17."
"Oh—I *think* I know where it is…"

This is humorous but real. People are more comfortable referring to features by name as opposed to number. And names are usually less apt to be forgotten or confused with other features than are numbers. The largest potential problem is often the *location* of the thermal feature.

A well-established rule that began with the 1870 Washburn party has grown up in Yellowstone with regard to names of thermal features. With only a few (now historically entrenched or otherwise official) exceptions, no names of *people* are allowed to be applied to hot springs, geyser, mudpots, or steam vents. Instead, names of thermal features are descriptive or otherwise characteristic of appearance, activity, or location, such as *Blue Star Spring*, *Constant Geyser*, or *Fountain Paint Pot*.

According to the rules of the **U.S. Board on Geographic Names**, anyone can propose a name for a previously unnamed natural feature, and this includes thermal features. Persons who wish to formally propose names for thermal features by submitting a letter to the park superintendent should consider the following before making their proposal(s) and should place relevant information from this list in their proposal(s):

1) The park wishes to avoid duplicate names, so if a name proposal is submitted that duplicates an existing *active or obsolete* name, it will be summarily rejected (example: at least three geysers carry the name *Catfish* and there are five different individual springs each named *Fissure Spring*). Name proposals should be compared to several existing databases in order to check whether the name has already been used: a) both the active and obsolete sections of Lee Whittlesey's unpublished 2,123 page manuscript *Wonderland Nomenclature: A History of the Place Names of Yellowstone National Park* (1988), located in the park research library; b) the park's thermal Geographic Information System (GIS) database in the Yellowstone Center for Resources; c) the latest edition of T. Scott Bryan's book *The Geysers of Yellowstone*; d) experts on recent geyser and hot spring names as designated by the Geyser Observation and Study Association (GOSA). In the year 2004, such persons as Rocco Paperiello and Mike Keller are experts in the recent (thermal) names area.
2) A thermal feature cannot be named for a *person*, whether living or dead. Names such as "Joe Smith Spring," "Jim Bridger Geyser," or "Tom's Mudpot" will not be considered or accepted.
3) Names that are derogatory to persons, races, religions, etc. will not be considered or accepted.
4) The thermal feature should have at least *some* geologic stability before it receives a name. While this is admittedly sometimes difficult to judge, a relatively new feature in the process of moving through big geologic changes is generally not a good candidate for a place name.
5) Use of the terms "New so-and-so" or "Old so-and-so" will not be considered or accepted, because they have already caused much confusion in a chaotic names literature. No thermal feature is new for very long and old features can rejuvenate.
6) Use of the term "Little so-and-so" ("Little Blue Lemon Spring") will not be considered or accepted, as this term too has caused confusion.
7) The proposer should avoid overly simple descriptive names such as "White Bubbler" or "Green Boiler" because the feature may change and because the name may have already been used.
8) Because of the transitory nature of steam vents (fumaroles), names should not be proposed for or given to them.
9) Names should generally be avoided for springs in acid tracts, where thermal waters do not percolate to great depths and where sinter formation is lacking, because the potential for change in these areas is too great. Alkaline areas of deep-water circulation where sinter deposition occurs are generally better considerations for place names.
10) Cliché words that have been commonly used in place names around the nation such as *elk, bald, round, duck, mud,* and *cottonwood* should be avoided. The proposer should strive for originality.
11) Location(s) of the spring(s) must be clearly delineated. This is one of the most important considerations for a place names proposal. Proposers should include in their submitted proposal the following three criteria at minimum: a) at least one photo of the spring that is taken from a distant enough vantage point to show surrounding features in order to help future researchers and park officials identify the spring's location; b) a close-up map that shows the distance and directional relationships between the proposed spring

and other nearby named or unnamed springs or other natural or cultural features; c) a numeric location based upon Global Positioning System (GPS) technology. This location can include latitude/longitude information if it is carried down to at least tenths of seconds, Universal Transverse Mercator designations, or detailed descriptions using several known nearby natural features ("33 feet east of Constant Geyser or 31 feet north of Whirligig Geyser or 25 feet south of Africa Geyser"), or (best of all, for those of us worried about being able to find your spring in the future) *all of these things*. In addition, the proposer should describe the technology he uses (i.e., "Garmin GPS III+ unit used on (date) that is accurate to within three feet"). And the proposer should a) include a description of the methodology he used to arrive at the numeric location(s) of the spring(s); b) tell us what kind of precision his measuring instrument has and its likely error rate; and c) tell us the kind of coordinate system and map projection they used.

12) Other scientific information about the spring(s) that may help future researchers locate it/them, such as size of the spring, water chemistry (Ph) data, sinter or rock formations, shape of exterior or interior craters, water discharge amounts, temperature on a given date, height/duration/ interval of eruptions if any, pool level, or pool depth.

The formal proposal should be submitted to Park Superintendent, P.O. Box 168, Yellowstone National Park, Wyoming 82190 with all necessary attachments and a covering letter.

The park will generally respond by turning the proposal over to the Park Historian (a place names expert) who will confer with the Park Geologist as to whether the proposal meets the basic (above) rules. If passed back to the superintendent, the proposal can then be acted upon or not by the Park Resource Council.

If the Park Resource Council approves the proposal, the Park Historian will then forward it to the NPS's Rocky Mountain Regional Office (Director) and the Washington Area Service Office of Policy and Planning (Chick Fagan). They in turn will submit the formal proposal to the U.S. Board on Geographic Names. The USBGN may then act on the proposal, or not.

If the USBGN acts favorably on the proposal or declines it, notice will generally be sent to Yellowstone National Park who will distribute that notice to the proposers after placing copies of the correspondence in the Yellowstone Archives.

Editorial Follow–up:

The Website of the U. S. Board on Geographic Names is located at http://geonames.usgs.gov/bgn. As of November 23, 2004, that page included four links of interest:

• A long (44 pages) PDF document titled "Principles, Policies, and Procedures: Domestic Geographic Names" that presents considerable detail about the naming process. Within this are numerous links to other pages, including Appendix C.

• A PDF version of Appendix C, the "Domestic Geographic Name Report" that one uses to propose a new or revised name. It is available at http://geonames.usgs.gov/A-C.pdf.

• A series "Dockets..." that are sequentially numbered and dated lists of proposed names organized alphabetically by state. "Docket 387," for example, includes 71 names on 43 pages that were to be considered at the USBGN meeting of October 20, 2004.

• The minutes of the meetings, giving the decisions that were made at that time. Unfortunately, the most recent of these was dated February 2004.

As noted in the above document by Whittlesey and Heasler, in Yellowstone a name proposal can be made by letter addressed to the Park Superintendent. Or, I presume, the form of Appendix C can be used, also to be sent to the Superintendent.

About the Contributors

Gordon R. Bower grew up in Idaho Falls, Idaho, and frequent childhood trips to Yellowstone were the source of a lifelong interest in science and nature. Now a resident of Fairbanks, Alaska, he received Bachelors degrees in geology and mathematics and a Masters degree in statistics from the University of Alaska. Gordon's research interests include mathematical models of geyser and volcano periodicity. After two years as a seismic data analyst at the Alaska Volcano Observatory, he is now a research technician with the International Arctic Research Center (IARC). He spends spare time as a bridge teacher and tournament director, and plays violin in the Fairbanks Symphony Orchestra.

T. Scott Bryan (M.S., Geological Sciences, University of Montana) has visited Yellowstone during every summer starting with 1970. He worked in the park as a summer seasonal employee from 1970 to 1977 and 1980 to 1986, and served as a volunteer in several additional years. He has visited the geysers of California, Nevada, Oregon, Mexico, Kamchatka, Fiji and New Zealand. One of the founding Directors and the first President of GOSA, Scott is the editor of this volume and author of *The Geysers of Yellowstone*, *Geysers: What They Are and How They Work*, several articles in previous volumes of *The GOSA Transactions*, and travel articles to the commercial trade.

Jeff Cross first visited Yellowstone at the age of four, in 1979, and began serious independent observations of geysers in 1988. He received the Bachelor of Science degree in Chemistry from Walla Walla College, Washington, in 1998 and is presently pursuing graduate work in Organic Chemistry at Colorado State University.

Tara Cross became interested in geysers as a child on family vacations. Although she enjoys all geysers, her main interests are Fan and Mortar Geysers and Yellowstone's backcountry areas. In May 2001 she graduated from Southern Adventist University with a Bachelor of Arts in History. Now, after 3½ years of employment in the Yellowstone Research Library, Tara is pursuing a Masters degree in Library and Information Science at the University of Washington.

J. Alan Glennon received the Master of Science degree in Geoscience from Western Kentucky University, where in 1999 he co–founded the Hoffman Environmental Research Institute. Prior to that he served as a Research Hydrologist for the Center for Cave and Karst Studies. He worked eight seasons as a National Park Service interpretive ranger at Mammoth Cave National Park, Jewel Cave National Monument and Great Basin (Lehman Cave) National Park. Alan is presently a doctoral student in geography at the University of California, Santa Barbara.

Stephen Michael Gryc is a classical composer who earned four degrees in music from the University of Michigan. He is currently Professor of Music Composition and Theory at the Hartt School of the University of Hartford in Connecticut. His interest in both sound and geysers led him to make digital audio recordings of Yellowstone's thermal features. Some of his recordings were used in the soundtrack of *A Symphony of Fire and Water*, a film about current research into various aspects of Yellowstone's hot springs. Dr. Gryc has been visiting Yellowstone National Park since 1963, and previously has contributed articles to *The Geyser Gazer Sput* and *The GOSA Transactions*.

Mike Keller has lived and worked in Yellowstone National Park since 1987, where he is employed by Xanterra as the general manager for the company's hotels and lodges in the Old Faithful area. He received a degree in Geological Engineering from Montana Technical College in 1991. His geyser specialties are Giant Geyser, the Myriad Group and the Kaleidoscope Group, which he has studied in detail. Mike and his wife, Cynthia, additionally serve as volunteers for the National Park Service, primarily assisting with the monitoring and cleaning of thermal features.

William P. (Will) Moats holds a Bachelors degree in Geological Engineering and Geology from the New Mexico Institute of Mining and Technology, and a Master of Science degree in geology from Arizona State University. He is employed as a manager in the Permits Management Program, New Mexico Environment Department Hazardous Waste Bureau. He became a geyser gazer in 1996 and has previously contributed to GOSA publications.

Clark Murray is employed by Qwest Communications, where he manages the telephone company operator network for 16 western and midwestern states. He spends the better part of vacations in Yellowstone, where for the past 22 years he has done extensive backcountry hiking and explorations of remote thermal areas. Clark also spends time hiking in Utah's Wasatch Mountains and southern canyon country. His education continues as a computer science major at Westminster College of Utah.

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Rhonda M. Pfaff holds both a Bachelors degree in Political Science and a Master of Science degree in Geoscience.In 2001, she worked as a cartographic technician for the Spatial Analysis Center, Yellowstone Center for Resources. Research interest include karst landscapes and geothermal systems, and recent work has included a Graphical Information System (GIS) analysis of Mammoth Cave, Kentucky, the geochemistry of Narrow Guage Terrace at Yellowstone's Mammoth Hot Springs, and the hydrothermal activity of the Andes Mountains of Chile. Rhonda presently works as a GIS software documentation specialist for the Environmental Systems Research Institute (ESRI) in Redlands, California.

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Lynn Stephens is Professor of Accounting at Eastern Washington University, where she teaches courses in accounting, business statistics and decision making. She started volunteering as a thermal observer in Yellowstone in 1988, which duties include the collection and analysis of geothermal data, and preparation of the electronic version of the Old Faithful Visitor Center logbook. She has had several articles published in previous editions of *The GOSA Transactions* and is a frequent contributor to *The Geyser Gazer Sput.*

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List of Readers

Each article in this volume was read by two or more content reviewers, who provided copyediting and corrective comments to the editor and authors. Some articles also received additional peer review at the author's respective colleges and universities. With great thanks to these people for their time and efforts, they are:

Andrew Bunning
Bill Johnson
Bill Warnock
Chris MacIntosh
Clark Murray
Dave Taylor
Diane Clark
Dick Powell
Fred Kallien
George Schroeder
Gordon Bower
Graham Meech
Holly Zullo
Jake Frisbee
Janet Chapple
Kevin Leany
Lynn Stephens
Mario Durrant
Mary Beth Schwarz
Nancy Cross
Paul Strasser
Ralph Taylor
Stacy Glasser
Steve Gryc
Thom Fisher
Vicki Whitledge
Will Moats
and three who asked to remain anonymous.

List of Photographers

Several people in addition to authors provided photographs for use in this volume. They are:

Bill Masella
Pat Snyder
Scott Bryan
Joe Erlanger and Debby Stahl
Andy Casterline
Bob Witzke
Mike Keller
Robert Bower
Mike Newcomb
Tom Dunn
Cynthia Keller
Clark Murray

Lion Geyser (Upper Geyser Basin) at sunset, May 28, 2003. [Photo by Pat Snyder]

Researchers are encouraged to produce articles for *The GOSA Transactions*, Volume X, which is expected to be published during early 2006. Please advise the Editor about your article topic and anticipated length at the earliest possible date. Submissions guidelines are available upon request.

The GOSA Transactions
Volume IX, January 2005

The Geyser Observation and Study Association

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GOSA