GOSA TRANSACTIONS

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The Geyser Observation and Study Association

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Cover Photograph:

Daisy Geyser and its relationship to other groups of geysers is analyzed in one of the articles in this issue. Photo by T. Scott Bryan.

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GOSA

Notes on a Cleanup of Blue Star Spring

Upper Geyser Basin, Yellowstone National Park

reported by Mike Keller

Abstract

An October 1993 attempt to clean out Blue Star Spring was imminently successful— vastly more kinds and quantities of trash were retrieved than had been anticipated. This short paper reports on this "treasure."

Commentary and Technique

From October 16 through October 28, 1993 an extensive attempt to clean out Blue Star Spring was conducted. Blue Star lies next to the boardwalk that loops around Old Faithful Geyser. It is, therefore, visited by tremendous numbers of people, too many of whom use the pool instead of the trash cans.

Over 100 hours were spend on the clean up task. The only instruments used were two metal poles measuring 6 and 12 feet in length. Attached to the end of these poles was a coffee can. These were used to drag along the bottom of the crater to collect all loose sediment and trash. We assumed we would find a few different items, but nothing like the following.

American Coins

The following United States coinage was recovered:

Cents:	2,821 @ .01 each =	$28.21
Nickels:	172 @ .05 each =	8.60
Dimes:	110 @ .10 each =	11.10
Quarters:	65 @ .25 each =	16.25
Half dollars:	3 @ .50 each =	1.50
TOTAL:	3,171 coins equalling	$65.66

Other Coins

The following non–American coins and tokens were also found:

1	"Loonie" Canadian dollar coin
1	Italian lira coin
1	Mexican one peso coin
1	Japanese 1/2 yen coin
1	Colorado tax token
1	Wall Drug Store token
1	$5 play money coin

Miscellany

The following items were also found:

1	"New York Kids Police" badge
4	Bottle tops
3	.45 caliber bullet slugs
1	Button
1	Die (6–sided, for gambling)
1	Fishing hook
1	Glass pendant
1	Union Plaza Hotel (Las Vegas) key chain
1	Light bulb
11	Marbles
4	Nails
1	Peach pit
1	Pocket knife
40 lbs	Rocks (approximate weight)
1	Rubber door stop
1	Sardine can
75 lbs	Sand (approximate weight)
3	Bobby pins
4	.22 caliber bullet cases
1	30–06 bullet slug
1	Crystal pendant
1	Pencil eraser
1	Kodak flash bulb
1	Key
1	Wyoming lapel pin
1	Silver, Hilton lighter
1	Paper clip
6	Unknown pieces of metal
1	Pencil sharpener
10	Soda can pull tabs
1	Piece of rope, 1 foot long
1	Rubber piece of unknown origin
2	Small screws
10 lbs	Waterlogged sticks (approximate weight)

PLUME GEYSER:
History and Recent Changes

by: Ralph C. Taylor

Abstract

Plume Geyser has a history of periods of consistent activity punctuated by significant changes in behavior. Plume underwent such a change in function during 1992 and 1993. A noticeable diurnal variation in interval became evident in 1992. An 84-hour continuous study of Plume Geyser in early August by the author and other GOSA members revealed a less pronounced diurnal cycle than had been detected earlier in 1992. Observations of Plume Geyser in September, 1992 noted a return to the level of diurnal variation noted in July 1992.

In late 1992 Plume began to have longer intervals, which developed into long dormant periods in early 1993. In the spring of 1993, apparently triggered by an eruption of Giantess Geyser, Plume resumed activity, but with pronounced changes in its eruptions. Both long-term temperature monitor studies and visual observations confirm the changes from 1992 and earlier years.

INTRODUCTION

This paper gives a brief history of Plume Geyser, and then describes some major changes in the behavior of Plume Geyser between 1992 and 1993. The history of Plume Geyser is relatively brief, since Plume is a relative newcomer to the Yellowstone scene. Plume's history begins with the initial breakout in 1922. Plume has had several major shifts in behavior during its seventy years of activity, often caused by significant geological events such as steam explosions or earthquakes. Between these events, Plume tends to be stable and regular in its activity.

Following the history of Plume's origin and development, this paper gives an overview of the behavioral changes between 1992 and 1993. A substantial change in behavior occurred between September 1992 and early 1993. Following a period of increasingly erratic eruptions, Plume went nearly dormant in early 1993. An eruption by Giantess Geyser on 4 May 1993 stimulated Plume into eruption with shorter intervals than had been seen since the summer of 1992. Following the Giantess eruption, Plume remained active but with substantially longer intervals and with much more variation in both interval and character of its eruptions. Plume also began to exhibit a new behavior pattern: extended periods of dormancy lasting for several hours, almost daily. For all of the summer of 1993, this pattern continued, punctuated by two to three day periods of regular 30 minute intervals whenever Giantess Geyser erupted.

In preparing this paper, Plume's behavior was studied by examining data from many sources. For the overall behavior pattern, the complete set of Plume observations from the Old Faithful Visitor Center (OFVC) geyser log provided a picture of the intervals and the gross eruptive pattern. The information in the log consists primarily of eruption times, so few details of eruption character or power can be deduced from this source. The author made more detailed observations in three trips to Yellowstone in 1992 and two visits in 1993.

The most extensive direct observations used in this paper were made during an 84-hour continuous watch of Plume Geyser. This intensive study was a GOSA Research Division project undertaken specifically to examine the diurnal variation of Plume's activity that had been reported in recent years [Day, 1991], [Bryan, 1991]. Earlier in the summer of 1992, Yellowstone's Research Geologist Rick Hutchinson conducted a 96-hour measurement of Plume's intervals using a temperature recording device to measure the runoff water temperature. The data from this study and Scott Bryan's July, 1992 study of Geyser Hill demonstrated a stronger diurnal variation than had previously been observed.

During the 84-hour GOSA study, the project team recorded all of Plume's eruptions, noting the start and duration of each burst of each eruption. This information provided a detailed picture of Plume's behavior during the study period. Coincidentally, the Plume study started when Beehive and Beehive's Indicator were in the first days of over thirty days of anomalous behavior. During this time, Beehive ceased erupting and Beehive's Indicator began having extended eruptions several times per day.

PLUME GEYSER: History and Recent Changes

The author next visited the Old Faithful area for ten days in late September 1992 and made a number of observations of Plume Geyser. During the September observations, Plume's eruption pattern had changed substantially from the August observations. Where previously all eruptions had four or five bursts, some September eruptions had two or three bursts, and many bursts were much weaker than those seen earlier in the summer of 1992.

By early 1993, Plume had changed significantly. The eruptions typically consisted of two bursts and intervals were known to increase substantially late in the day [Bryan 1993a]. In March Plume had become almost dormant, with intervals over 24 hours reported [Bryan 1993b].

Direct observations by the author during the 1993 summer season confirmed the changes in the behavior patterns, both in the eruption frequency and burst patterns. The Plume overnight dormancy periods (referred to as "sleep periods" by many gazers) were confirmed by the use of markers during early June.

Rick Hutchinson and Heinrich Koenig placed a temperature monitor on Plume from 9 July through 13 August 1993. Data from the monitor revealed the extent and regularity of the "sleep" periods, and also convincingly demonstrated the strong relationship between Giantess Geyser and Plume Geyser.

A BRIEF HISTORY OF PLUME GEYSER

Before describing the 1992-93 changes in Plume's behavior, an examination of the history of Plume's discovery and reported eruptive behavior is useful to provide some historical context. The material in this section is presented with thanks to Rocco Paperiello, who kindly provided extensive research notes to the author. Much of the following is taken directly from Paperiello [Paperiello 1993].

Plume Geyser is of relatively recent origin. It was reported to have broken out some time before May, 1922 and had established a regular interval of 19-20 minutes by May, 1922 [MRofS May, 1922]. Later that summer, Plume "shortened its average interval to 18½ minutes" [MRofS Aug, 1922].

Plume Geyser remained active in 1922 and 1923. In May of 1923, it was reported that "the small geyser near the Beehive that broke out last year is still very active." [MRofS May, 1923]. By 1927, Plume was still active but had become much less frequent, and the eruptions had weakened, as described by Charles Phillips in the *Ranger Naturalist Manual* of 1927:

> Nearby [from Anemone] is a jagged opening in the sinter that was blown out in 1922. This is the so-called New Geyser; it was very active for two years playing every 20 minutes but is rarely seen of late and then only with much reduced vigor. [Phillips 1926]

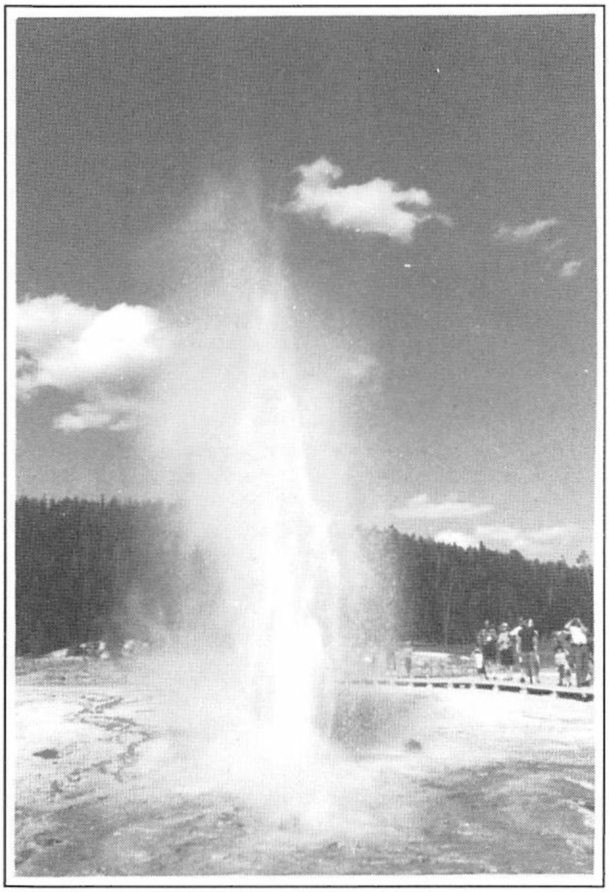

Figure 1 - Plume Geyser in eruption, August 1968

The next known record is an unpublished report by H. Lystrup [1930]: "Small geyser between Beehive & Anemone (unnamed) erupts frequently to a height of 10 ft. - 15 ft." Plume apparently experienced several years of dormancy in the 1930s. There is no record of observed eruptions in the 1930s, and Chief Park Naturalist Condon, who was stationed at Old Faithful in 1933, 1934, and 1939 had no recollection of Plume Geyser activity. [Parkinson 1956]

In 1940, Plume resumed activity. Marler [1940] noted activity in Plume, although he called it "Sinter Geyser". In his *Inventory of Thermal Features...* Marler states that he first observed Plume in 1941 and that for the next ten years Plume erupted "with marked regularity." He further states that "The great majority of the intervals showed little more than two minutes variation, being between 59 and 61 minutes." [Marler 1973]

By 1947, Plume had become a regular performer. Marler wrote "During the current season the activity [in Plume] takes place at intervals varying between forty-five minutes and an hour. The height of an eruption is about thirty feet, lasting about five minutes." [Marler 1947] In his 1949 report, Marler added:

> * Plume Geyser: As during the two previous seasons, this geyser has been a frequent and interesting performer. The duration of the activity is from four to five minutes and the height from twenty to thirty feet.
>
> The 1942 season was the first I had ever observed any activity in this geyser [but Marler states in the *Inventory...* that the year was 1941, and, by his own reports, it was actually 1940]. From then until 1946 no observations were made. During 1946 no activity was observed. Since the beginning of the 1947 season it has been a frequent and regular performer; the eruptions occurring every forty-five minutes to an hour.
>
> The Plume is located about 100 feet west of Anemone on Geyser Hill. Its tube is small, about a foot in diameter at the surface and bending into the geyserite about a foot below the surface. No water, or any evidence of a surface connection with a water supply is suggested during the quiet phase.
>
> * This geyser has no official name as yet [in 1947]. The name Plume has been suggested by Chief Park Naturalist David de L. Condon. The name is descriptive, the play of water suggesting a plume. [Marler 1949]

In 1952, Plume's intervals averaged 60.37 minutes for 54 intervals. The reported intervals ranged from 54 minutes to 65 minutes, but no mention is made of any time of day related variation. [Armitage 1952]

Ted Parkinson wrote of Plume in the Jan-Feb 1956 Yellowstone Nature Notes in an article titled *PLUME GEYSER IS CHANGING*:

> The Plume Geyser is located about 100 feet west of Anemone Geyser and about 20 feet north of the new Geyser Hill boardwalk.

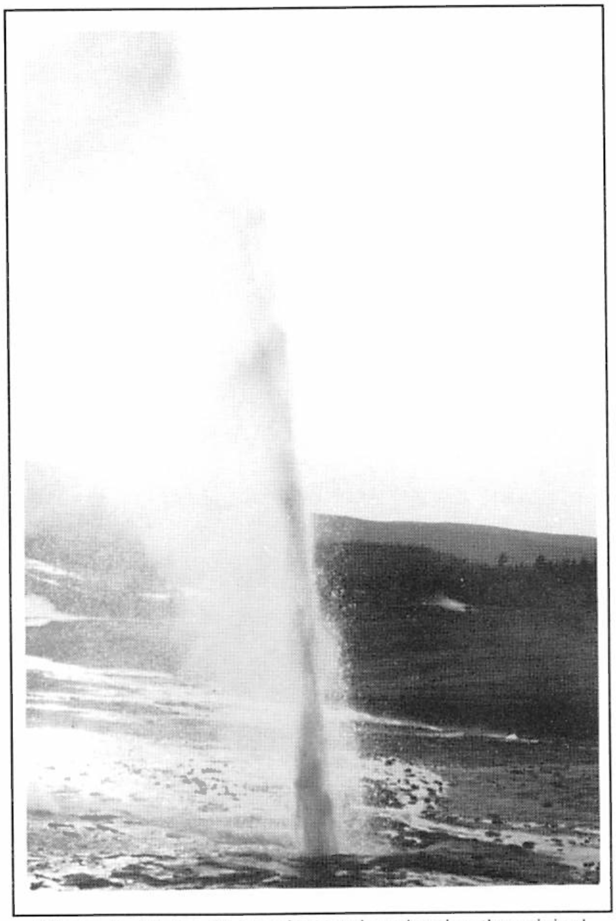

Figure 2 - Plume Geyser in eruption showing the original slender water column, August 1971

An eruption was considerably different in 1955 than today, as shown by this description from the same article:

> ...Just before an eruption, boiling water rises in the tube and steam starts to emanate from the opening in a manner suggestive of a half filled teakettle starting to come to a boil. When the eruption begins, about a full minute is required before it reaches maximum height of around 35 feet. The Plume does not play quite vertically. When the right kind of breeze carries the water slightly more to the side, making a graceful curve as the water starts to fall, it is easy to see why Chief Park Naturalist Condon was inspired to give it the name Plume Geyser in 1947. Plume is a most appropriate

> descriptive name for one of our most beautiful geysers. The successive, more or less continuous bursts of boiling water will gradually decline in height and power after a couple of minutes. Steam gradually displaces water, but the steam phase is short and mild. The whole eruption lasts about 5 minutes. [Parkinson 1956]

In 1955, Parkinson reports that the average of 84 intervals was 68.21 minutes, ranging from 59 minutes to 85 minutes. Plume had not only lengthened its intervals, but its variation also increased substantially. [Parkinson 1956]

Between 1955 and the 1959 Hebgen Lake Earthquake, little else was recorded about Plume. Following the quake, Plume's activity changed substantially. Marler, in his 1959 geyser report, notes:

> Plume Geyser: Prior to August 18, the Plume erupted about every 65 to 75 minutes. For several days after the quake, activity was infrequently observed. It was noticed that water was flowing into Plume's crater from a steadily erupting spring which started playing the night of the 17th. Diversion of this flow resulted in a marked response in Plume. The earthquake had greatly stimulated its activity, the average period being 44 minutes. [Marler 1959]

This is the first report of surface water affecting Plume's eruptions. In his 1961 report, Marler reports on further changes in Plume's activity:

> Plume Geyser: Until October 1960, Plume's intervals were about twice as long as prior the quake. It had been determined in September 1959 that this delayed activity resulted from water flowing into Plume's crater. This water came from springs which had their origin the night of the big tremor.
>
> During the first 9 months of 1960, the intervals varied from 2 to 3 hours. After the first of October it began playing with greater regularity and on much shorter intervals. Some of this increase in activity apparently resulted from diminished flow of the new springs lying directly above Plume, however, an additional factor, or factors would seem to be involved.
>
> Since September, most of Plume's eruptions have occurred on intervals of less than an hour. In October, I checked one interval of 33 minutes. This is the shortest one on record. [Marler 1961]

Marler, in his annual reports for 1961, 1962, 1963, and 1964 notes that Plume's average intervals shortened to 32 minutes in 1961, 27 minutes in 1962, and then to 24 minutes in 1963 before rising to 27 minutes in 1964. In 1962 the eruptions were about 2 minutes in duration with a height of 30 to 35 feet. [Marler 1961-64]

This pattern of activity continued until 1973.

Some time in 1965 or 1966 a second vent developed to the west of Plume's main vent. Marler noted in his 1968 geyser report that:

> The vent that developed a few years ago on the west side of Plume continues to grow. The fact that it erupts simultaneously with Plume might suggest that if there is further enlargement of its crater it will eventually alter the present nature of Plume's function. During the current season Plume's intervals varied between 25 and 29 minutes. [Marler 1968]

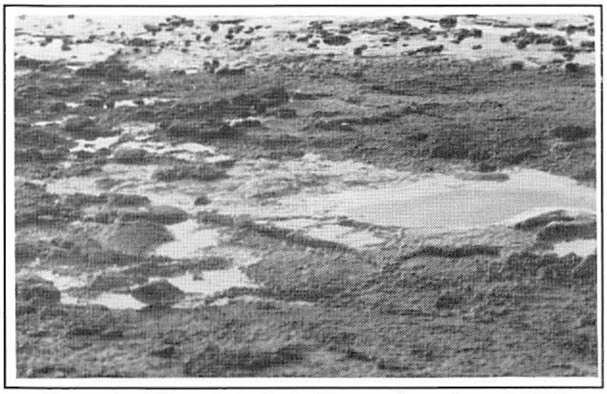

Figure 3 - "Plume's Indicator" in overflow, August 1971

By 1971, the west vent was being called Plume's "indicator" because the rising water level within the west vent preceded Plume's eruption. During Plume's eruption, the west vent would splash about 1 to 2 feet. When the eruption ended, both vents would drain with a sound resembling a flushing toilet. [Wolf 1975]

In February, 1973 a new vent (the third vent) was "blown out". Rick Hutchinson reported in his 1973 report:

> During February [1973] a new vent was explosively blown out between the indicator pool and the main vent and by May had grown larger than the main vent. Slabs several inches across lay about its opening. In

PLUME GEYSER: History and Recent Changes

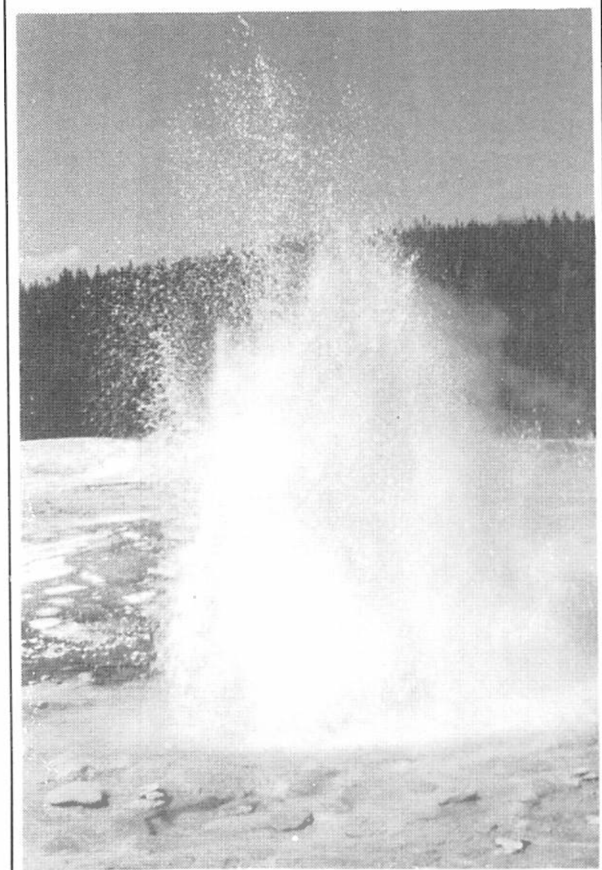

Figure 4 - Plume Geyser in eruption in August 1980. Note the massive burst from the 1972 blowout crater.

> previous years it had been reported that the indicator pool would spurt water 1-2 feet during an eruption and then drain simultaneously with its neighboring main vent—producing a sound similar to a flushing toilet. Now the indicator quietly overflows, then drains more slowly after an eruption which has caused its characteristic sound to be lost...
>
> Durations are said to be half as long as last year but about an equal amount of water is discharged... [Hutchinson 1973]

This explosive event created the Plume formation as it still existed in 1992-1993. The once-graceful plume of water that gave Plume Geyser its name was replaced by a low, massive bursting eruption. Marie Wolf described the change:

> The slender, graceful Plume was ruined; water surged to about 6 feet from the new vent on the first burst, then splashed 1 to 3 feet the rest of the time, while the main vent shot quick, thin, ragged jets to 20 feet. As the summer progressed, the initial bursts from the new vent grew higher and more massive. And by late June, the two top vents had developed the habit of always dying down at least once, and sometimes 3 or 4 times, toward the end of the eruption, and surging up again. The indicator vent no longer splashed at all during the eruptions, and the almost comical gurgle of the draining craters was gone. [Wolf 1975]

By the winter of 1974 Plume had established the pattern of activity that it would follow for the next two decades. On the initial burst, the new vent (the middle vent) produced a massive burst of water to a height of about nine meters. This burst would last approximately seven seconds, accompanied by quick, ragged bursts jetting from the main vent. Eruptions generally consisted of between two and five bursts. After a total eruption time of about a minute both craters would drain. [Wolf 1975]

In October of 1983, Plume Geyser was affected by the Borah Peak earthquake. Heinrich Koenig, Marie Wolf, and Paul and Suzanne Strasser observed Plume quietly overflowing prior to an eruption on 29 Oct 1983, the day after the earthquake. Before the earthquake, Plume slowly rose to a water level about 3 cm below overflow at the moment the pre-eruption surge in water level started. [Koenig 1994]

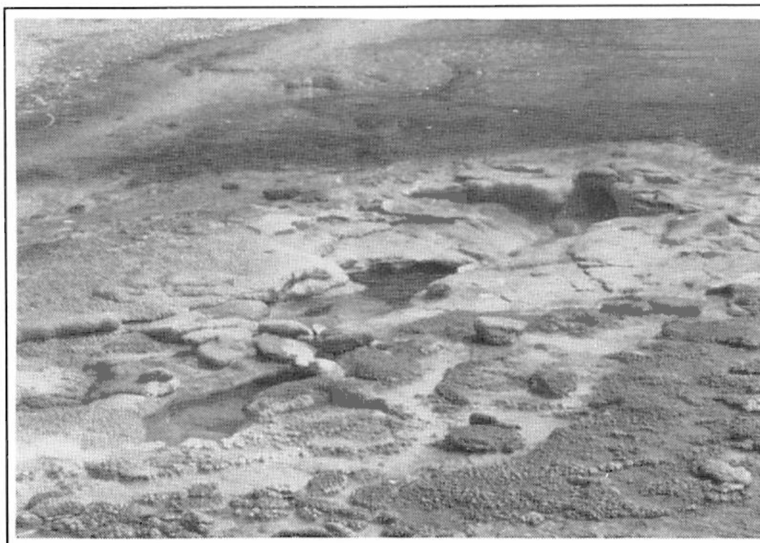

Figure 5 - Plume Geyser formation, view looking ESE, September 1993

PLUME GEYSER: History and Recent Changes

In May of 1985, Koenig noted a small chunk blown out of the eastern vent of Plume. The new opening, on the south edge of the opening, was triangular in shape. The base of the triangle measured about 30 and the height of the triangle was about 15-20 cm. Koenig first noticed the new opening on 28 May, but relates that the explosion may have occurred over the winter of 1984-85. [Koenig 94]

PLUME GEYSER'S APPEARANCE, 1992-3

In 1992 and 1993, the Plume Geyser formation consisted of three vents arranged in a line extending southwest from the original (1922) crater. The vents lie just northeast of a line from Anemone Geyser to Beehive Geyser, to the inside of a sharp bend in the boardwalk circling Geyser Hill. The vent to the northeast is the original 1922 vent, which still participated in most eruptive episodes. This vent was surrounded by extensive geyserite beading. The central vent is the largest, approximately 1.5 meters by .75 meters. The water level in this vent was usually several centimeters below overflow between eruptions. Immediately following an eruption the water level dropped from view from the boardwalk, refilling to near overflow in a few minutes. The westernmost vent is the indicator pool that appeared in the late 1960s. This pool did not erupt in 1992-3, but overflowed near the time of an eruption. Figure 5 shows the Plume Geyser formation as it appeared in September 1993.

PLUME GEYSER'S 1992 BEHAVIOR

For the first eleven months of 1992, Plume erupted fairly consistently at intervals of between 30 and 50 minutes, with occasional intervals as long as 56 minutes. This is shown by the 1992 interval vs time graph shown in Figure 6. Plume's intervals ranged from 30 to 40 minutes, generally starting each day near 40 minutes and decreasing to 30 minutes as the day progressed. This pattern continued through the winter season. There is a gap in observations between mid March and mid April when the Old Faithful area was closed between the winter and summer seasons. When regular observations resumed, the interval range had doubled, with daily maximum intervals of 50 minutes on some days, and daily minimum interval still around 30 minutes. This relatively large daily range continued until early July. By early August the daily interval range was only 10 minutes, from 30 to 40 minutes.

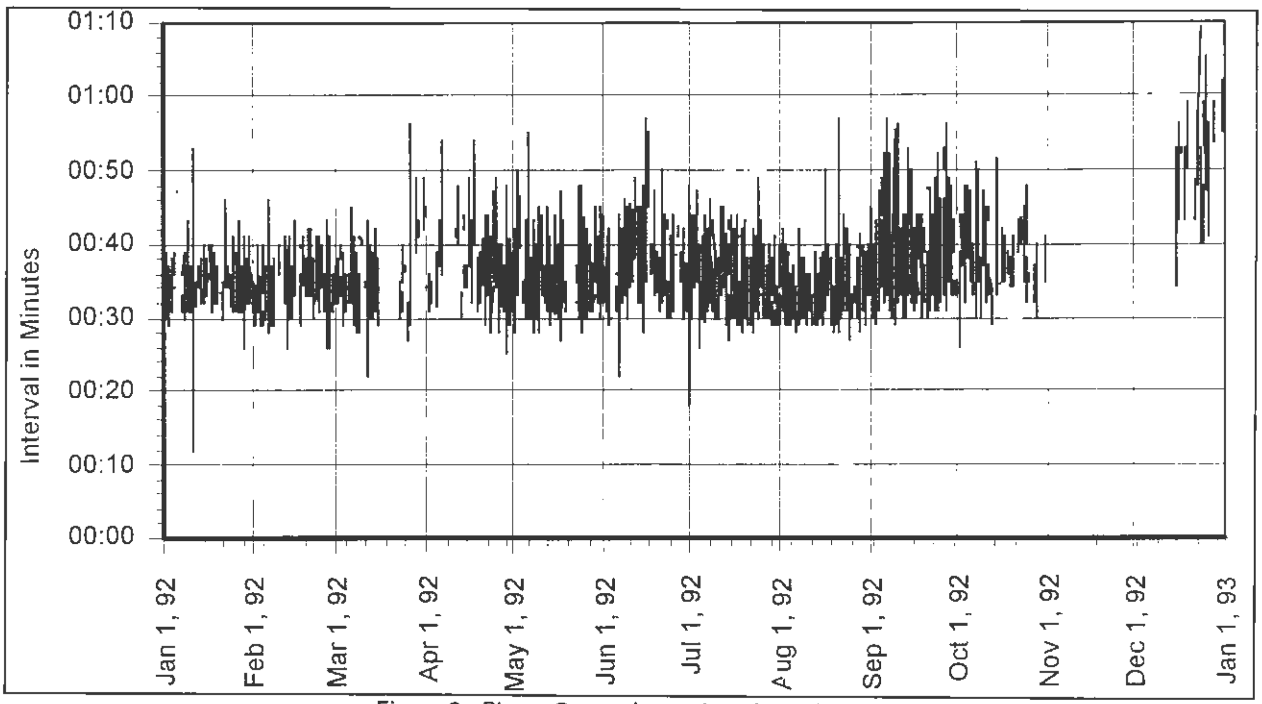

Figure 6 - Plume Geyser interval vs time, all 1992

Additionally, there was a pronounced cyclic variation in the daily maximum interval, with peaks in early April, mid June, and mid September. The cause of the variation is not apparent.

When the daily variation is examined more closely, it becomes evident that the typical pattern was for long intervals in the early morning hours, with decreasing intervals as the day proceeded. The daily change in intervals was first observed by Jens Day [Day, 1991] and discussed by Scott Bryan in [Bryan 1993d] and [Bryan 1993e]. The latter papers discuss Geyser Hill activity including Plume's diurnal behavior. These observations of Plume's diurnal changes of interval were based largely on daytime observations.

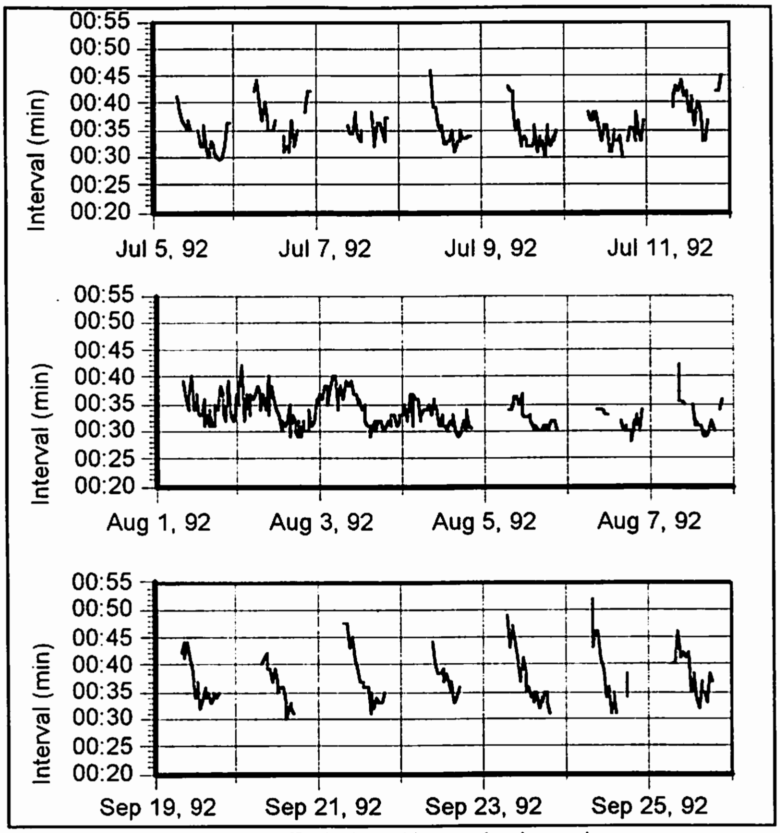

Figure 7 - Typical weekly eruption intervals

Another series of observations was performed by Yellowstone's Research Geologist, Rick Hutchinson, and reported in [Bryan 1993d], page 18. The monitoring was performed using a temperature monitoring device to sample Plume's overflow water temperature under the boardwalk to the west of Plume's crater. From the temperature surges caused by Plume's eruption, it is possible to determine the eruption times and intervals. These measurements extended for 96 hours and showed a pronounced daily change in interval, peaking in the morning hours and reaching a minimum of about 30 minutes by noon.

Based on early reports of these measurements, and on the author's own observations of Plume Geyser during the 1980s (which did not show any diurnal variation), the author organized a study under the auspices of GOSA's Research Division to watch Plume Geyser continuously to determine the detailed nature of the diurnal effects. The study was conducted by the author, Michael O'Brien, Lynn Stephens, and Brenda Taylor. The project team observed 150 eruptions of Plume, giving 149 closed intervals. The observation period began at 07:31 on Saturday, 1 August 1992 and ended at 19:30 on Tuesday, 4 August 1992. During this time, the time and duration of all bursts was recorded. The purpose of the study was to determine the nature of the diurnal variation in interval and to determine what variation, if any, in burst count, burst duration, and burst spacing occurred.

Coincidentally, the GOSA study began just as a significant change in Geyser Hill activity began. On the day the Plume study began, Beehive Geyser began a month long dormancy, and Beehive's Indicator began having regular eruptions. This unprecedented activity in the nearby Beehive-Beehive's Indicator system did not appear to have any direct effect on Plume, but comparison of the interval variations for all of 1992 shows that the variations were less during the study period than at any other time in 1992 (see Figure 6). It is possible that whatever caused Beehive to go dormant and Beehive's Indicator to begin a long series of independent eruptions might have also affected Plume's interval variation.

PLUME GEYSER: History and Recent Changes

The GOSA study and the author's other spring and early summer 1992 observations showed the activity of Plume Geyser to have a noticeable diurnal variation in eruption interval but to have a remarkably constant pattern of activity within an eruption. As we will see later, this internal consistency changed radically as 1992 progressed.

PLUME'S DIURNAL VARIATION, 1992

Figure 6 shows the total eruption interval picture for all of 1992, but the daily variation is not visible on this scale. Figure 7 shows the daily interval variation for selected weeks in July, August, and September of 1992. In all cases, the daily variation is clear, although in early August the variation is as little as five minutes while in July and September the variation is 15 to 20 minutes.

In order to quantify the diurnal effect, the author obtained all of the recorded Plume intervals for 1992 from the OFVC logbook, adding some missing eruptions from personal observation notes. These sources contained a total of 4523 observed eruptions, for a total of 3549 closed intervals. By observing the interval trends, a number of intervals were determined to be double intervals. Splitting these inferred double intervals into equal parts allowed an additional 398 eruptions to be inferred, for a total of 4921 eruptions, giving a total of 4345 intervals, including both observed closed intervals and intervals inferred from double interval observations.

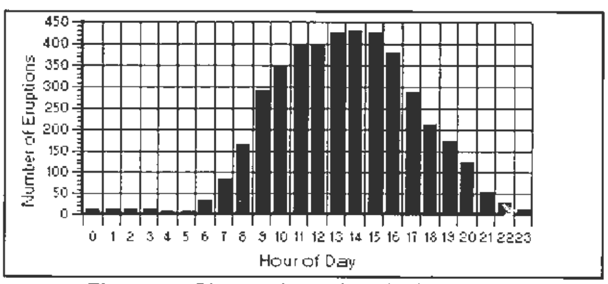

Figure 8 - Observed eruptions by hour, 1992

There is a very strong bias toward daylight hour observations in this data set, as shown by the histogram in Figure 8, which shows the number of observed eruptions for each hour of the day. The nighttime observations are almost exclusively those from the GOSA Research Division study in August, 1992. Nevertheless, the patterns are believed to be significant.

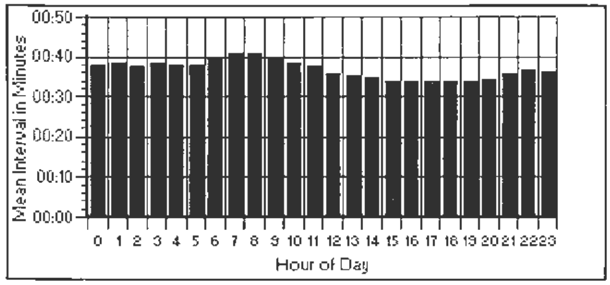

Figure 9 - Mean interval by hour, 1992

Figure 9 shows the mean interval for each hour of the day for all of 1992. The intervals peak at about 41 minutes at 0800, then gradually decrease until by 1700 the mean interval is about 34 minutes. The intervals then gradually increase through the night. Plots for shorter intervals of time showed that the shape of the distribution was essentially the same for all of 1992. There was clearly a diurnal shift in interval of eight to ten minutes operating for almost all of 1992.

PLUME'S EARLY 1992 ERUPTIONS

This section describes the shift in the nature of Plume's eruptions. Excepting the diurnal shift in eruption intervals, Plume's eruptions had remained much the same for several years. This section is a detailed analysis of Plume's eruptions in the spring and summer of 1992; the behavior in 1990 and 1991 was, in the author's experience, quite similar.

In the spring and summer of 1992, the author personally observed approximately 100 eruptions of Plume Geyser. The eruptions were remarkably similar in character. All of these eruptions had either four or five bursts. Between eruptions, the water was well below the surface, standing several centimeters below the overflow level in the west pool (the "indicator pool" of the 1970s). As the next eruption approached, the water level would rise very slowly, until the geyserite knob at the north side of the central vent (the 1972 crater) was just at water level. Often a series of 1 cm bubbles would appear in the main vent on the southern side as much as 10 minutes or as little as two minutes before the next eruption.

There would usually be a dozen or so bubbles, separated by several seconds, quietly rising through the water. The bubbles were usually followed by a return to a quiet pool. Between one and three minutes prior to the eruption, the water level usually surged up and down slightly, the total change in water level never exceeding a centimeter or two.

A typical eruption during early August 1992 began with a sudden rise in water level in both the main (center) vent and the indicator pool (west vent). The rise reached the point of overflow from the west vent in five to ten seconds. The water then surged up strongly, producing a flood of water from both the west and main vents. The water domed strongly over the main vent, causing a wave of water to surge from the main vent and providing a noticeable audible warning of the impending eruption. This whole chain of events, from the start of the rise to the doming and wave of runoff, lasted perhaps 20 seconds. The water level would stabilize for a few seconds, maintaining the flood of overflow, and then the first burst of the eruption exploded from the original vent and the central vent. The central vent bursts were massive, and usually inclined to the northwest. The strongest bursts reached 8 meters in height. The burst from the original vent was more slender but often fully as high as the central vent activity.

Burst	Mean Duration	SD	Number of bursts
1	7.85	1.05	150
2	8.21	1.22	150
3	8.08	1.28	150
4	9.36	2.46	150
5	9.04	2.79	27

Table 1 - Burst durations, 1-5 August 1992

The bursts averaged under ten seconds in duration, as shown in Table 1 and Figure 10. The first three bursts had remarkably constant duration for all of the eruptions observed in May, July, and August of 1992. During the 84-hour continuous watch from 1-4 August, we observed 150 consecutive eruptions. Of these, 27 had five bursts and 123 had four bursts. The first burst averaged 7.85s in duration, with a Standard Deviation of only 1.05 seconds. This is a very small variation, especially considering that the times are recorded to the nearest second with an accuracy of no better than 0.5 sec.

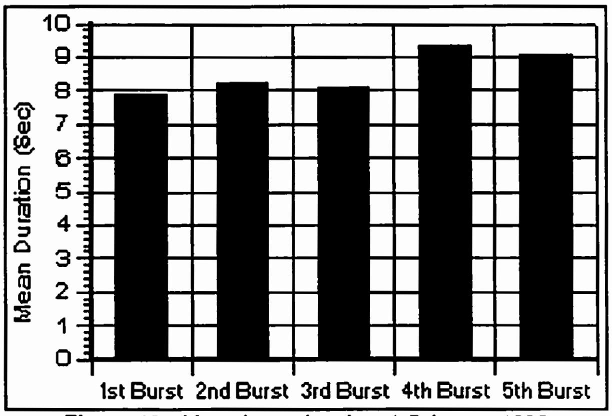

Figure 10 - Mean burst duration, 1-5 August 1992

The second and third bursts were almost as consistent as the first, and about the same length; 8.21s and 8.08s respectively. The fourth burst tended to be longer and exhibited considerably more variation, averaging 9.36s with a Standard Deviation of 2.46s. The first four bursts were almost always sudden and powerful, achieving heights of between four and eight meters. The fifth burst was sometimes weak, reaching only two meters in height on some occasion. These smaller bursts were often extended in duration. The overall mean duration for the fifth burst was 9.04s, with a Standard Deviation of 2.79s.

Burst Interval	Mean Interval	SD	Number of Intervals
1-2	15.08	1.22	150
2-3	16.76	1.24	150
3-4	17.41	1.41	150
4-5	22.59	3.23	27

Table 2 - Interburst intervals, 1-5 August 1992

The interburst intervals were also consistent from one eruption to the next in early August of 1992 as shown in Table 2 and Figure 11. The interburst intervals showed little variation, with Standard Deviations between 1.2 and 1.4

seconds for the first four bursts, increasing to 3.23 seconds for the interval between the fourth and fifth bursts. The interburst interval increased by about one second for each of the first four bursts, then by over five seconds for the last burst.

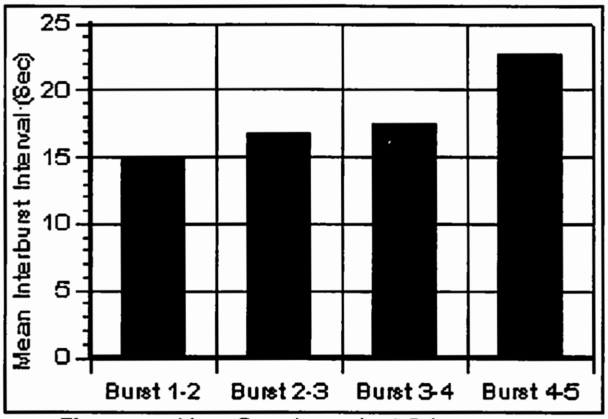

Figure 11 - Mean Burst Intervals, 1-5 August 1992

Often the fifth burst occurred after a noticeably longer interval than that between the first four bursts. On several occasions, the water rose in the crater at the time a fifth burst would be expected but then simply sank out of sight without any bursting or bubbles.

Figure 12 shows the burst intervals, durations, and burst counts for all eruptions observed during the August Plume watch. The graphs clearly show the stability of the eruption pattern. The interburst interval and the burst duration both show no strong trends. The five burst eruptions are clustered around noon on 1 August and between midnight and noon on 3 August. Plots of the durations for each burst and the separate interburst durations closely resemble the composite plots in Figure 12.

PLUME'S BEHAVIOR IN SEPTEMBER 1992

The author visited Yellowstone again in late September of 1992. At that time, another series of detailed observations of Plume (mostly between 06:00 and 22:00) revealed some noticeable changes from the pattern of the early August eruptions. The most noticeable change was the appearance of a considerable number of eruptions having three bursts. Other notable changes were a larger daily variation in eruption interval, and more variation in the burst durations and burst intervals. The appearance and character of the eruptions had also changed significantly.

Figure 7 shows the larger eruption interval variation in September as compared to July and August. Figure 13 shows the burst interval, duration, and count for the author's 10-day stay at Old Faithful in September 1992. There were numerous three burst eruptions, and five burst eruptions were rare. Another change was the much greater variation in both burst interval and duration compared to the same graphs for August. In August almost all of Plume's bursts lasted between seven and 11 seconds. By September the typical range was five to 15 seconds, with some as short as three seconds and many lasting well over 15 seconds. Similarly, the interburst intervals

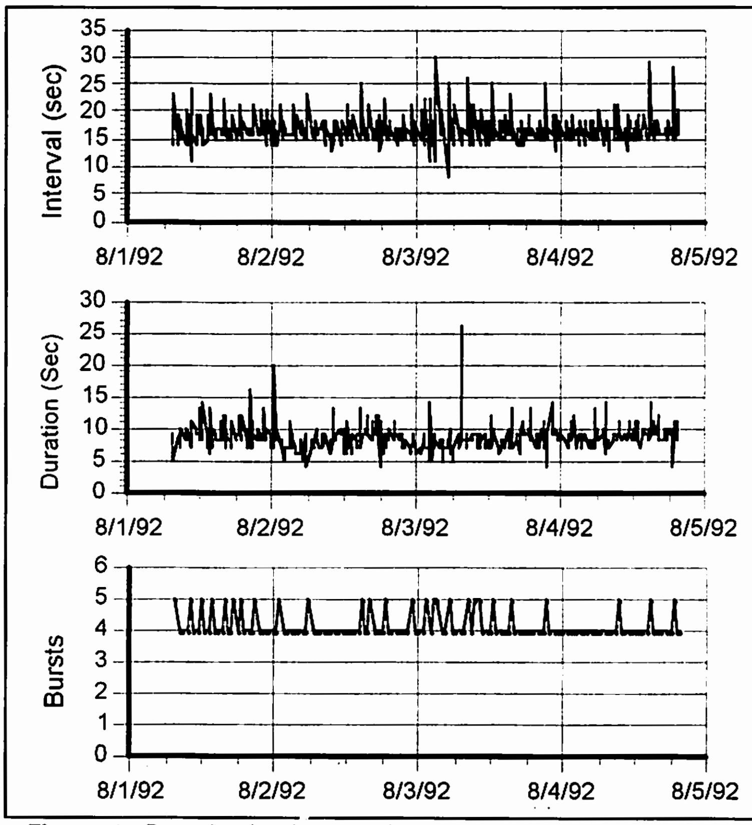

Figure 12 - Burst duration, interburst interval, and burst count, all eruptions 1-5 August 1992

shifted from 15-20 seconds in August to 12-20 seconds in September.

The nature of the eruptions also changed significantly. In September, Plume's eruptions were still commonly preceded by 1 cm bubbles in the main vent three to five minutes before the start of the eruption. The first burst of the September eruptions was often weak and slow in starting in marked contrast to the explosive first burst common in August. Some of the September eruptions started from the northeast vent (the original vent), while others started from the main vent. The August eruptions tended to start simultaneously in both the center and northeast vent.

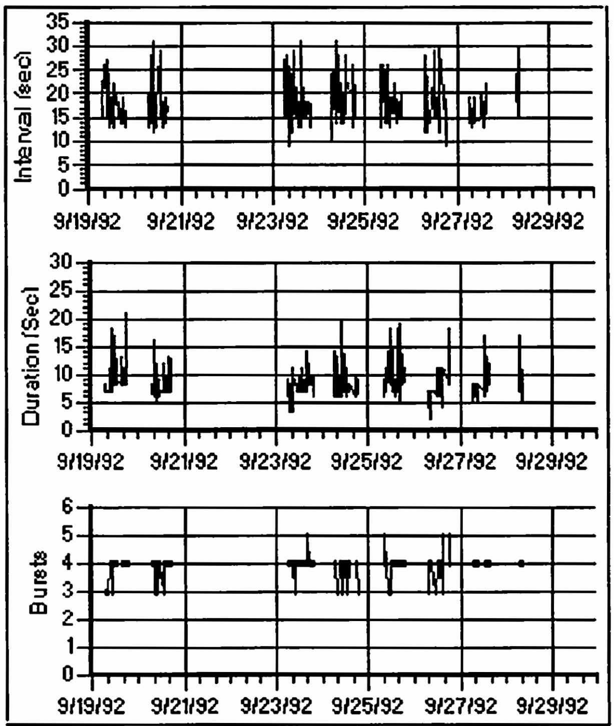

Figure 13 - Burst duration, interburst interval, and burst count, all eruptions, 19-29 September 1992

Another September change was in the eruption power. Many eruptions had second or third bursts only one or two meters high. Weak bursts were seen in August, but always as the last burst of a five burst eruption. In September, the weak bursts (which could be any burst, not just the last) sometimes were quite long in duration, merging almost without pause into a full strength subsequent burst. The pause between a weak burst and the following normal burst was sometimes less than five seconds, contrasted with the 10 to 15 second pauses seen in August.

The burst duration statistics for late September 1992 are shown in Table 3 and Figure 14. The graph includes the August data for comparison. The mean first burst duration for September was over one second longer than that for August, and the Standard Deviation was almost 4 seconds. The occasional weak burst, which tended to be prolonged, contributed to the high Standard Deviation. The second and third bursts were shorter than their August counterparts but had similar variation. There were only four eruptions with five bursts out of the total of 108 eruptions observed in September.

Burst	Mean Duration	SD	Number of bursts
1	9.20	3.95	108
2	7.47	1.42·	108
3	8.15	2.54	108
4	9.80	3.20	90
5	12.50	3.87	4

Table 3 - Burst durations, 19-29 September 1992

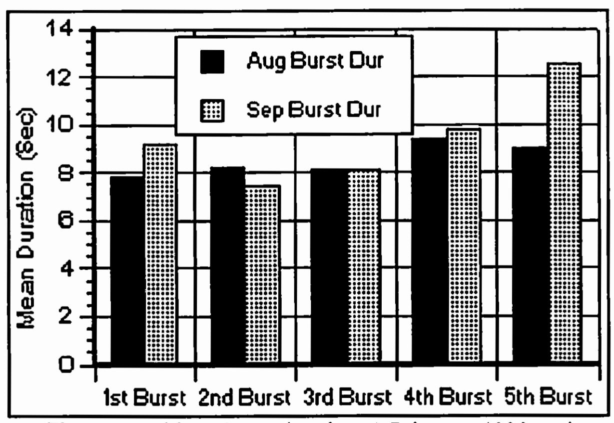

Figure 14 - Mean burst duration, 1-5 August 1992 and 19-29 September 1992

The September eruptions had a larger increase in burst duration as the eruption continued when contrasted with the August eruptions, which had nearly constant length bursts.

The interburst intervals for September are shown in Table 4 and Figure 15. Unlike the burst durations, the mean interburst intervals were more consistent in September, although the variation between eruptions was much higher, as noted previously and indicated by the much higher Standard Deviations.

Burst Interval	Mean Interval	SD	Number of Intervals
1-2	17.76	4.94	108
2-3	17.12	1.79	108
3-4	18.52	3.57	90
4-5	19.25	8.73	4

Table 4 - Interburst intervals, 19-29 September 1992

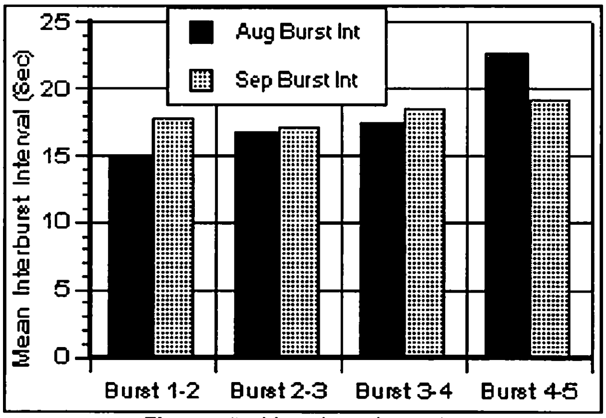

Figure 15 - Mean burst intervals, 1-5 August 1992 and 19-29 September 1992

In summary, by late September 1992 Plume's eruptions had substantially more diurnal shift in interval than in early August, and the eruptions were more varied, with fewer bursts and with more variation in the power, duration, and spacing of the bursts. One or two meter "wimpy" bursts were seen on many occasions. This shift proved to be a harbinger of greater change in the months ahead.

WINTER 1992-3—PLUME GOES DORMANT

Plume continued its activity at approximately the September level through the end of the Summer season. When the park reopened in December, Plume was having much longer intervals than previously. Figure 6 shows the intervals increasing to nearly 70 minutes in late December. Scott Bryan noted that the daily short intervals were around 40 minutes, and "...the mean of 41 intervals recorded after the park reopened was 50 minutes." Furthermore "...some eruptions of three or four bursts have been seen, [but] the majority consist of just two bursts." [Bryan 1993a]

By March, 1993 Plume had slowed to the point that markers were being used to determine the intervals, which were as long as 48 hours, and eruptions were reported to consist of "two or three weak to average bursts." [Bryan 1993b] April saw Plume slowing even more. Intervals of between days and a week were reported, and Rick Hutchinson reported in a letter on 12 April 1992 that "Plume is still dormant as shown by light orange cyanobacteria growing in the lower southwest vent..." [Bryan 1993c]

Plume continued in this manner until the evening of May 4-5, when Giantess Geyser erupted. The eruption of Giantess triggered Plume into regular activity, with intervals between eruptions of around 32 minutes. The renewed activity continued through the rest of the spring and summer of 1993, and was still continuing as of the latest information available to the author.

Figure 16 shows Plume's intervals for all of 1993. The intervals were gathered from the OFVC logbook and from temperature monitoring performed by Heinrich Koenig for Rick Hutchinson, shows the pattern of activity for 1993. The eruption data for January through May is sparse, partly because the park was closed between the winter and summer seasons from 16 March to 15 April, but largely because Plume was erupting infrequently (see discussion below). Plume was watched closely in April, but there were few eruptions.

The pattern of eruptions in January is a continuation of the increasing interval play seen in December 1992. Note that the trend is sharply upward through January, with mean intervals increasing from around 50 minutes in early January to nearly an hour in late January.

Few eruptions were reported between early February and the rejuvenation coincident with the Giantess eruption on 4-5 May. During this period, Plume was under observation from the OFVC during the daylight hours, with experienced observers including Tom Hougham

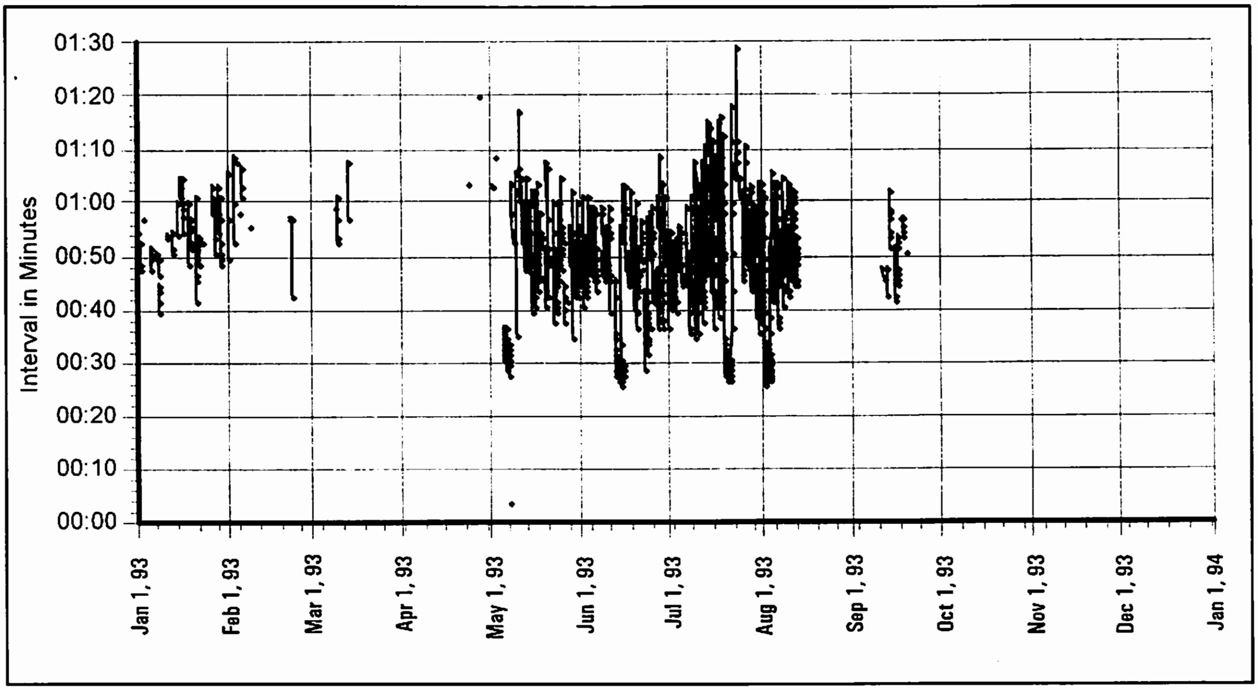

Figure 16 - Plume Geyser interval vs. time, 1993

and Ann Deutch on duty much of the time. Examination of the record for Plate Geyser shows no recorded observations between 31 October and 15 December, which parallels the gap in the Plume record. In 1993, the Plate Geyser record is continuous from the first of the year to 16 March, then stops until 15 April. The Plume graph shows very few eruptions between early February and 4 May. During the periods 1 February to 16 March and 15 April to 4 May Plume was under close observation but only a handful of eruptions was recorded.

The eruption record from 4 May to 13 August is a mix of visual observations recorded in the OFVC logbook and the continuous temperature monitor record from 9 July through 13 August.

Once Plume had recovered following the Giantess eruption, the eruption pattern was quite different from 1992's play. The variation throughout the day was greater, ranging from 35 minutes to nearly two hours. But the increased variation was only part of the story of Plume Geyser in 1993.

PLUME'S "SLEEP" PERIODS

Following the recovery in early May, Plume often experienced long periods of inactivity, most often overnight. These "sleep" periods were characterized by quiet overflow from the southwest vent and generally quiet demeanor from the whole complex. Occasionally the water would "rock" from side to side, and show other signs of disturbance. The water level fluctuated gradually during the sleep period, dropping enough to stop overflow periodically, then resuming overflow. The periods of low water lasted for approximately 30 seconds. As the first eruption following the sleep period approached, the water level in the center and west vents rose and fell at irregular intervals, the rises becoming stronger as the eruption neared. Finally, one of the incidents of rising water level led to heavy overflow and the eruption would start, approximately 30-40 seconds after the strong rise in water level.

The existence of the sleep periods was fairly well established by the end of May. The author established the duration of some of the sleep periods in late May and early June using markers. At that time, Plume was known to sleep frequently, but the actual time and duration of the sleep periods was not known. It was clear that Plume slept most mornings, resuming activity in the late morning hours, but the last eruption times were late at night and not recorded. For example, the author observed Plume quietly overflowing from 06:00 until 09:16 on 29 May, from 06:00 to 10:23 on 30 May, and 07:00 to 10:47 on 31 May. The late evening activity was not observed on 29 May. On 30 May the last observed eruption was at 22:27, and the intervals were not noticeably increasing. On Monday 31 May, the last observed eruption was at 23:23, at slightly longer intervals than the preceding intervals (54m 18s as opposed to 52 minutes for the previous three intervals). On Tuesday 1 June, Plume first erupted at 11:13, and the last eruption noted was at 23:40, with a possible eruption reported at 00:21 on 2 June. Plume was active by 10:21 the next morning, and possibly did not sleep at all that night.

At this time (early June), there had been no accurate determination of Plume's sleep duration nor the precise time of the last eruptions before the sleep commenced. The author obtained permission to mark Plume (this is a bit tricky—the constant flow of water from higher on Geyser Hill tends to wash markers, and many points accessible from the boardwalk are not suitable because markers do not wash reliably). The first attempt, overnight on 2-3 June, was only partly successful. By the time I set the markers at 02:40, Plume was already sleeping. The markers were still in place at 03:12. Plume had been having its first eruption by mid-morning, but on 3 June, Plume foiled the attempt to determine the sleep period accurately by starting early. An eruption was reported by 07:09, and was not known to be the first eruption.

On the evening of 3-4 June, Plume was marked at 01:15. The previous eruption was not seen, but Plume was quietly overflowing. The markers were still in place at 01:45. At 07:59 on 4 June the markers were still in place. The first eruption occurred at 12:11, for a known sleep interval of over 11 hours. An attempt to mark Plume on the night of 4-5 June revealed that Plume sometimes does not sleep at night. Eruptions occurred at about 45 minute intervals regularly until 03:00, when the attempt was abandoned. Plume erupted at 08:05 and 08:54 the next morning, apparently having continued through the night.

PLUME'S 1993 ERUPTION PATTERNS

In 1993, Plume's eruptions had changed substantially from the 1992 patterns. The author has too few detailed observations from May and June to present a clear statistical picture, but several changes were clear from the limited observations. First, the number of bursts per eruption varied widely, ranging from one to seven. Second, Plume often had bursts that reached barely one meter in height, so it was not possible to count bursts unless one stood on the boardwalk in the immediate vicinity of the vent.

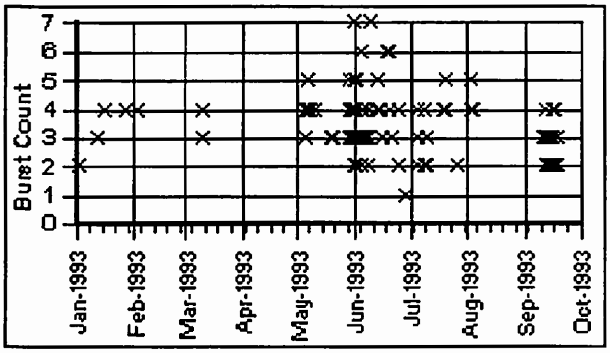

Figure 17 - Bursts per eruption, 1993

The wide variation in the number of bursts per eruption is evident in Figure 17. The higher number of bursts typically occurred during the first eruption following a sleep interval. These first eruptions after a sleep interval tended to be the most energetic, with more bursts and more powerful bursts. They were often accompanied by a popping sound, reminiscent of firecrackers or popcorn popping, apparently caused by near surface steam explosions.

Eruptions during 1993 occurred from the northeast vent (the original vent, farthest from the boardwalk near Beehive), the main vent, or both. The bursts from the northeast vent tended to be weak, sometimes only half a meter high. Bursts from both vents tended to be the most vigorous. Some bursts started with weak play from the northeast vent and then merged into a full strength burst from both vents. Overall, the character of the eruptions was highly variable in 1993.

PLUME GEYSER: History and Recent Changes

TEMPERATURE STUDIES, SUMMER 1993

During the summer of 1993, Heinrich Koenig, working for Rick Hutchinson, was experimenting with thermal recorders to measure the long term behavior of geysers, especially the Grand group. In order to study how to detect eruptions automatically from runoff water temperature studies, he placed one of the NPS thermal recorders in the runoff channel of Plume Geyser, at a point under the boardwalk where the main runoff channel passes under the walk on near Beehive Geyser. He chose Plume primarily for its frequency of eruptions and convenient access, but the long term record of Plume's eruptions proved very interesting itself. [Koenig 1993] The recorder measured the temperature of the runoff stream every minute, measuring with a resolution of 0.1°C. The location under the boardwalk shielded the temperature monitor from direct solar heating.

The water in this runoff channel was a mixture of water flowing around Plume's formation from Giantess Geyser and several small thermal features on the hillside above Plume. Some of this flow entered the crater of Spume and Spew Geyser, which has been dormant for many years. Day speculates that this influx of cold surface water, especially following rain, had the effect of slowing Plume Geyser down; temperature studies tend to confirm this hypothesis, as we shall see later. [Day 1992]

When Plume erupted, it sent a cascade of hot water down the runoff channel. The abrupt rise in temperature was easy to detect in the recorded data, allowing the Plume eruptions to be detected reliably. Since the temperature was recorded only once per minute, it was not possible to determine the number of bursts in the eruptions, nor to make any determination about the power or duration of the eruption.

The temperature recorder remained on Plume Geyser from the afternoon of 9 July through the afternoon of 13 August. This continuous record for 35 days provided several interesting results. First, it was possible to record the full, round the clock eruption history of Plume for over a month. Second, the observation period included two eruptions of Giantess Geyser, with the attendant marked changes in Plume's eruption pattern. Third, the continuous monitoring of the runoff water temperature provided some insight into the mechanism that causes Plume's sleep behavior.

DETECTING PLUME'S ERUPTIONS

The temperature record consists of a data file containing a temperature reading for each minute Because of the thousands of data points it was necessary to write a computer program to analyze the data and detect the eruptions automatically. The author wrote the data analysis program with consultation on the data formats and on eruption detection

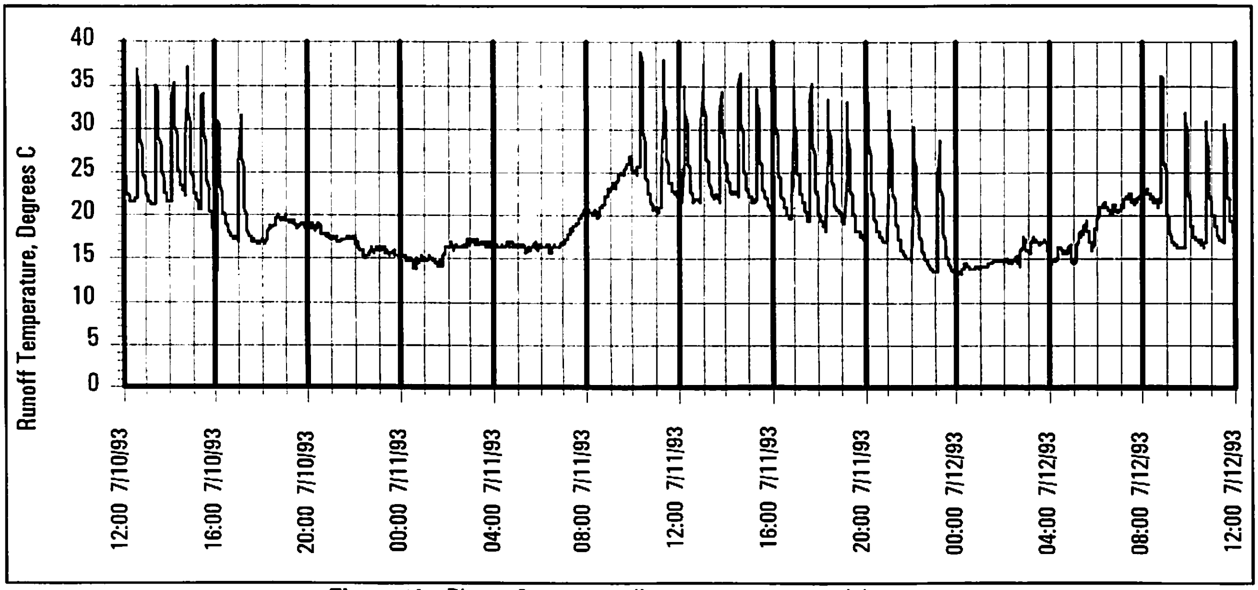

Figure 18 - Plume Geyser runoff temperature, 10-11 July 1993

methods from Heinrich Koenig, who was exploring methods of detecting eruptions from the temperature record. The author's work was independent of Koenig, but we compared techniques and shared examples and data.

Figure 18 shows a typical plot of the raw temperature data for a two day interval in July of 1993. Several items are immediately obvious from the plot. First, the sharp spikes clearly indicate Plume's eruptions. The runoff temperature rose abruptly from about 20°C to over 35°C within one minute. The temperature then slowly dropped as the water cooled. Second, the sleep periods are evident as long intervals with no eruption spikes in the runoff temperature. Third, there is a pronounced daily cycle in the base temperature of the runoff water, which generally coincides with the sleep periods. Plume tended to erupt when the runoff temperature was high and sleep as the runoff temperature dropped, supporting Day's hypothesis that cool surface water entering Plume's plumbing system (possibly via the crater of Spume and Spew Geyser, located just uphill from Plume) causes Plume's diurnal interval variation and the sleep periods.

Figure 18 is plotted at too small a scale to illustrate the shape of the temperature profile for one eruption, and understanding this shape is basic to the automatic detection technique. Figure 19 shows a four-hour period containing two eruptions and the start of a sleep period. The temperature rise is very sharp, and the recovery has the typical exponential decay shape. For Plume Geyser the sharp rise is the key to automatic detection of eruptions.

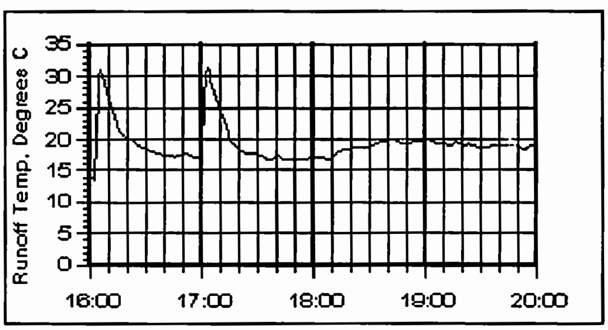

Figure 19 - Plume Geyser runoff temperature vs time
10 July 1993

Examination of a plot of the difference in temperature between successive readings makes the onset of an eruption even more clear, as is shown in Figure 20. Here we see that there is a rise of 8 to 10 degrees Celsius within two minutes at each eruption. The key to accurate detection of an eruption for Plume was establishing a two-step test. The test used for this paper determined that an eruption was beginning when the temperature increased by at least 0.3°C at one sample point followed by an increase of at least 0.9°C on the next point.

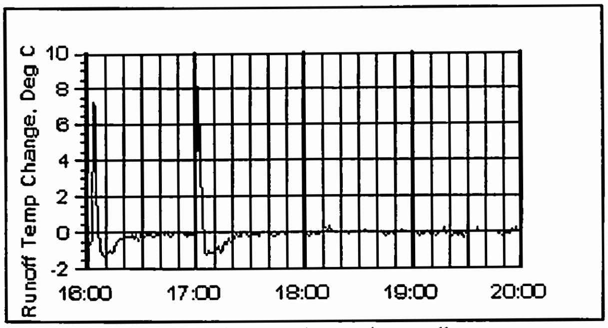

Figure 20 - Plume Geyser change in runoff temperature,
10 July 1993

An eruption could be reliably detected by a simple test for an increase of more than 1°C, but this missed the initial surge in many cases and detected the eruption one minute late. Using the two step threshold test produced results that agreed perfectly with visual observation for all cases for which visual records were available. There is a constant one minute lag between directly observed eruption times and eruptions detected by temperature changes. This delay is simply the time required for the hot water from the eruption to reach the western edge of the boardwalk where the monitoring device was located and the one minute sample period of the monitor.

PLUME'S SLEEP TIMES

One of the most striking changes in Plume's behavior in 1993 was the sleep periods that occurred almost daily. This behavior was probably an intensification of the diurnal interval increase observed in 1992. At first, the sleep periods were thought to be simple nighttime inactivity. However, there were enough periods of inactivity at other times (beginning during the day, initial eruptions in late afternoon, and so on) that it was not clear just what pattern, if any, was present.

Based on 35 days of temperature monitor data, the most consistent aspect of the sleep periods was the time of the first eruption after the sleep period. Figure 21 shows the tendency for Plume to awaken between 11:00 and 13:00 following a sleep period.

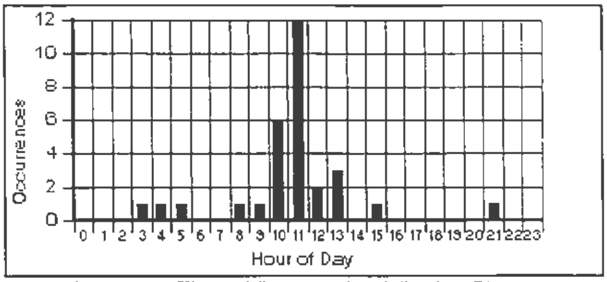

Figure 21 - Time of first eruption following Plume's sleep periods

The duration of the sleep periods (Figure 22) and the start of the sleep period (Figure 23) show less regularity. The duration graph shows all of the sleep periods (arbitrarily defined as any interval exceeding 90 minutes).

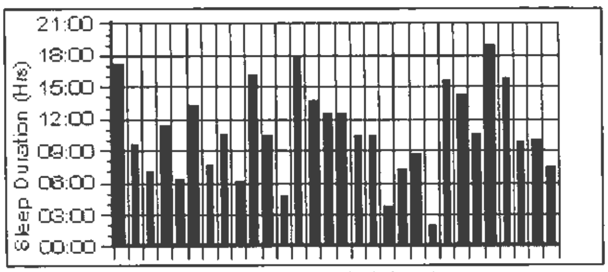

Figure 22 - Sleep period durations 9 July 1993 to 13 August 1993

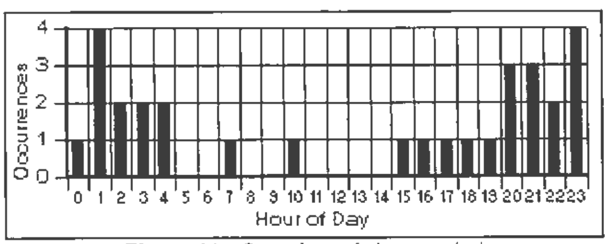

Figure 23 - Start time of sleep period

The sleep period durations vary widely, the majority being from six to 12 hours long. The two sleep periods over 18 hours long occurred just after eruptions of Giantess Geyser. The declining sleep durations thereafter show Plume's recovery from the Giantess eruption.

There was a tendency for Plume's sleep periods to start between 20:00 and 04:00, but the peak in sleep start time is broader than the peak in the wake-up time.

DIURNAL BEHAVIOR IN 1993

What has happened to Plume's diurnal interval shift? The 1993 sleep periods generally started during the hours when Plume formerly increased its eruption intervals. The end of the sleep periods generally coincides with the 1992 minimum eruption intervals also.

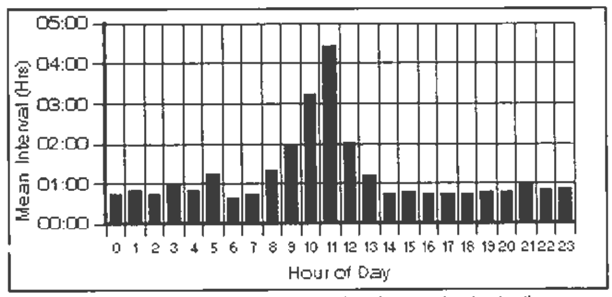

Figure 24 - 1993 Mean eruption intervals, including sleep periods

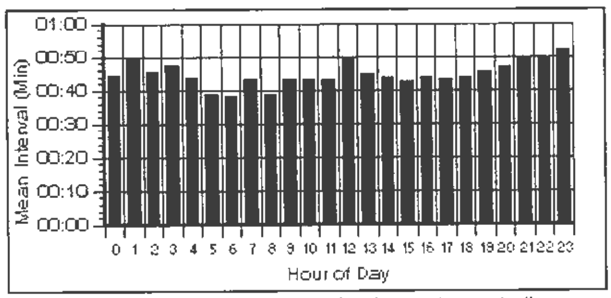

Figure 25 - 1993 mean eruption intervals, excluding sleep periods

The 1992 eruption pattern was revealed best by the histogram of mean eruption interval for each hour of the day (see Figure 9). The corresponding plot for the portion of 1992 covered by the temperature monitor shows a very different pattern, as shown in Figure 24. This graph shows the mean interval for eruptions *ending* during the hour on the horizontal axis.

The sharp peak is caused by the large number of sleep period ending eruptions that occurred around 11:00. Plotting the same histogram with the sleep intervals excluded (Figure 25) reveals a rather different pattern of interval shift from that seen in 1992.

PLUME GEYSER: History and Recent Changes

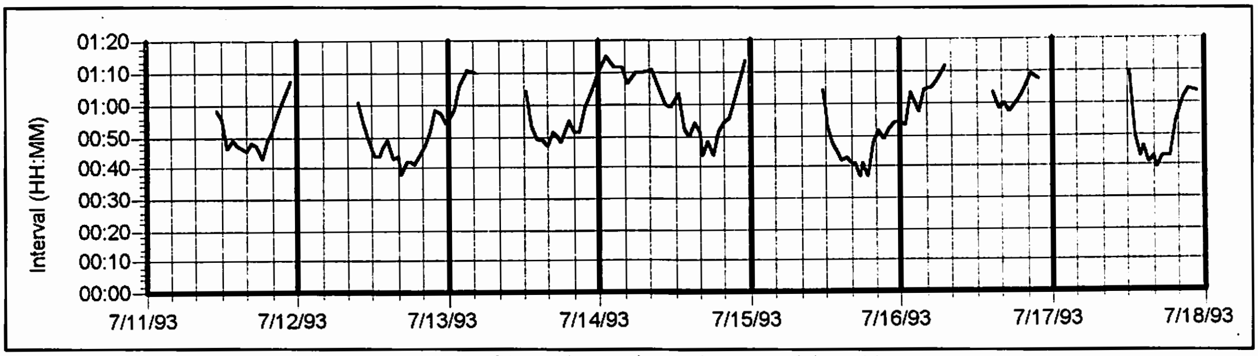

Figure 26 - Plume Geyser intervals, 11-17 July 1993

As in 1992, the mean intervals tended to increase in the late afternoon and evening. The pronounced decline in interval from early morning to midday was absent, and the mean intervals were considerably longer (40 minutes compared to 34 minutes for the midday hours).

Although the mean intervals do not show the daily shift in intervals, the plot of intervals for a full week (Figure 26) clearly shows the daily trend in intervals. Every day, the intervals fall during the afternoon hours, typically from 50 minutes or more to a low of 40 to 50 minutes. Typical changes were on the order of 20 minutes in any given day. This graph also illustrates that Plume does not always sleep, as there was no sleep period on 14 July.

A reasonable explanation for the apparent lack of diurnal interval shift shown by the mean interval histogram is that whatever caused the longer nighttime intervals in 1992 also caused the sleep periods in 1993. Excluding the sleep intervals obscured the effect.

THE GIANTESS EFFECT

Plume Geyser has been known to be affected by eruptions of Giantess Geyser since Sam Martinez described the effect in the 1970s. [Koenig 94] Hutchinson noted a shortening of Plume's intervals for the two days following an eruption of Giantess Geyser in 1982. [Hutchinson 1982] Koenig, who recorded much of the data for the 1982 episode cited by Hutchinson, reports that Plume's intervals at the time of the Giantess eruption on 1 July 1982 rose immediately following the start of the Giantess eruption, then dropped from 36-38 minutes to 29-32 minutes the following day. The intervals remained shortened for about two days. The number of bursts per eruption also changed from a mixture of three and four burst eruptions before the Giantess eruption to a steady four bursts per eruption during the period of reduced intervals. [Koenig 1994]

In 1986, the author noted a shift in Plume's behavior following an eruption of Giantess. Before the Giantess eruption, Plume was erupting following a period of overflow. Intervals were in the 38-45 minute range and eruptions had between two and four bursts. Following the Giantess eruption on 15 July 1986 at 10:26, the intervals dropped to 28-30 minutes and there were always four bursts in each eruption. [Taylor 1986] In 1989, the author again observed Plume's reaction to Giantess. At this time, Plume was not overflowing before eruptions. However, the mean interval again dropped following the start of the Giantess activity, again to 28-30 minutes. The lower intervals were seen for four days, then the intervals recovered to the 30-32 minute range that was evident before the eruption. [Taylor 1989] The eruption of Giantess Geyser on 25 March 1992 was accompanied by the same sort of interval decrease to 28-30 minutes.

In 1993, the magnitude of the effect of Giantess on Plume was substantial. Four Giantess eruptions occurred during the spring and summer of 1993, at 17:44 on 4-5 May, 11:31 on 12-13 June, 10:55 on 20-21 July, and 02:06 on 2-3 August. In all cases Plume responded by erupting with great regularity at 26 to 32 minute intervals, with no sign of diurnal variation or sleep periods. The first Giantess eruption rejuvenated Plume after a period of near dormancy. The subsequent eruptions merely interrupted the 1993 pattern of sleep intervals and generally long daytime intervals with consistent sets of eruptions at 28 to 32 minute intervals. The intervals during the "Giantess Effect" paralleled those noted in previous years. The complete absence of diurnal interval variation and sleep periods in 1993 was notable.

The graph of Plume's intervals for the week following the Giantess eruption shows the dramatic effect of Giantess Geyser on Plume's activity (see Figure 27). Giantess began its eruption at 10:55 on 19 July. Plume reacted by a two short intervals of 30 and 34 minutes, then had a very long interval of 1h13m, one of 46 minutes, and then settled into a pattern of intervals near 30 minutes. The intervals shortened from 30-32 minutes to 28-30 minutes as the Giantess eruption continued. Once Giantess stopped, Plume's intervals promptly lengthened to nearly one hour, then a series of long sleep periods separated by short periods of activity with eruptions occurring at 60 to 70 minute intervals. The active phases only lasted for three to five eruptions before the next sleep period occurred. During the next week Plume settled down to a routine of about 12 hour sleep periods separated by active periods consisting of eruptions at 50 to 60 minute intervals, gradually shortening to midday intervals of 40 minutes.

RUNOFF TEMPERATURE AND SLEEP PERIODS

The placement of the temperature monitor in the runoff channel provided additional information, since between eruptions of Plume, the runoff water is entirely from Giantess Geyser and several small thermal features to the east (uphill) from Plume. The software that detected the Plume eruptions was extended to detect times when the temperature of the runoff water changed by less than ±0.15°C. This resulted in a curve reflecting the temperature of the runoff water between the Plume eruptions, possibly modified by preliminary runoff from Plume.

The runoff temperature curve for the period of automatic monitoring in Figure 28 shows a clear daily cycle, primarily caused by atmospheric cooling at night and a combination of warmer air temperatures and direct solar heating of the water during the day. The line at the bottom of the graph shows the sleep intervals (when the line is at the 5°C ordinate) and normal eruptions (when the line is at the X axis). The start of the sleep periods coincides with the bottom of the runoff temperature curve in every case recorded during the monitoring. The beginning of the sleep interval generally occurred when the runoff temperature reached a point between 10°C and 15°C. In fact, on the nights when Plume did not sleep, the runoff temperature only dropped to 15°C and then began to rise. The first eruption following the sleep interval occurred when the runoff temperature rose above 20°C, usually during a period of sharp runoff temperature rise. Whether or not there is a direct causal relationship between the surface runoff temperature and Plume's sleep periods is not clear, but the coincidence of the sleep period and the lowered runoff temperatures strongly suggests that there may be such a relationship.

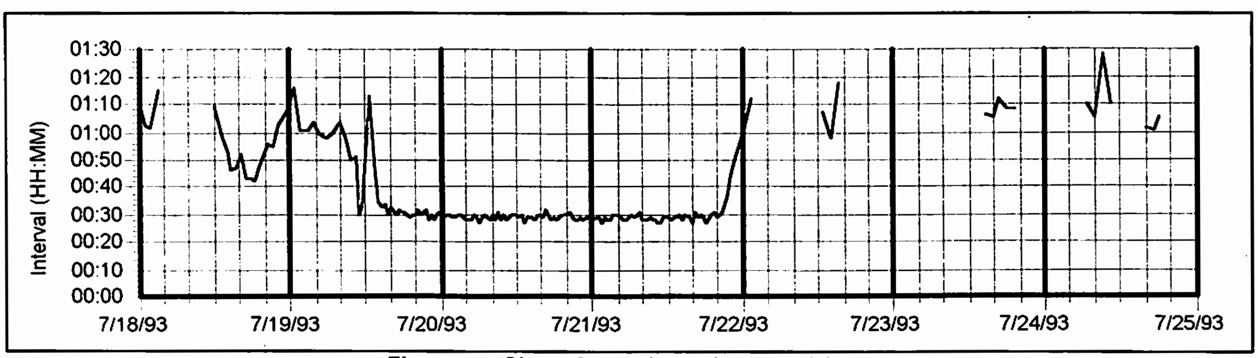

Figure 27 - Plume Geyser Intervals, 18-24 July 93

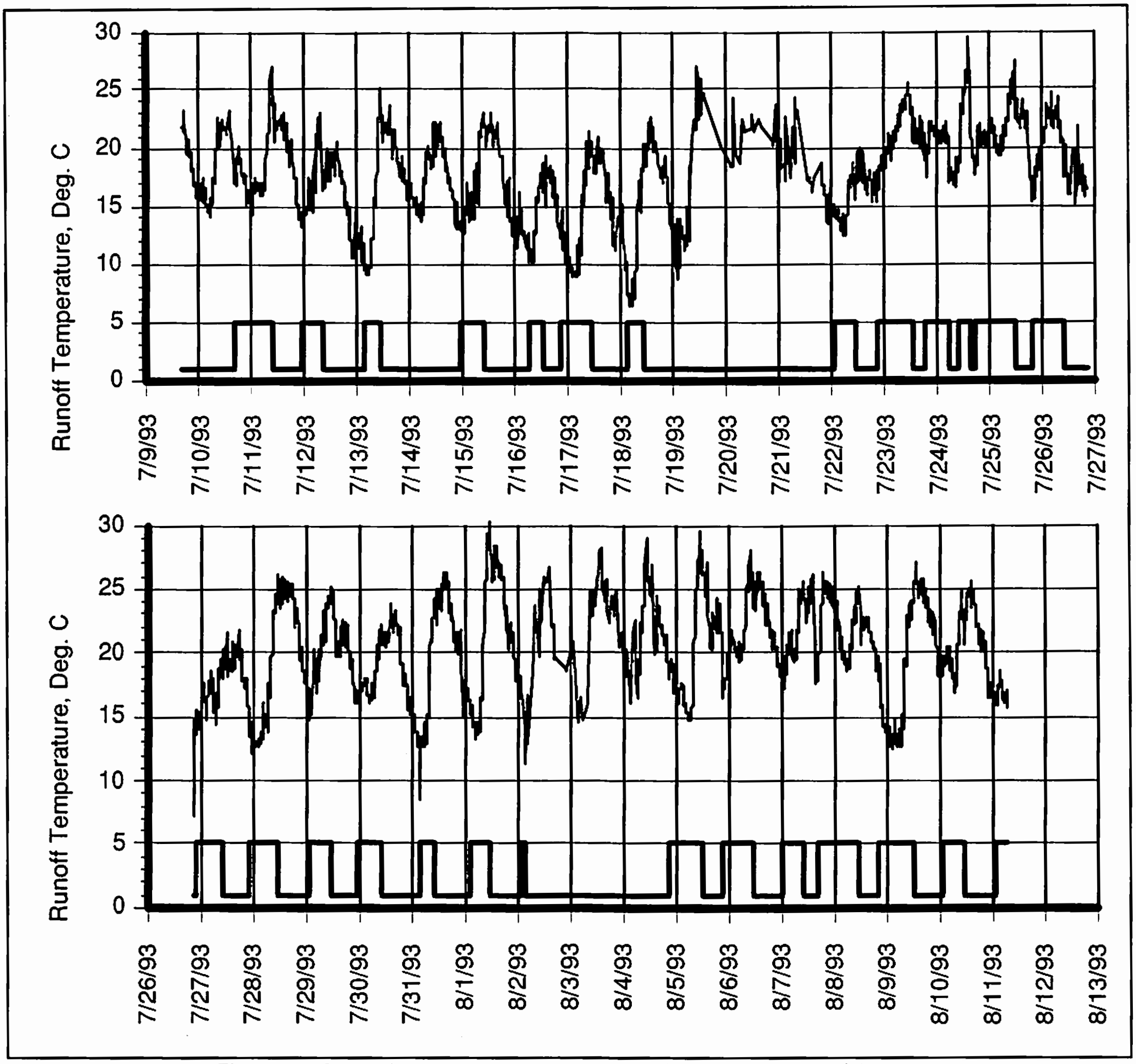

Figure 28 - Plume Geyser runoff temperature and sleep periods, 11-18 July 1993

There was one example of a temperature-sleep relationship outside of that just described. On 26 July, the sleep period began just at the minimum runoff temperature (15°C in this case) as in the other cases, but the sleep persisted through the daily temperature rise, and ended as the runoff temperature *dropped* to about 18°C from a peak at 08:00 of 24°C. The cause of the drop in temperature between 08:00 and 16:00 on 26 July is not clear, but may be weather related.

SUMMARY AND CONCLUSIONS

As we have seen, Plume Geyser underwent a significant change in function during the 1992 and 1993 seasons. At the beginning of the period, eruptions were uniformly of four or five bursts, and were uninterrupted around the clock. As 1992 progressed, the diurnal change fluctuated but remained evident, with daily interval shifts of 10 to 30 minutes. The intervals were uniformly longer in the morning and shortest in the mid afternoon hours.

PLUME GEYSER: History and Recent Changes

In September 1992, eruptions began to change, having fewer bursts and occasionally having some very weak bursts, reaching only 1 meter in height. The structure of the eruptions also changed; both interburst intervals and burst durations were much more variable than had been the case in August.

By December 1992 Plume was having longer intervals. In January 1993 the intervals continued to increase and the average number of bursts per eruption decreased. Between February 1993 and May 1993 Plume became nearly dormant. Intervals of days were recorded.

The eruption of Giantess on May 4-5 restored Plume to activity, but with even more variation in the burst count, duration, and intervals. Furthermore, Plume had even more extreme diurnal behavior, often sleeping for many hours, generally in the late night and early morning hours.

Monitoring of the surface runoff water temperature suggests that the sleep periods may be related to variations in the runoff temperature. Plume tended to stop eruptions when the runoff water temperature dropped to around 15°C and resume when the temperature climbed to 20°C.

The power of continuous, automatic monitoring of geysers was shown clearly by this study. The collection of 84 continuous hours of Plume eruption data required the efforts of four dedicated observers. Determination of Plume's sleep periods using markers was difficult, and I only succeeded in determining one night's sleep duration in a full week of attempts. The temperature monitor was able to capture all of the eruptions, the sleep periods, and also interesting data on the surface water temperature. Direct observation is still valuable to note the character of the eruptions, the form, sound, size, and other characteristics of the eruptions that simple monitors cannot capture. The temperature monitor used was only able to record temperatures once per minute and still have a reasonable time span of data collection. Improved versions can capture data for longer intervals or more frequently.

The relationship between Giantess and Plume was strikingly illustrated by the shift in Plume's behavior during Giantess eruptions. During all four of the Giantess eruptions between May and August 1993 Plume's intervals dropped to a constant 28 to 32 minutes, and all diurnal variation and sleep interval behavior stopped. As soon as Giantess stopped erupting, Plume returned to its longer intervals, showing both substantial change in interval during the active periods and a return to having sleep periods. The suspension of sleep periods occurred even though the runoff temperature during one of the Giantess eruptions reached 15°C for a relatively long time.

Plume has a long history of shifts in activity followed by long periods of constant behavior. The diurnally varying intervals and the appearance of "sleep" intervals on an almost daily basis is perhaps one of the most intriguing of these changes. Plume deserves close scrutiny during the next season to determine whether the 1993 patterns will continue or whether some new variation will appear.

Plume Geyser certainly provided an interesting challenge during the 1992 and 1993 seasons. As soon as one set of new behaviors became established, and theories to explain them appeared, Plume would evolve yet another strange twist to its behavior. It certainly kept the Geyser Hill Gazers well occupied and entertained.

This study leaves several interesting questions unanswered. The statistical relationship between the runoff temperature and Plume's intervals deserves close study. Correlation of Plume's eruptions with Beehive Geyser is a natural follow-on, as is a comparison of the Plume record with the Geyser Hill Wave described by Bryan. Another interesting possibility would be simultaneous automatic monitoring of Anemone Geyser and Plume Geyser. I have never detected any correlation, but it takes a lot of concentrated effort to record the frequent Anemone activity, and I have no long term data for the comparison.

PLUME GEYSER: History and Recent Changes

ACKNOWLEDGEMENTS

The author is greatly indebted to several fellow Geyser Gazers for their help in the research behind this paper. The GOSA research project team of Mike O'Brien, Lynn Stephens, and Brenda Taylor put in long hours in all sorts of weather, from blazing sun in the afternoon to rain and cold wind at night. Mike and Lynn spent long night hours, and Brenda spent a great many hours in the hot sun and August Geyser Hill crowds to obtain the extensive and detailed set of data that revealed Plume's behavior. As compensation, we were witnesses to Beehive's sudden dormancy and the beginning of Beehive's Indicator's long series of independent eruptions.

Rocco Paperiello provided voluminous research notes on Plume's history, which greatly enriched this paper. Almost all of the historical material before the 1970s was contributed by Rocco.

Heinrich Koenig provided the TempMentor data and much valuable information and advice on its interpretation. This continuous record for 35 days, spanning two Giantess eruptions, provided another very interesting perspective on Plume's behavior. Heinrich also provided transcriptions of the OFVC geyser log of Plume's activity, which provided an essential overview of Plume's activities during 1992 and 1993, and suggested many improvements to an earlier draft of this report.

Many thanks to all of the contributors. I am grateful to all of these Gazers for their help in this project. Their help made much of this paper possible. Any errors in the paper are entirely the author's mistakes.

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Goggles Spring and North Goggles Geyser
Upper Geyser Basin, Yellowstone National Park— A Comparison Between Eruptive Episodes in 1985 and 1993

by T. Scott Bryan

Abstract

Goggles Spring and North Goggles Geyser are normally minor members of the Lion Group of geysers. North Goggles has undergone occasional brief episodes of major geyser activity, however, and in 1985 that action was joined by Goggles Spring. The eruptions in other years, such as 1993, have mostly been of a minor character. The differences between these two modes of activity are revealed in this paper.

Introduction

This article is speculative. Most of its statements are based on relatively sparse data. That of 1985 is believed to be complete. That of 1993 might well omit a substantial number of eruptions that went either unobserved or unreported. Nevertheless, it is my belief that the basic conclusions are valid.

Description of the Springs

The vents of Goggles Spring and North Goggles Geyser open at the top of a gently raised geyserite platform a few feet northeast of the large sinter mound and cones of the Lion Group of geysers. Both have raised sinter rims about their craters, of which North Goggles' is the more prominent. Water rises and falls simultaneously in the two springs, showing a very direct subsurface connection between them. The overall nature of the springs' activity additionally implies that they are members of a greater "Lion Geyser Complex", affecting and affected by the other members of the Lion Group.

The earliest descriptions of these springs were written by A.C. Peale during the 1878 expedition of the U.S. Geological Survey. Goggles Spring was his #25. It consists of two parts. An open crater to the south ["a)"] was then, as it is now, the more important main vent; it measured about 7 by 10 feet, was 7 feet deep, and had a large fissure-like opening at its bottom. The northern vent ["b)"] was 7 by 8 feet, nearly circular, and only inches deep with a "small orifice." Vent "a)" has hardly changed; vent "b)" on the other hand now appears to contain neither a vent nor a water source of its own. Probably choked by tourist-induced rubble years ago, it is a shallow saucer lined with orange cyanobacteria maintained by the periodic overflow from the main vent.

Goggles Spring received its name via informal local usage between 1915 and 1919, just when early automobile traffic and driving goggles became common in Yellowstone. With a brief transition to "Devils Goggles," the name became official in 1927. As discussed below, it probably acted as a geyser during the 1920s prior to 1927, but the name apparently was not attached to the activity at that time.

North Goggles Geyser was Peale's #26: "3 feet by 3 feet... small triangular geyser-like cone." It was not known to erupt until after the 1959 earthquake, when it was named by Marler. (In his *Inventory...*[1973], Marler gives 1960 as the year of first activity, but North Goggles is listed in his thermal report for 1959.)

History of Eruptive Activity

Goggles Spring—

In the 1927 edition of the *Ranger Naturalists Manual*, Phillips [1927] wrote; "A large irregular hole in the sinter at the base of Lion's mound erupts with much vigor..." That such a statement does not appear in the 1926 edition of the *Manual* implies that these eruptions occurred during 1926.

Years later, Marler [1973] equated

Phillips' statement to North Goggles Geyser, even though his own description echoed Peale [1878] with "small triangular shaped spring." Clearly, "large irregular" and "small triangular" are different. I believe that Phillips described eruptions by Goggles Spring, not North Goggles Geyser. Marler had an unfortunate tendency to disbelieve (or ignore) reports of erupting springs he had not personally witnessed, and this seems to be one of those cases. In any case, that Goggles Spring can act as a geyser was proven during 1985.

Following the October 1983 Borah Peak earthquake, large scale exchanges of function took place on Geyser Hill. The entire Lion Complex was rendered dormant. When rejuvenation occurred in 1985, it was with relatively long intervals but considerably increased vigor from before. Not only were Lion and Little Cub active, but Lioness and Big Cub Geysers underwent violent boiling and frequent "false start" action. (Big Cub finally responded with a single solo eruption in August, 1987, its first and still only play since 1952.) Goggles Spring and North Goggles Geyser joined the others with a vengeance.

Eruptions by Goggles Spring were never common. I have specific record of just three eruptions, within notes pertaining to North Goggles; considerably more than that took place. Memory seems to recall sightings on a nearly daily basis for much of the 1985 summer season after the first eruptions were observed in mid-July. All of the known eruptions took place while Lion Geyser was in an active cycle *and* either in concert with or immediately following major eruptions by North Goggles Geyser. Steamy blasts of water were jetted out of the empty crater at a low angle toward the boardwalk. There was never any warning, and people on the boardwalk were sometimes sprayed with uncomfortably warm water. The actual above–ground height of the eruptions was small (not more than 6 feet), but the horizontal throw reached as far outward as 20 feet. Durations were only a few seconds.

It is reasonably certain that Goggles Spring cannot undergo the 1985 style of eruption without North Goggles Geyser simultaneously having a major eruption to empty its crater. Since North Goggles has not had a major eruption since 1985, Goggles has seldom done more than bubble or boil slightly through the years since then. Eruption potential remains, however. During the 1993 episode of minor eruptions in North Goggles, Goggles often boiled vigorously, and at least one weak eruption was observed during August (after the time frame of this study). Also, although there is no known record of North Goggles being active at any time prior to 1959, there is the apparent record of solo Goggles eruptions during the 1920s..

North Goggles Geyser—

The form of North Goggles Geyser's cone, surrounding sinter platform, and runoff channels make it certain that it had a history of eruptive activity prior to the exploration of Yellowstone. It is one of the smaller examples of a cone-type geyser, a steady gushing or jetting of water (as opposed to bursting) thoroughly inundating the platform and filling the channels with a sudden, erosive flood. As noted previously, though, the first activity of record followed the 1959 earthquake.

It is believed that North Goggles underwent at least some eruptive activity during every year from 1959 through 1969, excepting only 1962 and 1963. It was dormant in 1970, active in 1971-1983, dormant again along with the entire Lion Group in 1984, and spectacularly active as a major geyser in 1985. It then rested from 1986 through 1992 before rejuvenating with minor activity in 1993.

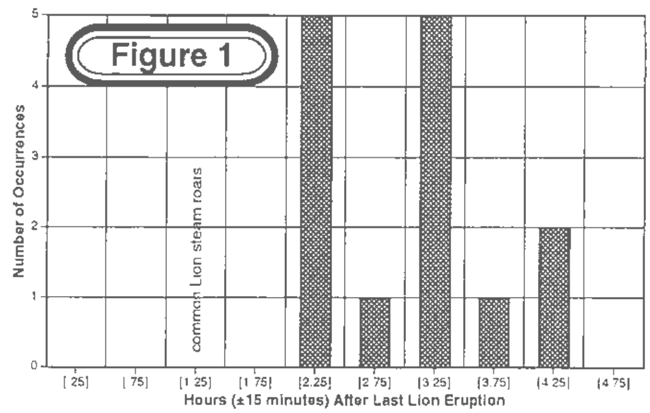
North Goggles exhibits two types of eruption. *Major eruptions* are very spectacular but also very rare. None were reported until 1971. North Goggles apparently then had a few major eruptions during each year until the dormancy of 1984. With the 1985 rejuvenation, major activity became the dominant form taken by the geyser— 31 of the 34 eruptions recorded between May 6 and August 27 were major. None have occurred since that season. Table I summarizes the 1985 activity.

Major eruptions began in much the same fashion as minor eruptions (see below), with small bursting quickly building into a steady eruption jet. The minimum height recorded was 20 feet; most eruptions easily exceeded 30 feet, and one was triangulated at 52 feet high. The duration of this jetting was between 2½ and 4½ minutes. A loud steam phase lasting another 1 to 3 minutes followed, so that a typical total duration was greater than 5 minutes. It was a very impressive display, especially with the boardwalk not more than ten feet away and the occasional concerted action of Goggles Spring equally close.

Available records imply that North Goggles is likely to have major eruptions only when Lion Geyser *is* actively undergoing a series of eruptions. As indicated by Table I, not less than 87% (27 of the 31 recorded eruptions) took place while Lion was active or still producing roaring gushes of steam before falling into its quiet cycle interval. Lion's status was unknown for another case, leaving only 3 of the 31 major events (9.6%) occurring when Lion was inactive, within its quiet cycle interval. Given that such cycles had intervals of around 1½ days and durations of 9 to 12 hours, this high percentage seems to make a Lion-North Goggles relationship conclusive. (Statistical analysis of this relationship is precluded by a near total lack of eruptive data for Lion. My notes were about North Goggles; in most cases, Lion's activity is indicated only as "Y"es, "N"o, or "?".)

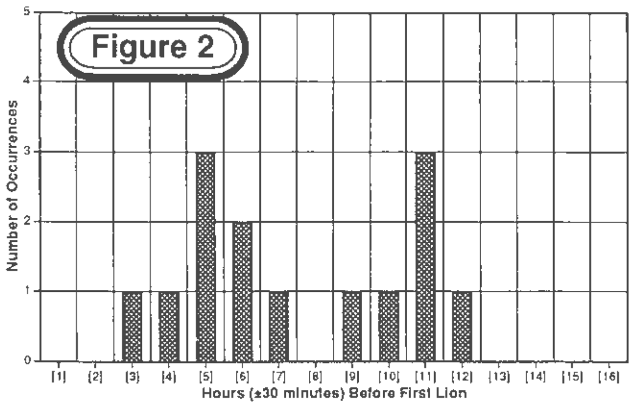
Minor eruptions comprise the vast majority of North Goggles' known eruptive record. With durations of 25 seconds or less, they reach only 6 to 10 feet high; 1993 was a bit unusual in that some reached between 12 and 15 feet. Most records are of single eruptions on intervals of at least a few hours; again, 1993 was different in that series of as many as seven eruptions at intervals of 13 to 65 minutes were seen on several occasions. Table II summarizes the 1993 activity.

With a single exception among 20 cases, all of North Goggles' 1993 minor eruptions took place when Lion Geyser *was not* in an active series. The eruptions were not randomly distributed in time, however. With only that one exception again, the time span between the last eruption of a Lion series and the eruption (or the first of a series) of North Goggles was between 1½ and 4¼ hours. This applied whether Lion's full cycle interval was 6 hours or 19 hours (the approximate 1993 range). Although this data is relatively sparse, a graphical representation of these Lion-to-North Goggles intervals is shown on Figure 1. Note the groupings at roughly 2.25, 3.25, and 4.25 hours. We know that about one hour after Lion has its final series eruption, it undergoes a series of steam roars as if trying to play again. The pattern here shows North Goggles continuing Lion's 1+ hour intervals, apparently continuing the series beyond Lion's "failure".



During 1985, only three minor eruptions were recorded (Table I), but they also occurred when Lion was not active. Still more remarkable is that even though Lion's cycle intervals were then on the order of 36 hours, these three minor eruptions fell at about 2.0, 4.5 and 4.75 hours after the last eruption of the previous Lion series— very similar to the 1985 pattern.

There was also a clear relationship between the eruption times of North Goggles and that of the initial eruptions of the subsequent Lion series. This, which is graphically shown in Figure 2, is perhaps even more remarkable than the "after Lion" relation. It is very clearly bimo-



dal, with modes centered on 5 and 11 hours. This does *not* relate to whether or not the North Goggles action was a solo or series of eruptions. The control for this distribution is unknown.

Summary of Eruption Types and Patterns

Condensing the above discussion, the two types of eruptions shown by North Goggles Geyser appear to be very different events, as if North Goggles is two geysers in one.

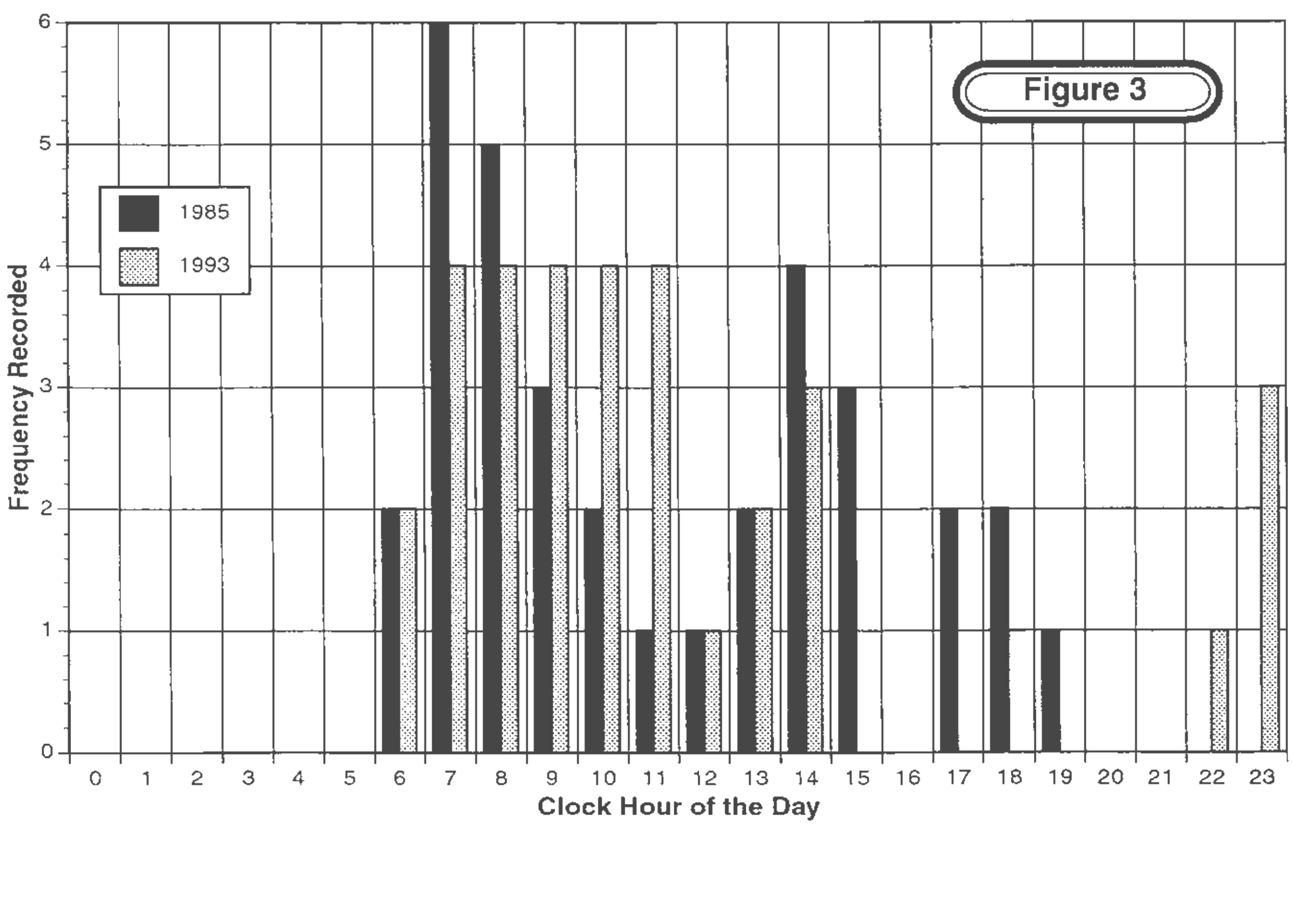
Minor eruptions tend to take place when Lion *is not* within an active eruption series. They are weak and brief, and show signs of being a continuation of the previous Lion series.

Major eruptions are rare events which, based on 1985 observations, are most likely to take place only when Lion *is* active. North Goggles then becomes another large player in the Lion Group.

Does North Goggles Show A Diurnal Activity Pattern?

Readers familiar with other reports about Geyser Hill activity might well groan at the very mention of North Goggles exhibiting a diurnal control, but in fact both the 1985 and 1993 records indicate that this is so. Data for both years is illustrated by the column chart of Figure 3. The columns represent the number of eruptions recorded per clock hour of the day.

If the activity of North Goggles was truly random (beyond any relationship to Lion), then the counts should be evenly distributed throughout the day. Obviously, they are not. My perception is that the tendency for North Goggle to erupt during the morning hours is real. For example, during July, 1993 I personally spent fully as much observational time on Geyser Hill in the evening hours as I did in the morning hours, yet I did not see a single afternoon or



evening eruption. The same can be said for other observers. Indeed, because of the nearness of the Old Faithful area lodgings, Geyser Hill probably receives the greatest amount of geyser gazer observation during the evening hours. In 1985, most of the records were accumulated by the general naturalist staff observing throughout the day, yet a diurnal eruption distribution much like that of 1993 is shown. The remarkable similarity between the two years is surely beyond chance.

Diurnal variations are an established fact for Plume Geyser; diurnal controls have been suspected if not outright proved for Beehive and Giantess Geysers; and such variations have been suspected in the activity of Aurum, Depression, and several other geysers on Geyser Hill. Now, although its action is relatively uncommon, North Goggles Geyser also exhibits a diurnal pattern. As is the case for all the other features, why is unknown.

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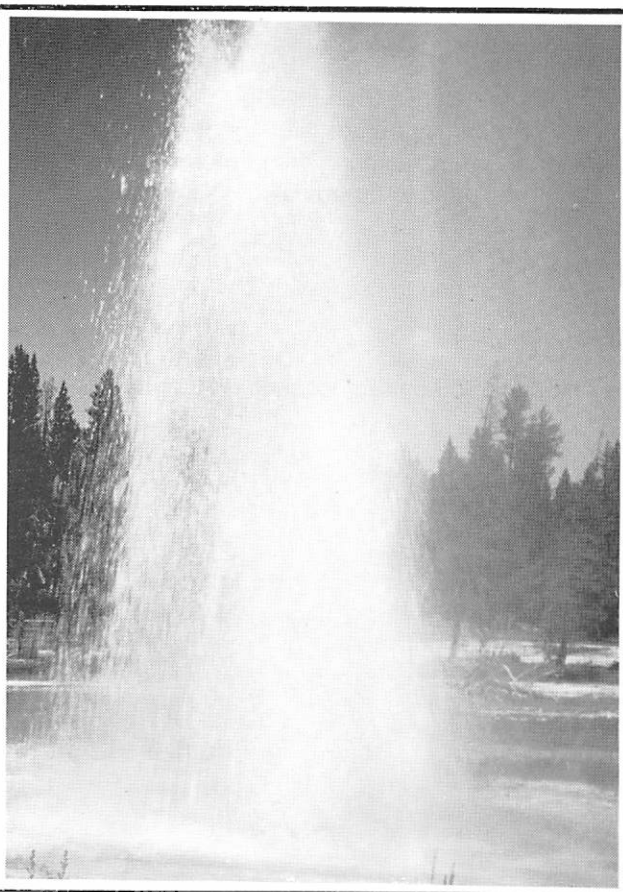
Note to Readers— It was hoped that additional data for 1993 could be included in this article, but it proved logistically impossible to obtain the volume of data needed to make its use worthwhile. However, the few reports that were received imply that the above conclusions are valid.



North Goggles Geyser during a major eruption in July 1985. Note the jetting, columnar nature of the play. Photo by T. Scott Bryan.

North Goggles Geyser during a minor eruption in July 1993. Note the bursting nature of the play. Photo by T. Scott Bryan.

Table I
NORTH GOGGLES GEYSER, MAJOR ERUPTIONS OF 1985

DATE	TIME	WATER DURATION	HEIGHT	LION ACTIVITY	COMMENTS
5/6	0710			Yes	
5/10	1044		40	?	No Lion eruption recorded 5/6 to 5/14
5/18	1458		30	Yes	
5/24	1525			Yes	
6/10	0708			Yes	
6/21	0707			Yes	Last Lion of series 28m earlier
6/23	1020	3+ min	20	Yes	
6/28	1813	3 1/2 min	30	Yes	
7/4	1437			No	First Lion of series 6h 29m later
7/6	1334			Yes	
7/7	0845			No	First Lion of series 11h 48m later
7/9	0852	2 1/2 min	30	Yes	
7/10	[1907]	<1 min	<15	No	Minor eruption
7/12	0850			Yes?	Last Lion of series 1h 01m earlier
7/15	1515	3m 38s	40	Yes	
7/18	0700	4+ min		Yes	
7/20	0836			Yes	
7/22	0919	4m 18s	52	Yes	Eruption height triangulated; Goggles active
7/28	0917		25	Yes	
7/29	0645		50	Yes	
7/29	[1541]	16 sec	<10	No	Minor eruption 4h 27m after last Lion of series
8/3	0926	2m 45s	30	Yes	
8/3	≈1405			Yes	Weak steam phase at 1415; last Lion ≈2h earlier
8/4	1228	3m 57s	40	No	First Lion of series 2h 59m later
8/6	0646 i.e.			Yes	Last Lion shortly before (wet cone)
8/8	[1427]	25 sec	<15	No	Minor eruption; last Lion 4h 45m earlier
8/14	1310	4 min	35	Yes	Goggles Spring to boardwalk
8/15	0820	4 1/2 min	40	Yes	
8/18	1843		25	Yes	
8/20	0709	3m 11s	30	Yes	Goggles Spring to boardwalk
8/22	1119		35	Yes	
8/22	1758		30	Yes	
8/23	1758	3 min	30	Yes	Times of 1758 correct for both 8/22 and 8/23
8/27	0733	3 min	30	Yes	

Table II
NORTH GOGGLES GEYSER, MINOR ERUPTIONS OF 1993

DATE	TIME	SERIES INTERVAL	LAST LION	INTERVAL	NEXT LION	INTERVAL
5/13	1520		1205	3h 15m		
5/16	1049				1609	5h 20m
5/18	1100		0942	1h 28m	2034	11h 02m
5/19	1447		1021	4h 26m		
5/20	1215		0823	3h 52m	2050	12h 27m
5/26	overnight					
5/28	1330		1128	2h 02m		
	1416	46 min				
	1511	55 min				
	1547	36 min				
6/1	2325		2325 i.e.	zero		
6/3	0958		0736	2h 22m	1500	5h 02m
6/5	1029		0700 i.e.	≈3h 29m	1658	6h 29m
6/6	1043		0749	2h 54m	1540	4h 57m
6/15	1128		0713	4h 15m	1809	6h 41m
6/18	1239		1031	2h 08m	>2345	>11h
6/28	0853		0546	3h 07m	1827	9h 34m
7/2	1122		0911	2h 11m	2237	11h 15m
	1207	45 min				
	1254	47 min				
7/4	0848				1503	6h 15m
	0901	13 min				
	0922	21 min				
	0951	29 min				
	2228		2008	2h 20m		
	2315	47 min				
	2354	39 min				
7/6	0743				1641	8h 58m
	0848	65 min				
7/9	1132		0831	3h 01m		
7/11	1054		0728	3h 26m	1418	3h 24m
7/15	0734				1201	4h 27m
	0812	38 min				

History of the Round Spring Group

by

Rocco Paperiello

ABSTRACT: The following is a brief history of the Round Spring Group with an emphasis on geyser activity. It is hopeful that this record will clear up some historical facts concerning this group of springs.

The Peale survey members gave this group of springs its name in 1878 "because the prevalent form is circular, seven out of the nine springs having large, flat, circular basins". [Peale 1883]

Hague's unpublished manuscript [circa 1911] added the following information about the group:

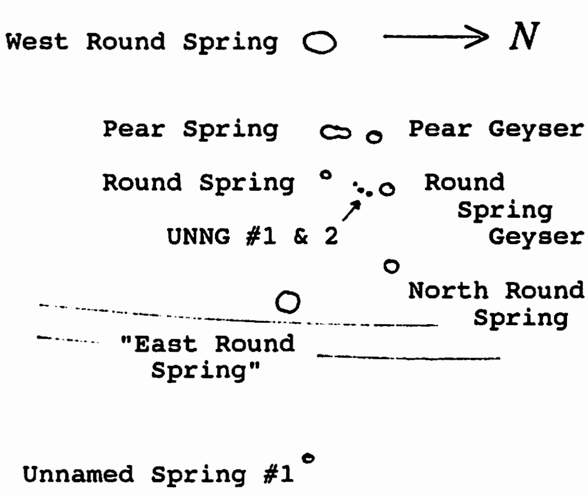
> Below the Spanker the Firehole makes a broad semicircular curve, without any evidence of thermal springs lining its banks. Beyond this curve, at the same elevation as Orange Pool, but back 150 feet from the stream, lies a group of eight or nine springs known as the Round Springs, from the symmetrical form of their shallow basins. They differ in size, are seldom full to the brim, in fact they vary from time to time in their water level. As regards temperature, they range widely, always hot, yet seldom stand near the boiling point. They are mainly turbulent, intermittent springs, changing but little, yet occasionally breaking through the thin overlying crust, apparently caused by the inrushing of steam from below...
>
> The Round Springs attract little attention. Their interest is found in their mutual relations and the fluctuating supply of thermal waters which seem to be derived mainly from sources still higher up. [Hague circa 1911]

It so happens that about half the vents within this small group have had at least some history of geyser activity, and one additional vent "looks" like it should be a geyser although no record of such activity has yet been found.

"East Round Spring"

(Note: This spring was Marler's "Round Spring")

On Gustavus Bechler's 1872 map, this spring was labeled "Hot Basin" with good discharge. [Wheat 1963] Six years later, in 1878, conditions had changed somewhat. This spring, designated No. 1 of Peale's Round Spring Group, was described as a "red and green lined pool [16 by 31 feet]. The water [did] not fill the basin." [Peale 1883] In 1883 the spring was "brown lined." [Weed 1883] By 1887 Walter Weed noted that a further reduction in water level left the spring only 4 feet in



ROUND SPRING GROUP

diameter. [Weed 1887]

At least as early as 1941, George Marler referred to this feature as "Round Spring". Although modern usage has continued to ascribe the name of "Round Spring" to this spring, it is not the original "Round Spring" of Peale [1883]. The 1904 Hague *Atlas...* is unclear as to which feature of the Round Spring Group is labeled "Round Spring". Using only the original map of the Upper Geyser Basin included in Peale [1883], or the Hague [1904] *Atlas...*, it is easy to mistake which spring had actually received the name of "Round". But using the map in Peale [1883], in conjunction with the text, it is clear that the correct placement of the name of "Round Spring" is on Spring No. 3, the smaller spring immediately southeast of Pear Spring.

It is not clear who made the original error in the placement of this name, but it is evident that Marler, [1941, 1973] at least, continued in this error, as did the USGS. [1966] I first proposed the name of "East Round Spring" for this feature in 1985, to replace the name of "Round Spring" which had become erroneously attached to it. Scott Bryan [*GOSA Transactions* 1992] in his article on the Round Springs Group has also so used the name of "East Round Spring".

The first and only report of geyser activity that I could find for this spring occurred in 1941. In his August, 1941 report Marler wrote:

> Round Spring: At 2 P.M. on the 16th [Aug, 1941], I observed this Spring take on geyser proclivities. It erupted to a height of not less than 20 feet. The activity lasted 3 minutes. This is the first I have ever seen the Round Spring erupt. [Marler 1941]

I could find no other reports of this spring erupting. Reports by Marler of a "Round Spring" erupting in 1940, 1942, 1946, & 1947 are almost definitely that of Round Spring Geyser, another nearby feature. [Marler August 1940, May 1942, June 1942, 1946, 1947].

North Round Spring

This spring was designated No. 2 in Peale's Round Spring Group. It was located in a "basin... 38 by 46 feet. Spring in center [was] 15 by 16 feet." [Peale 1883]

The name of North Round Spring first appeared in George Marler's 1960 geyser report. Previous names of "Trefoil Spring" [Weed 1883], and later that of "Cloverleaf Spring" were both given to this spring by Walter Weed in the 1880's. [Whittlesey 1988]

In 1887 Walter Weed reported that the spring was 11'x 12' with a "lining [of] soft siliceous sediment, tinted greenish yellow by algae. [There was a] steaming break... between this spring and the road..." [Weed 1887]

This spring has no known history of geyser activity.

Round Spring

(Note: This spring was left unnamed by Marler).

This is the spring which was actually named "Round Spring" by Peale in 1878, and was designated No. 3 of his Round Spring Group. It was described as having a "yellow-lined flat basin [18 feet in diameter]; with funnel-shaped orifice [3 feet in diameter]." [Peale 1883] (See entry on Round Spring above). But this was not its first name. Six years earlier, Bechler must have been impressed enough by this spring to have named it "Alabaster Hot Spring". [Wheat 1963] In 1883 this spring's basin was dry with water filling only its funnel vent. [Weed 1883]

This spring has been observed as a geyser on at least two separate occasions. In 1897 Walter Weed recorded geyser activity for this spring to 5 feet. [Whittlesey 1988] Another surprising episode of geyser activity occurred in 1990. On May 25th of that year there were "numerous eruptions to over 30 feet, and one certainly surpassed 50 feet. The major action was confined to that one day; a few small eruptions were seen on the morning of May 26, but that was the end." [Bryan in *Sput*, May-June, 1990] (See also "Major Geyser Activity in the Round Spring Group," by Scott Bryan, *GOSA Transactions*, Vol III, 1992).

Pear Spring

This name first appeared on Bechler's 1872 map of the Upper Geyser Basin. [Wheat 1963] Peale continued the use of this name and designated it No. 4 of his Round Spring Group in his 1878 report. He described the spring as

"37½ by 10 feet and 21 feet, [with a] double white-lined basin; water [had a] greenish-white tint." [Peale 1883] By 1883, the water level was lower, a clear emerald in the larger lobe and yellow in the smaller. [Weed 1883] In 1887 the spring had a leathery lining with no overflow. Weed noted an old disintegrating runoff channel. [Weed 1887]

This spring was reported to have had a rare eruption on the night of the 1959 earthquake, but there were no follow-up eruptions. [Marler 1973] One additional report of geyser activity in 1972 is questionable. A "Pear Spring" was listed as an active geyser in Rick Hutchinson's report for 1972, but no further information was given. I wonder if this report should have been for Pear Geyser instead, since this geyser was definitely active this year and Hutchinson's report failed to report this.

Pear Geyser

On Bechler's 1872 "Map of the Upper Geyser Basin", this spring was called "Flat Spring" possibly because of its relatively flat and shallow basin. [Wheat 1963] This spring was later designated No. 8 of Peale's Round Spring Group in 1878, but was listed without any name. It was described as having a "basin [19 feet in diameter] not full. The spring [7 by 7½ feet, had] a small fissure in the center." [Peale 1883] Walter Weed [1883] stated that this spring was "evidently a spouter," the water filling only the fissure in the center of a large shallow basin. (Weed used the terms geyser and spouter interchangeably). By 1887 the sintered basin was disintegrating with water only filling the vent. [Weed 1887]

The name of Pear Geyser was given to this feature by George Marler and first appeared in his 1961 geyser report.

There is no modern record of Pear Geyser having eruptive activity until November of 1958. In a report made by Riley McClelland [1959] dated April 12, 1959 he wrote the following:

> In [mid-]November, 1958 [this geyser] was first observed in eruption. It has been active periodically ever since then. This geyser plays to a height of 10 to 12 feet for usually less than a minute. When active, it plays on an interval of 7 to 8 minutes; however, it has had frequent periods of several days during which it has not erupted at all. There are no records of this geyser having erupted in the past several years before it began its present active phase.

This geyser apparently went dormant before Marler returned to the basin in late Spring of 1959. [Marler 1959, 1960, 1961] Its next known period of activity occurred in the winter of 1960-1961, and at this time was given its name. The following is from Marler's 1961 report:

> The most noted change in [the Round Spring] group occurred during the 1960-1961 winter. An unnamed spring on the north side of Pear Spring turned into a geyser. During all of 1961, it played with great regularity, the eruptions occurring about every 5 minutes, to a height of about 12 feet. It has been named the Pear Geyser.

Pear Geyser has since been known to have been active in 1964 when it had "intermittent and infrequent eruptions" [Marler 1964], and then again in 1971. During this year Marler wrote that "the thermal energy shifted [on August 18 and 19] to Pear Geyser which is located about 10 feet north of Pear Spring,... result[ing] in eruptive activity. The eruptions were from 10 to 20 feet high. During Pear Geyser's quiet phase Pear Spring would overflow." [Marler 1971] Pear Geyser has also been known to have had active periods in 1972, 1974, 1978, 1982, 1989, and 1990.

In August of 1972, a single eruption of Pear Geyser to about 10 feet was reported by Sam Martinez [1972]. He stated that "no others [eruptions] were known to have occurred".

In mid-summer of 1974, there was about a week of activity reported by Marie Wolf [1991]. Eruptions occurred in cycles with intervals between eruptions of about 1½ to 3 hours, durations minutes long, height about 10 to 12 feet. About 2 to 5 eruptions occurred each cycle.

Little information for its activity in 1978 can be found other than that it was active. [Wolf 1991]

In 1982, one eruption was seen either in May or early June by the author. Conditions about its basin indicated that it had had at least a few days of prior activity. It was dormant later in the summer.

After an apparently long period of dormancy, Pear Geyser was again noted as quite active from at least late Fall, 1989 to early Spring of 1990. At least three eruptions occurred on October 15th and 16th, 1989. Durations of 3 and 4 minutes with maximum heights of 10 and 12 feet respectively were recorded. [Keller 1993] On April 28, 1990 another eruption was recorded by Mike Keller. It had a duration of 3½ minutes and reached 12 feet. The condition of the basin and runoff channel indicated that an lengthy period of activity had taken place. [Keller 1993] This geyser was also seen active by the author in the first part of May. At least one additional eruption was noted in late August of that year by Lynn Stephens -- to a height of 6 - 10 feet. [Bryan 1992]

West Round Spring

In 1872, this spring was merely labeled "Quiet Hot Spring" by Bechler. [Wheat 1963] This spring was later designated No. 5 of Peale's Round Spring Group in 1878. It was described as having a "[gray] outside basin [52 feet in diameter]...; inner one [was] greenish-yellow." [Peale 1883]

A report indicating possible geyser activity for this spring in 1883 is found in an 1887 report by Walter Weed:

> The intermittent character of the spring seems well established and the slabs of laminated sinter torn up by the spring that were noticed in 1883 are nicely coated with a fresh deposit, circular in form, at the edge of the inner pool, and the permanent water level is about 40' by 45'. The deposit resembles that of the Green Spring. [Weed 1887]

Arnold Hague [1911] described it as follows:

> The largest pool [West Round] is situated farthest from the river, near a low mound of glacial gravels, dotted over with a low growth of pines. The spring consists of two basins, the inner one measuring 50 feet, and the outer or enclosing basin 62 feet in diameter. The larger basin is apt to be dry, the water seldom overflowing from the inner and deeper bowl. The volume of water seems somewhat larger in springtime than in autumn, yet the overflow channels are usually dry.

The name of West Round Spring was given by Marler and first appeared on his 1959 geyser report. During the night of the 1959 earthquake this spring erupted.

> The eruption of West Round [Spring] appeared to have been very violent. [...heavy wash extended back at least 6 to 8 feet from the crater in the loose sinter]. There was no further activity, and none had ever been recorded previously. [Marler 1959, 1973]

Geyser activity was again recorded for West Round Spring in 1960 [Marler], but it was not described. The next recorded active episode was again recorded by Marler in his 1971 report:

> On August 20... I saw an eruption [of West Round] which rose to a height of about 6 feet. Since this date there have been periodic eruptions. Some are quite vigorous, attaining a height of from 15 to 20 feet. It is a splashing type eruption. If there is any regularity it has not been determined as yet. An eruption of West Round lowers the water level in Pear Spring from 15 to 18 inches.
>
> During the entire time I have been in the Upper Basin I never previously have observed West Round Spring erupt. There has been no physical evidence that one occurred. Its present activity is due to a rise in temperature of over 20° F. [Marler 1971]

In 1972 West Round had minor geyser

activity. It would periodically ebb, and then have heavy overflow and boiling to about a foot. This overflow and boiling would gradually decrease and then the pool would again ebb. [Wolf 1991, Martinez 1972]

On May 25, 1990, along with the reactivation of Round Spring as a geyser, West Round Spring was also noted to have had at least two eruptions to about 3 to 6 feet. [Bryan 1992] In the summer of 1992, a very strong ebb and flow cycle was again quite evident. [author]

Round Spring Geyser
Unnamed Geysers #1 & #2

(NOTE: Round Spring Geyser here is the geyser labeled RSG-1 by Scott Bryan [1992]; Unnamed Geyser #1 is his RSG-2).

Just east of Pear Spring and Pear Geyser is a series of 4 small vents. The three vents to the north are small geysers, and at least during some period of their history have been known to have acted independently. The final vent to the south has the look of a geyser vent but I do not know of any geyser activity for this vent.

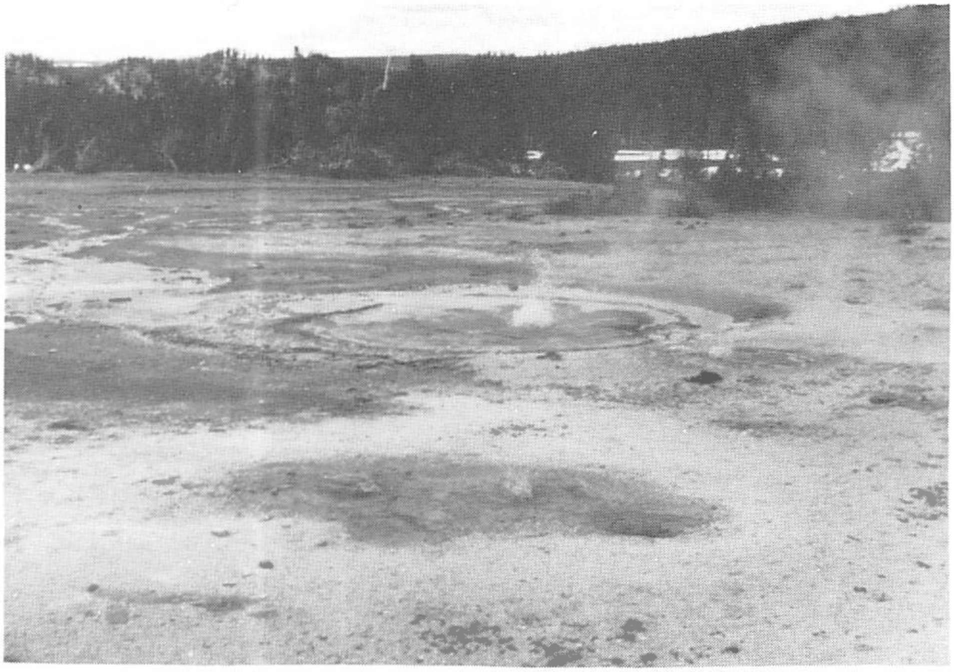
Round Spring Geyser, the vent farthest north, was shown as a spouter on Bechler's 1872 map. [Wheat 1963] This vent was also No. 7 of Peale's Round Spring Group; in his 1878 report he too described it as a "small spouter" in an 8 foot diameter basin.

Unnamed geysers #1 and #2 are most likely Peale's No. 6a and No. 6b respectively. They were merely described as having "two small basins [6½ feet and 2 feet in diameter] with small orifices." [Peale 1883] In 1883 Walter Weed noted that these vents were "spouters", and in 1887 described them as "intermittent bubblers, without overflow, but with beaded deposit." [Weed 1883, 1887]

The next mention I could find of these three geysers was in a report by Philip Fix in 1937:

> Three little geysers in this group, all together in a line, have erupted many times during each day to a height of as much as five feet. Sometimes all three go at once, at other times they are separate, but I think they are all connected without question. [Fix 1937]

The next record is found in Marler's report



UNNAMED GEYSERS #1 & #2 (foreground) ROUND SPRING GEYSER (in back)

of August, 1940. Here too is the first use of the name Round Spring Geyser. Since 1940, this geyser has been reported as active for the majority of seasons. Reported activity in the other two vents is less common, and has only occurred when Round Spring Geyser itself was active.

Marler merely reported Round Spring Geyser to have been active in 1940, 1942, & 1946. (There were no reports by Marler from 1943 through 1945).

In 1947 Marler wrote:

> In... the Round... Spring Group a small geyser has been observed in frequent activity this season of which I have no previous record. [Marler 1947a]

Since Round Spring Geyser was also listed as active for this year [Marler 1947], (and since the time of Walter Weed, Pear Geyser was first reported as an active geyser in 1958), I would surmise that what Marler was talking about is either Unnamed Geyser #1 or #2. Strangely, Marler seems to have abandoned the use of the name of "Round Spring Geyser" from 1948 through 1959. In addition, Marler stated in his *Inventory...* that he had not seen either of these 2 unnamed geysers until 1956. But in apparent contradiction to what Marler has written in his *Inventory...*, five of his annual reports from 1949 through 1954 listed 2 unnamed geysers active in the Round Spring Group. (A conundrum). From 1947 through 1959 Marler reported at least 1, and frequently 2, (3 in 1956) unnamed geysers active in the Round Spring Group. Probably one of these is Round Spring Geyser. In 1956, Marler wrote the following:

> During the past season three small geysers in the [Round Spring] Group gave definite indications of subterranean connections with the two mentioned springs ["East Round Spring", and North Round Spring].
>
> When the thermal energy has been directed to the unnamed spring the water level in the Round would be just below the overflow. Regardless of which spring would be flowing, a small geyser 100 feet northwest of the Round showed activity most of the time. This season two new geysers of similar size

came under my observation for the first time; also for the first time the water in the bowl of Round Spring has, one or more times each day, ebbed about a foot below the rim of the bowl, at which low level it would remain for several hours. During those periods of ebb in Round Spring the new geysers would be active.

The new geysers seem to be openings to the same fissure from which the geyser of long record plays. As during previous seasons, this latter geyser has been active most of the current one. Its dormant periods were of short duration, and only at the conclusion of the activity of the new geysers. Following their cessation of play it would also cease, but renew activity in about two or three minutes. After about 20 minutes the new ones would start, all three playing in concert for about one minute. When the Round Spring was overflowing no activity in the new geysers was observed. [Marler 1956]

In his April 20, 1958 report, Riley McClelland wrote about Round Spring Geyser and the two unnamed geysers:

> Until [March 20, 1958], the only geyser observed erupting was the one about 100 feet northwest of the Round Spring. It played very frequently each day.
>
> On March 20, 2 other small geysers near the aforementioned one were seen in eruption. On several occasions that day all 3 geysers played together...
>
> Eruptions of all 3 geysers were seen each day from March 20 through March 24. But after the 24th the 2 again lapsed into dormancy.

In his April 12, 1959 report, Riley McClelland recorded additional information concerning the activity of these geysers, labeling them in order A, B, and C:

> Geyser A, a small spouter, has been erupting frequently as is usual. Geysers B and C, which have been seen infrequently in the past, were not known to erupt at all during the fall, winter, or spring.

From 1960 through 1972, I could find only three years of dormancy for these geysers -- 1967, 1968, and 1972. (Activity for 1965 and 1966 is unknown). In his 1960 report, Marler again used the name of Round Spring Geyser for the most active of these three geysers. In 1961 it was observed erupting on "infrequent occasions". [Marler 1961] In 1964 Marler wrote that "Round Spring [Geyser] erupted constantly..." [Marler 1964]

All three geysers were definitely active in 1972. Of the three geysers, Round Spring Geyser was the most active, erupting frequently to about 2 to 5 feet. But this year the southern vent was the highest, reaching as high as 5 to 10 feet. The middle geyser seldom hit more than a foot. During the eruption cycles the energy would shift back and forth from geyser to geyser for several hours. Intervals for Round Spring Geyser would be about 2 to 8 minutes with the eruption lasting a minute or less. The southern vent was mush less frequent. Activity in these vents were seen frequently all summer. [Martinez 1973, Wolf 1991]

Similar activity as above was seen again in 1974. From that time either little or no activity occurred until 1982. These geysers apparently reactivated that year but with a slightly different pattern. [Wolf 1991]

During the past 10 years or so (since 1982), Round Spring Geyser has usually been the most active one in this small group, and has produced heavy discharge running to the north.

Earlier in the season of 1982, Round Spring Geyser would be seen erupting a quick spurt every few seconds; after an extended period of these eruptions, this geyser would be quiet for up to an hour or so. At the renewal of activity, Unnamed Geyser #1 would have a small eruption. [Wolf 1991] But either later in 1982 or by early 1983, this above pattern was again substantially changed. All three of these geysers would now all act in a cyclic manner. Also in contrast to its activity in the 1970's, Round Spring Geyser would erupt much more often, and have a much larger eruption than either of the other two. Its intervals would typically lie between 2 and 8 minutes, and erupt to a height of 4 to 6 feet. Gradually these eruptions would increase in vigor, height, and duration, when finally unnamed geyser #1 would erupt along with Round Spring Geyser to a height of about 1 to 3 feet. On infrequent occasions unnamed geyser #2 would also erupt along with the other two. But this geyser would only reach a height of 1 to 1½ feet. From 1983 through at least 1984 this pattern was generally maintained. From about 1985 through 1991, these geysers have been mostly active; however, play from Round Spring Geyser has greatly predominated. Activity from unnamed geysers #1 and #2 has been much less frequent and smaller. In addition, the overflow from Round Spring Geyser has been very heavy; this has possibly led to the ebbed condition in "East Round Spring" and in North Round Spring over the past few years.

Unusual activity for Round Spring Geyser coincided with the brief eruptive episode of Round Spring in May of 1990. (See 1992 *GOSA Transactions*, pg 34, "Major Activity in the Round Spring Group" by Scott Bryan).

In the Spring and Summer of 1992, activity for Round Spring Geyser was again observed to be cyclic in nature. This geyser would periodically erupt for a few hours causing an ebbed condition in North Round Spring and most noticeably in "East Round Spring". During periods of non-eruptive activity, water levels in these two pools would again gradually rise.

Unnamed Spring #1

The final spring of Peale's 1878 Round Spring Group was designated No. 9 and described as "a clear [vigorously] boiling spring [3½ by 6 feet] in a white basin." By 1883, its "basin was 4 by 5 feet, with a gray & dusty edge and lining." [Weed 1883] Its location, about 200 feet WSW of Inkwell Spring on the Upper Geyser Basin Map included with Peale's 1878 report, corresponds very well with the location of a spring on the current USGS maps which strangely is labeled "Chromatic Spring". [Peale 1883, USGS 1966] (This spring is not to be confused with Chromatic Pool over 500 feet to the east).

Exactly how this feature acquired the name of "Chromatic Spring" on one of the 1966 USGS thermal maps [V. B.] of the Upper Geyser Basin, and then on later USGS maps, is unclear. Lee Whittlesey [1988] wrote the following about this spring:

> This place name seems to have been an error as it appeared on the 1970s USGS maps, probably translocated from nearby Chromatic Pool. Nevertheless the name remains on the maps.

In addition to the above confusion, this spring also appears to have changed dramatically from the time of the Peale survey. In recent years it is more of a somewhat colorful seeping spring. Since the above use of the name "Chromatic Spring" is clearly in error, I have chosen to list it in this report as an "Unnamed Spring".

Discussion:

I realize that the similarity of names in the above group might have become a bit unwieldy, but I do not know how else to address the problems associated with them.

Deciphering the history of these features, and especially that of Round Spring Geyser, has been surprisingly difficult for a whole list of reasons. The most important of these was Marler's penchant for giving as little information as possible in his reports concerning an adequate physical description or location of many of the geysers about which he reported. (This tradition unfortunately has been copied by many reporters since Marler). In addition to the above switching of names, a complication not mentioned above is the fact that West Round Spring, for a time, was also called Pear Pool.

Further problems came from the fact that Marler, and many others, were in the habit of naming a "newly discovered" geyser by using the same name of another nearby feature. Thus we have "Chain Lake Geyser", "Bottomless Pit Geyser", "Orange Spring Geyser", and "Beach Geyser", to name a few. An additional layer of confusion then sometimes occurred if the afore-mentioned "spring" later became active as a geyser itself. This is exactly the case with Round Spring and Round Spring Geyser. (This has also occurred with Beach Spring). Then to put the finishing touch on the situation, Marler (and others) frequently omitted the word "geyser" when listing active geysers. Thus there are many reports where "Round Spring" is listed as an active geyser. Yet I have eventually determined that in fact it was "Round Spring Geyser" that Marler was reporting.

I would make the following plea to all who will eventually write geyser reports. Always assume that 20 years later the people reading your report about some geyser are NOT ALREADY aware of its location. Unless the feature's location can be determined, what has been written loses much of its value.

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I am grateful to Lee Whittlesey who provided me with the material from Walter Weed and Arnold Hague used in writing this paper.

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Daisy Geyser:
Possible causes of variation in activity
Upper Geyser Basin
Yellowstone National Park, Wyoming

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Abstract

Daisy Geyser has been one of the most frequent and regular major geysers in Yellowstone since its recovery from dormancy in the early 1970s. In the past few years, it has become increasingly irregular. Possible effects of seismic phenomena, other thermal activity, and weather conditions upon Daisy are discussed. A new model of how Daisy is affected by wind and a revised set of necessary and sufficient conditions for an eruption to occur are proposed.

Introduction

Given first is a summary of Daisy's typical activity pattern. A series of other geysers and hot springs are then considered one at a time. The activity of each thermal feature is briefly described; following this is a discussion of the spring's relationship to others and any statistical analysis of the data collected for that spring. The third main section briefly considers the effect of earthquakes. A fourth section is devoted to weather-related changes in Daisy's behavior.

Much of the data used for this report was collected by the author between August 1 and August 16, 1992. Some data from the NPS logbook and shorter periods of observation in May, June, and October were also included. Personal observations and logbook records throughout the 1993 summer season were used for comparison purposes.

Typical Behavior of Daisy

All observed eruptive cycles in 1992 and 1993 followed the same basic pattern. Water became visible in the crater only a few minutes after the conclusion of the previous eruption. During the next hour, the water slowly rose to within 20 cm of overflow, boiling gently but constantly.

The first preplay, 16 to 30 minutes before the eruption, consisted of a few droplets tossed from the large cone on the west side of the crater. This gradually developed into constant splashing to 30-50 cm over a period of about five minutes. The smaller cone on the east side of the crater begins activity 3 to 18 minutes before the eruption, generally almost exactly nine minutes after the west cone first splashed. The east cone's splashing became continuous much more rapidly, often within a minute, but rarely exceeded a height of 25 cm. The NPS information board often tells visitors to watch for these two cones to begin splashing 20 and 10 minutes before Daisy erupts. This rule of thumb worked fairly well most of the time; mean lead times were 21 and 12 minutes. However, most of Daisy's irregularity, especially due to the weather, manifested itself after the onset of preplay. This points toward the preplay not being a "Geyser X will erupt in Y minutes" type of precursor, but simply an indication that a certain amount of energy recovery has taken place since the last eruption. The observations of preplay also form the basis of a proposed mechanism by which the weather affects Daisy (discussed below.)

Boiling over the main vent became more energetic after the preplay began. The water continued to rise, reaching overflow three to six minutes after the east cone started to splash. Eruptions were always immediately preceded by a sudden increase in the violence of the boiling. Sometimes there were two episodes of strong boiling, consistently very close to three minutes apart.

For data collection purposes, the start of an eruption was defined as the moment the surging reached a height of one meter. The water column, angled to the northwest, rapidly climbed to height of 15-20 meters, then gradually became more powerful, generally reaching its peak after about 1m45s. It then died down gradually, declining to semi-continuous splashing for the final seconds. An eruption was deemed over when more than a second passed without a splash exceeding one meter in height. The secondary cones chugged impressively as water poured back into the main vent. As described below, a fissure on the north side of Bonita Pool sputtered noisily during and immediately after Daisy's eruption.

During August 1992, the average of 123 closed intervals was 99m22s, with a standard deviation of 5m45s. The range was from 82 to 128 minutes. Inclusion of 101 inferred intervals raised the average to 100m28s. (The time between starts of successive eruptions is referred to as "interval" in this paper. Some authors prefer the term "period," using "interval" to denote the time from the end of one eruption to the start of the next.) The average of 84 durations was 3m22.6s, with a standard deviation of 9.6s. The range was 2m59s to 3m48s. A duration of 4m02s was recorded in June. The only longer intervals during 1992 occurred after eruptions of Splendid Geyser in September and October. Statistics for 1993 were only slightly different. A sample of 137 intervals ranged from 93 to 134 minutes, averaging 103m56s, with a standard deviation of 5m26s. The average of 74 durations was 3m24.4s, with a standard deviation of 11.4s and a range from 2m58s to 3m46s. Longer intervals (up to at least 155 minutes) occurred after Splendid's eruptions. More details on Daisy's intervals and durations appear in Table I.

Linear regression tests showed that there was not a strong enough correlation between duration and either preceding or following interval to make short-term duration records useful for prediction purposes. However, the average daily duration and interval appeared to rise and fall together over time (Figure 1.) Other linear regression tests (hereafter abbreviated "LR tests") were done to compare the length of the preplay period with the following duration and concurrent and following intervals. Duration was found to be independent of the preplay. As might be expected, preplay tended to last longer during longer intervals. The third pair of tests, which in effect tried to use the length of the preplay period to predict the next interval, gave conflicting results. More data must be compiled and analyze to resolve the discrepancy. Results of these seven LR tests are given in Table II.

The Daisy Complex

An eruption of Daisy causes water to ebb in Bonita and Brilliant Pools and Comet and Splendid Geysers. Daisy is also known to be connected to Daisy's Thief and Radiator Geysers. A variety of more distant connections have also been proposed over the years.

Bonita Pool - At present, Bonita is one of the less important of Daisy's close relatives. However, when it has overflowed in the past, it has halted eruptions by Daisy. Marler's annual thermal reports [1964-1970] indicate that Daisy had only a handful of natural eruptions during years of constant overflow from Bonita. Splendid Geyser was also dormant from 1959 to 1968 [Marler 1973.] The water level has risen a few centimeters in the past few years, during which time Daisy has become less frequent and regular, but it seems unlikely that such a slight change could have a major impact on the system.

The water level in Bonita's crater was observed to drop during each of Daisy's eruptions, then recover within a few minutes. On August 10, 1992, the temperature in the pool was measured for several hours. During a typical cycle, the water was about 68°C (154°F) as it drained away. Probably due to runoff from Bonita's Sputs (see below), the temperature rose to 74°C (165°F) five minutes after Daisy's eruption ended. After peaking at 76°C (168°F) several minutes later, it gradually cooled until the cycle began anew. The water always rose to about the same level. It was not practical to routinely measure how far the water dropped. In general, Bonita has changed little in the past few seasons.

Bonita's Sputs - Four small openings along a fissure on the north side of Bonita Pool sputtered to perhaps ten centimeters almost continually. One to two minutes after Daisy began to erupt, the activity increased to a vigorous spray to fifty centimeters, then died back down over a period of five minutes or so. The onset of the "eruption" was sudden enough for the time to be recorded, but the recorded end times were more subjective. There was considerable discharge from the vents, but all of it immediately drained into Bonita Pool.

The relationship between Daisy and Bonita's Sputs (hereafter abbreviated "BS") was fairly clear-cut. Table III gives the results of LR analyses on data for Daisy and BS. Unfortunately, the tests indicated that BS would be of little aid in predicting Daisy. The only relationship found was that longer BS durations occurred when either Daisy has longer durations or the delay between the start of Daisy and BS eruptions is shorter. The average delay was 2m04s, ranging from 1m09s to 2m45s, and the average duration was 3m12s, ranging from 2m10s to 4m05s.

During the 1992 observations, there were only four occasions on which the delay was less than ninety seconds. All of these exceptionally rapid starts occurred shortly before sunset. This was either a startling coincidence or a significant deviation from normal behavior. For instance, the possibility of this signalling a jump from a "day" to "night" mode of activity for Daisy was considered. However, no explanation for the phenomenon was found, and in 1993, the delay was consistently in the 60-90 second range. The causes and meaning of variation in delay length are interesting topics of speculation, but no answer has yet been suggested.

On the morning of July 17, 1993, BS erupted vigorously for two minutes, 67 minutes after an eruption of Daisy. The following eruption of Daisy was exceptional, one of the highest and longest seen during the season. Despite a brisk south wind, the interval during which BS erupted was the shortest of the day. Nothing unusual happened elsewhere in the Daisy, Grotto, or Giant groups that day, though Oblong erupted the following night. The author has not seen strong independent activity by BS at any other time.

Brilliant Pool - Brilliant typically overflowed during the latter half of Daisy's interval. No boiling or heavy overflow occurred, but occasional gas bubbles rose to the pool's surface. The temperature of the pool was high enough to prevent algae from growing in the crater.

During 1952, periods of boiling and continuous overflow from Brilliant prevented both Daisy and Splendid from erupting [Marler 1958]. A change in discharge from Brilliant, then, might have an impact on Daisy. There being no way to measure the volume of discharge, this possible cause of lower frequency and regularity could not be investigated.

Only limited records were kept of how long it took Brilliant to refill after Daisy erupted. The range was from 35 to 55 minutes, with longer delays after longer durations. This was useful for making rough predictions but did not aid in pinpointing the time of the next eruption.

During the August 1992 observations, there were a few occasions on which Brilliant ebbed slightly (~1 cm) in the minute or so just *before* Daisy's eruption began. Daisy's duration, interval, and height, as well as the BS delay and duration, were normal. This deviation from the normal pattern tended to occur when Daisy's preplay period was long (13+ minutes from the east cone.) This suggests that the extra pre-eruptive overflow from Daisy is the cause. This premature ebbing was observed frequently throughout the summer of 1993.

Comet Geyser - Comet's activity was continuous but fairly weak throughout the study period, ranging from strong boiling to three meters. There were reports of a possible eruption to ten meters in April 1992 and perhaps also in June 1991 [*SPUT* 6:3] but nothing nearly that powerful was seen during the study period. The water level rose and fell in sympathy with Daisy, but the effect was masked by the wide variation in the intensity of Comet's surging. Records were kept for several hours of the minute-to-minute strength of the activity. The activity tended to become more vigorous as the time for Daisy's eruption approached, but short-term variations made it very risky to base predictions on Comet's appearance. No further analysis of the Comet data was attempted.

Splendid Geyser - When active, Splendid can alter the activity of the entire complex drastically. During August 1992, Splendid did nothing more than boil vigorously within the crater. The best surges occurred a few minutes after Daisy's eruptions and reached two meters at most. At that time, at least, Splendid could hardly be called a major contributor to Daisy's irregularity.

Splendid had two eruptions in 1992 after the conclusion of the August study period, on September 14 and October 13. These occurred thirteen and eight minutes after eruptions of Daisy and had durations of roughly two minutes each. They were followed by Daisy intervals of 139 and 136 minutes, the longest recorded during 1992.

The occasional eruptions of Splendid continued throughout 1993. Durations of 1 to 2 minutes and heights of 15-25 meters were the norm, and each "active episode" consisted of only one eruption. It is a matter of debate whether these eruptions are a series of freak occurrences; precursors to another traditional active phase; or a new type of "normal" activity for Splendid.

Observation of the next few Daisy cycles after an eruption of Splendid provides some useful insight into the meaning of Daisy's preplay. The author happened to be on hand during the May 29, 1993, eruption of Splendid. Preplay for the next eruption of Daisy was somewhat delayed (104 minutes until the east vent activated, as opposed to the more typical 90 or so.) Extremely vigorous preplay continued for another 41 minutes as the depressed water level recovered, and Daisy erupted within seconds of reaching overflow. Interpretation of these observations led to the theory, presented below, of what constitutes necessary and sufficient conditions for an eruption of Daisy.

Other Members of the Daisy Complex - The long period of inactivity continues for Daisy's Thief, though the sinter beads within the vent are still in fairly good condition. If any eruptions of Radiator Geyser occurred, they were subterranean. No records were kept of activity from the small sputs near Splendid. Nothing in the vicinity of UNNG-DSG-2 ("Murky Spring") was active.

The Rest of the Daisy Group: Connected to Daisy or Not?

UNNG-DSG-1 - This is a group of a dozen or so shallow holes between Daisy and Bank geysers. Eruptions tended to be hours apart and several minutes long. These consisted of simultaneous weak splashing from several of these vents. Only the northernmost cluster of vents ever overflows, and it did not necessarily do so during an eruption. One of the vents in this cluster quietly filled and overflowed roughly one hour out of three. It is not known if the other vents also filled at these times or not. Neither the overflow nor the eruptions showed a clear relationship to Daisy. Detailed records on UNNG-DSG-1 were not kept for a long enough period of time to exhaustively search for a correlation.

Bank Geyser - Data on Bank's activity were periodically collected during 1992 and 1993. Four types of activity were noted: pulsing of the pool surface without breaking the surface; pulsing accompanied by boiling; minor eruptions, consisting of 1-5 lazy splashes up to one meter high; and major eruptions, consisting of 4-13 splashes up to two meters high, at least some of which were fairly explosive bursts. Only a handful of specific intervals and durations were recorded during 1992; the intervals between full eruptions were typically one to three minutes and durations were under twenty seconds. A less precise but more compact method of data recording was usually used, listing only the type of activity or number of bursts in each eruption that occurred during a 15-minute period. A typical data record read, "05 August, 1107-1122: 8B2B43P5P22BB1P131."

There was a short-term cyclical pattern to the magnitude of the activity. Sometimes a fifteen-minute data block included no true eruptions; at other times, up to seventeen. Observations scattered throughout the day showed several different activity patterns. This cyclic pattern was the topic of a short study by the author during

1993. Interestingly, though Bryan [1986] states that "during some years the eruptions degenerate to periods of mild boiling," the author was unable to locate any prior mention of these cycles.

A series of LR tests were performed in an effort to correlate the level of activity in Bank with the intervals and durations of Daisy. Results of the tests, presented in Table IV, were negative in every case but one.

During 1993 an effort was made to decipher Bank's cyclic activity, involving much more detailed recording of data and longer observation periods than in 1992. Only a summary of the results of that analysis will be given here.

Bank's activity depended primarily on two variables: whether or not overflow from UNNG-DSG-1 was pouring into Bank's pool, and the amount of energy available to Bank. The energy level gradually increased over a period of an hour or two, then dropped off rapidly. At the peak, it was possible to have three major eruptions in as many minutes; twenty minutes later, the water might merely pulse gently just below overflow. Minor eruptions resumed after half an hour or so, and gradually built up in intensity again.

The overflow from UNNG-DSG-1 added an interesting twist to this cycle. The cool water was enough to make Bank fall completely silent at the low point of the cycle. If the buildup phase was being smothered, it became more sluggish and enervated, with many more 1- or 2-burst minors than 3- or 4-bursters. Perhaps the most interesting part of Bank's activity occurred when overflow began during the peak. The explosive bursts were not as high but more massive than usual. Minor eruptions degenerated into boiling-without-bursting cycles, but had tremendous discharge. Surprisingly, though the overflow into Bank could dramatically lengthen the low part of the cycle, inflow beginning in mid-cycle did not "reset" the energy cycle to the bottom.

The combination of these two variables is enough to generate very complex patterns of activity. It can confidently be said that there is no direct connection between Bank and the Daisy Group. Any indirect connection is sure to be well hidden. It seems that the long-standing assumption of Bank's independence from Daisy is a valid one.

Pyramid Geyser - The basic activity cycle of Pyramid has undergone little change in recent years. During 1992, a period of preliminary boiling and overflow several minutes long, often including a pause, led up to the initial eruption of a series, averaging 48s in duration, ranging from 40s to 1m16s. The water column rapidly built into a near-perfect obelisk about five meters high at the peak of an initial. This was followed by a steam phase consisting of definite puffs. After 5-6 minutes, water reappeared, but was ejected in intermittent splashes rather than a column, with the strongest splashes (about three meters) in the final seconds of the eruption. Durations of second eruptions were more variable, with a range from 45s to over 2m. Usually a similar third eruption lasting 30-40 seconds occurred 5-7 minutes after the second; rarely, it went on to have a fourth. The principal difference from the description in Landis [1988] was that each series included only 2-4 eruptions instead of six. Steam under slight pressure escaped for about an hour after the last eruption. The cycle repeated regularly every 2¾ to 3 hours. In 1993, the typical series had only one or two eruptions (rarely three), and the cycle length had decreased slightly.

Much of the Pyramid data was collected using a temperature probe in the runoff channel. When compared with observed eruption times, the times of recorded temperature peaks were within three minutes. It was not possible to obtain duration data from the thermometer setup.

No correlation was found between Pyramid's intervals and activity in Daisy. There were not sufficient duration data for Pyramid to check for a correlation with Daisy. It seems very unlikely that such a relationship exists. However, there was a strong correlation between the duration of Pyramid's initial eruption and the interval until the second. The equation I(seconds)=69+7.02D(seconds) was found by LR. The value of the correlation coefficient was 0.814 and 55% of the variance was accounted for.

More Distant Connections?

The Round Spring Group

The only geysers active in the Round Spring Group during the study period were UNNG-RSG-1 and UNNG-RSG-2. Typical activity consisted of a long series of brief (2-23s, averaging 6.2), closely spaced (9-54s, averaging 19.5) eruptions of RSG-1, separated by longer eruptions of RSG-2 every half hour or so. The few tests that were possible with the limited amount of data collected did not indicate a connection.

The Grotto-Giant System

Speculation about connections between Giant and Daisy has been going on for decades. Marler believed such a connection existed, and mentioned the possibility in many of his writings. Bryan [1989] said that it "appeared that major hot periods [of Giant] could occur only within 1 or 2 minutes of a Daisy eruption start." (This has not been a hard-and-fast rule in the last few seasons, however.)

Giant - Giant itself was dormant during the study period, making a direct correlation check impossible. An eruption occurred without warning on September 24, 1992. Moss [1992] reported that, contrary to statements by Marler, water in the Daisy and Punch Bowl groups did not become murky in the days following the eruption. Splendid had erupted ten days before, but no other unusual activity in the Daisy group was reported. The author did not record enough data on nearby Bijou Geyser to include it in this study.

Oblong - There is fairly strong evidence that Oblong and Giant are connected. Oblong was frequent and regular during the study period, and few eruptions were missed, making it an ideal geyser in the Grotto-Giant system to analyze.

The mean and standard deviation of five subsets of the Daisy data were calculated: duration of the last Daisy eruption before Oblong, duration of the first after, the interval across Oblong's eruption (from the last eruption before to the first after), the previous interval, and the following interval. In all cases the 99% confidence intervals overlapped, indicating that there was no significant change in Daisy's activity. Results of these five computations are included in Table I. An LR test was then performed to check for a relationship between Daisy's average interval and the length of Oblong's interval. The equation was (Daisy interval)=100.62-

.00087*(Oblong interval), with a correlation coefficient of -.017. A plot of Oblong's eruptions with respect to Daisy's did not reveal the presence of a "window" around Daisy's eruptions during which Oblong tends to erupt. Therefore, it is concluded that there is no direct connection between Oblong and Daisy.

Oblong was dormant for most of the 1993 season. A temporary rejuvenation in mid-July did not coincide with unusual activity at Giant or Daisy.

Grotto - Given the dramatic effect Grotto has on so many geysers around it, and the large discharge produced by eruptions of it and its near neighbors, it seemed to be the one active geyser most likely to have an impact on Daisy. Though records were far from complete, a considerable amount of time during the study period was devoted to observing members of the Grotto complex.

During the study period, Grotto underwent a series of four to seven eruptions, 5½ to 9½ hours apart and lasting 1½ to 3 hours each. Ending each series was a single eruption lasting 10 to 15 hours, commonly known as a "marathon." The first eruption of the next series occurred almost exactly one day after the start of the marathon. Grotto Fountain's most powerful plays occurred early in a Grotto series, while Rocket majors took place about two hours after the start of nearly every Grotto. This pattern has been typical of the Grotto complex for several years [Bryan 1989.] A deviation from this pattern occurred August 11-13, when Grotto Fountain erupted powerfully with every Grotto, resulting in temporary inactivity in Rocket. Rocket and Grotto erupted nearly simultaneously on the first eruption of the next series, after which the traditional pattern returned. No explanation is offered for this peculiar activity, nor were any side effects to other geysers noted.

Daisy data were grouped into four subsets based on Grotto's status: marathon in progress, interval following a marathon, short eruption in progress, and the interval following a short eruption. Interval and duration were calculated for each of the four sets of data. Results of these calculations appear in Table I. At the 99% confidence level, none of these showed significant deviation from the overall averages. However, some of them came tantalizingly close. The most notable example was Daisy's duration during post-marathon intervals; not only was it several seconds longer than otherwise, it was also the only strongly bimodal subset of the 1992 data. Of the 26 durations in this group, 19 were within two seconds of either 3m20s or 3m33s.

It is possibly significant that unusual activity occurred in the Grotto Group on the days that Splendid and Giant were active in 1992. On September 14, Spa Geyser underwent a powerful eruption during a short Grotto eruption. Grotto marathons occurred on September 23 and 24 as well as on October 13.

Because of these provocative but inconclusive observations, considerable effort was devoted to a search for a Grotto-Daisy connection during 1993. The subdivision on interval and duration data based on Grotto's status was repeated for the summer 1993 data; again, no statistically significant deviations from the average were present. During the summer of 1993, a strikingly large number of Daisy eruptions started a few minutes after Grotto. Figures

2-5 plot the times of the last Daisy eruption before and the first one after the start of Grotto. A chi-squared analysis was performed to see if a sample from a uniform distribution could produce these results. The 1992 data could easily be due to chance (p=.714) but the 1993 data could not (p=.0091). This suggests that a connection does in fact exist, but that it has changed over time. Bryan's observation, mentioned at the beginning of this section, could well have been another manifestation of the same connection.

Riverside Geyser

Riverside data were analyzed in the same way as Oblong's data. As was the case with Oblong, the five mean and standard deviation calculations indicated that Daisy did not change its behavior at the time of Riverside's eruptions. Results of these five tests appear in Table I.

The LR test (Daisy average interval vs. Riverside closed interval), on the other hand, showed a weak but real correlation. The equation was (Daisy Interval)=69.51+ 0.07545*(Riverside Interval in minutes). The correlation coefficient was only 0.29 and only 4.6% of the variance was accounted for, but splitting the data into two subsets yielded similar results on each half. The reverse relationship, (Riverside interval)=292.76+1.132*(Avg. Daisy interval), was useful for increasing precision of predictions of Riverside. A comparison of Riverside predictions with and without use of this equation is given in Table V. Riverside and Daisy intervals from August 1 to 16, 1992, are plotted in Figure 6.

This correlation might be an indication of an underground connection between Riverside and Daisy. But no previous effort to show a connection between Riverside and another geyser has yet been successful. As described in greater detail below, an alternate explanation would be a lunar tidal effect on both geysers. Riverside's activity in 1993 was different enough from that of 1992 to make the old equation useless for prediction purposes, even if the equation was valid.

Other Groups of Geysers

Some have suggested that a Giant-Daisy connection could extend further, to the Punch Bowl Group or even Black Sand Basin. No observations were made in the Punch Bowl Group during the study period, and the only data from Black Sand Basin were a few sightings of Cliff and Spouter Geysers. It would hardly seem practical to search for such a connection until the Giant-Daisy relationship is more fully understood. No effort was made to correlate observed activity in the Chain Lakes, Morning Glory, or Cascade Groups with that of Daisy.

Tidal Effects

The earth's crust is distorted by the gravitational pull of the sun and moon in much the same way as the oceans are, though on a smaller scale. The plumbing systems of all geysers are constantly subjected to this compressing and stretching. A more detailed discussion of earth tides and their relationship to geysers can be found in chapter eight of Rinehart [1980.] Any effects on geyser intervals are usually masked by other variations, but these would be more easily detectable in data from highly regular geysers such as Daisy and Riverside.

Rinehart cited Riverside as a geyser especially susceptible to tidal influence, tending to have shorter intervals at the time of new and full moons. The summer 1992 data were consistent with this theory. New, first quarter, and full moons occurred on July 29, August 5, and August 13. The shortest Riverside intervals were August 1-4 and 14-16, while the longest intervals were August 7-9.

As shown in Figure 6, Daisy's intervals showed a similar rising and falling pattern. Based on inspection of the graph, it appeared as if Daisy responded to the lunar tide cycle fairly strongly. Possibly due to Daisy's shorter interval, it seemed to respond more rapidly, with the extremes in its activity falling only 1-2 days after the lunar phases rather than Riverside's 2-4.

Does the pattern hold up over longer-term observation? Figure 7 is a plot of Daisy's day-to-day average interval from January 15 to August 20, 1992. A rising and falling pattern is discernible, but it does not show a clear coincidence with lunar phases. This may be due partly to the fact that during the August study period, almost every eruption of Daisy was recorded, while observations were fairly scattered throughout the rest of the year, reducing accuracy of the calculated daily averages. The strength of the tidal influence also varies over time. Figure 8 is a plot of the same daily averages as were used in Figure 7, organized according to the phases of the moon rather than real time. Each "+" represents the average of three or more intervals from the same day, while each "·" represents a single interval from a day on which only one or two intervals were recorded. The line indicates the mean. Attempts to fit a sine wave with a period of 14¾ or 29½ days were only marginally successful. A fifth-order polynomial fit approximated the shape of a sine wave with minima at 4 and 16 days and maxima at 11 and 24 days, with an amplitude of about five minutes. The results leave much to be desired; lunar tides may or may not alter the length of Daisy's interval by a few minutes. Of course, working out the effect of the tides on geysers is not as simple as just looking at the phase of the moon; the method used to come up with these results is not very accurate.

Accurate daily averages of Daisy's durations could only be made for a handful of days. No effort was made to fit them to a sine curve; however, the rough relationship between duration and interval shown in Figure 1 indicates that if interval is related to the lunar tides, the duration is likely to be also.

An attempt was also made to find a correlation with the daily lunar cycle. Figures 9 and 10 are plots of interval and duration versus the number of hours after moonrise. No relationship at all could be found in the duration data; some subsets of the interval data seemed to show weak patterns, but none of these persisted throughout the sixteen days of observation. Because the results of the lunar tide investigation were sketchy and difficult to obtain, the weaker solar tides, which would influence Daisy even less, were not studied.

Earthquakes

It was the possibility of earthquakes causing Daisy's interval to increase that provided the inspiration for this study. In early spring 1992, the author compiled data on several major geysers from Vols. 1-5 of *The Geyser Gazer SPUT*. It was noticed that both Daisy and Riverside tended to maintain a fairly constant average interval, then abruptly jump. This was noted between fall 1987 and spring 1988, when Daisy increased its average from 77m to about 85m and Riverside rose from 6h15m to 6h45m. Between June and August 1989, Daisy's average rose above 90m and remained there for several months. In January 1991, For the first time in years, Daisy had frequent 100+ minute intervals and Riverside's average exceeded seven hours.

A few small earthquakes occurred between fall 1987 and spring 1988, but the author did not have enough data to determine which of these, if any, might have caused the changes. Landis [1988] discusses the earthquake of August 24, 1988, mentioning that Daisy's intervals were *shorter* than usual for a week afterward. *SPUT* 3:6 included an article about the July 26, 1989, earthquake, measuring 4.2 on the Richter scale. It mentioned several changes in geyser activity thought to have been caused by the tremor and suggested there probably were others. This fits in nicely with the increase in Daisy's interval. There was also a series of earthquakes centered northwest of Yellowstone on December 23, 25, and 30, 1990, again at the time of a dramatic lengthening of Daisy and Riverside intervals.

Daisy and its neighbors, Giant to the east and the Cascade Group to the north, have been affected in the past by major earthquakes. Thermal observer Paul Strasser commented to the author in August 1992, "what Splendid really needs is a good earthquake." Other researchers have also suggested that episodes of activity by Splendid, near Daisy, and Steamboat, at Norris, might be initiated by earthquakes [Paperiello 1984.]

Plans for this study had called for examination of Daisy data before and after recent earthquakes, and an attempt to correlate intensity of activity with the size and number of the slight earthquakes that are a daily occurrence in Yellowstone. Unavailability of geyser data from past years and seismic data for 1992 made this impossible.

Weather

Part of the "conventional wisdom" about the Daisy complex has long been that it, more than most other groups of geysers, is affected by changes in weather conditions. Landis [1988] said that "Daisy's intervals usually increased on windy days as much as ten minutes." Bryan [1986] states that strong south winds can delay Daisy up to half an hour and that Splendid tends to become active when a sudden drop in barometric pressure occurs.

Between August 2 and August 16, 1992, the author made over 400 observations of wind speed and direction, cloud cover, and precipitation. The goal of these observations was to develop a prediction method for Daisy that would take into account the weather conditions but not require a great deal of meteorologic equipment. Quantitative measurements of barometric pressure were originally to be part of the study, but it proved to be too difficult to obtain frequent, accurate readings.

Wind speed was recorded as a number from 0 to 100; this arbitrary scale conveniently turned out to be roughly equivalent to kilometers per hour. Rather than recording a single wind direction, each reading was expressed as the range of directions observed over a period of several minutes. Cloud cover observations consisted simply of what percentage of the sky was overcast at the time. Episodes of rain were noted in the weather data logs, but there was too little precipitation during the study period to include this information in the analysis.

Data were analyzed by grouping together eruptions of Daisy based on the direction the wind blew during the latter half of the interval. Eruptions were included in more than one category if the wind shifted direction during the interval. For each category, several statistics were computed. Mean interval length, wind speed, and cloud cover, along with their respective standard deviations, appear in Table VI; LR analyses, first of interval vs. wind speed, then with both wind speed and cloud cover as independent variables, appear in Table VII.

Winds tended to blow the strongest from the south and southwest, weakest from the east, with intermediate figures from the other directions. Cloud cover, on the other hand, averaged a fairly uniform 25% for all wind directions except east, which averaged 35%. The equations developed to predict the influence of the wind should be applicable year round. However, it should be kept in mind that weather conditions observed during a two-week period in midsummer are by no means representative of Yellowstone weather; the summary of weather conditions during the study period cannot is not applicable to other seasons.

As might be anticipated based on earlier research, southerly winds had the greatest effect on Daisy and showed the strongest correlation. When the wind blew from the southeast, up to 35% of the variance in the data could be accounted for by a lengthening in the interval of one minute for every 5 km/h of wind speed. Wind from all directions except east and northeast was found to lengthen Daisy's interval; results were not significant for these two headings, from which the wind rarely blew.

Surprisingly, inclusion of cloud cover in the equations did not greatly increase their accuracy. The coefficient for the cloud-cover term was invariably very small; it was sometimes positive, sometimes negative. Correlations were not consistently strengthened, either. Overall, it seems that considering cloud cover in trying to predict Daisy only introduces noise into the equations. If a distinction were made between types of cloud formations, it is likely that useful information could be gleaned. This hypothesis has yet to be investigated; in the meantime, one must be cautious about making Daisy predictions based on what it "looks like" outside.

Once it has been established that wind slows down Daisy, it is only natural to ask why and how. Landis [1988] showed that heat loss from the pool was substantially increased when wind blew across the crater. This is commonly cited as the cause of the delays due to wind. His statements about increased heat loss do provide an excellent explanation for at least some of the delay. Two observations, however, are not completely explained by this theory: wind *direction,* not just speed, was a major factor, and, based on when the preplay started, the wind's influence came mostly in the final few minutes before the onset of eruption. The following is proposed as an explanation.

Daisy's crater is elongated on a northwest-southeast line, opening onto an extensive terrace to the north and west. As

Daisy approaches overflow just before an eruption, a southeast wind could spill hot water from the crater onto the terraces, sapping available resources for an eruption. A south wind could have a similar but lesser effect. Winds from the west or north, on the other hand, could pile up water in the crater or blow cold water from the terraces back into Daisy, postponing the start of overflow. Qualitative observations of runoff volume just prior to eruptions agreed with what would be expected based on this theory.

To the dismay and frustration of anyone trying to predict Daisy, occasionally an interval ten or more minutes shorter than expected would occur for no apparent reason. Further study of the data revealed that such "freak occurrences" were actually the result of a well-defined sequence of events. The preceding eruption had to be shorter than usual, typically under 3m10s, and accompanied by a strong north or northwest wind. The next eruption could then start three to seven minutes after east vent preplay began only if a sustained north or northwest wind suddenly shifted to the west or southwest; this eruption was also of exceptionally short duration. These "unpredictable" events became fairly easy for the author to anticipate if he had witnessed the previous eruption. The theory discussed above provides a simple explanation for this seemingly very complex phenomenon. The north or northwest wind during the previous eruption could blow the water column back on itself and quench the eruption prematurely, minimizing water loss. Just prior to the next eruption, the wind shifted from along the crater to across it; water might have been piled up against the crater's higher southern rim, then suddenly allowed to escape when the wind changed. This release of pressure could trigger the early onset of a second eruption.

Daisy's setting on an open windy hillside and its regularity made it fairly easy to detect and analyze the influence of the wind. Only a handful of other geysers could be investigated as easily. However, the methods used here should be applicable to many other geysers with reasonably good results. Especially worthwhile would be similar studies of geysers that, like Daisy, experience some sort of diurnal effect—Plume, Beehive, and Morning, to name a few. Searching for correlations with weather conditions, which usually show diurnal patterns, could well give more accurate results than a study based only on time of day, as well as directly addressing a likely cause of the variations in activity.

Conclusion

How much more accurately can Daisy be predicted now than before this study was made? By the end of the study period, the author was able to make predictions with a five- to eight-minute window (± 2 to 4 minutes) that were about 90% accurate. For normally distributed data, a window of 1.65 standard deviations (±9 minutes, in this case) either side of the mean would be necessary to achieve this accuracy. This implies that careful observation made it possible to anticipate between sixty and eight percent of the variance in the data. No system of equations, like those developed in this paper, will continue to yield accurate results over long periods of time without frequent revision. It is expected, however, that this level of precision can be equalled or exceeded by anyone willing to devote enough time to careful observation of Daisy.

It was learned that the traditional model of preplay as an indicator of eruption time, though useful as a rule of thumb, is rather inaccurate. It is proposed that the necessary conditions for an eruption of Daisy are preplay in the east vent, indicating enough energy to sustain an eruption once it is initiated, and the reaching of overflow (not necessarily a period of overflow), indicating enough water to erupt. No eruptions have been seen when either of these conditions were not met, and an eruption invariably occurred within seconds or a few minutes when they were. In general, more energy is needed to initiate an eruption than to sustain one. The presence of this small excess is suggested as a sufficient condition. If this extra energy is already in the system, an eruption begins as soon as the water level is high enough; if not, presumably usually due to wind-caused loss, there is a period of overflow during which the needed energy is accumulated.

Daisy is still far from being fully understood. The question of tidal influence remains unsettled. It has been tentatively shown that Daisy and Grotto are related, but details about the relationship are very elusive. Only the briefest consideration was given to the important topic of earthquake effects. The discussions of water and energy flow were purely qualitative, not the result of any thermodynamic study. Other geyser observers are invited to tackle any of the unsolved problems and review any of the findings presented in this paper. And above all, they are urged to remember that even the "xerox geysers" are complex and varied systems, and that there is more to see in the northern Upper Basin than Fan&Mortar!

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Table I

Calculation of Daisy duration and interval statistics for various subsets of the data.
Durations in seconds, intervals in minutes.
"I.E." stands for "in eruption."

Subset Definition	N	Min	Q-1	Med	Q-3	Max	Mean	SDev	99%CI	Ni	Mi
All durations-June	22	192	210	216	221	242	215.0	13.1	7.4	---	---
All durations-August	74	179	197	203	209	228	202.6	9.6	2.9	---	---
All durations-1992	129	179	196	202	211	242	203.7	11.0	2.5	---	---
Before Oblong (Aug)	16	193	199.5	204.5	206	221	204.1	7.5	5.0	---	---
After Oblong (Aug)	17	184	196	205	211	221	202.6	11.1	7.2	---	---
Before Riverside (Aug)	21	188	199	205	207	221	203.0	8.6	4.9	---	---
After Riverside (Aug)	26	186	197	203	209	216	202.5	8.5	4.4	---	---
Short Grotto I.E. (Aug)	17	188	194	201	204	219	200.7	7.5	4.7	---	---
After short Grotto (Aug)	29	179	196	202	208	221	201.9	9.4	4.6	---	---
Marathon I.E. (Aug)	14	186	196	201	205	218	200.6	9.8	7.0	---	---
After marathon (Aug)	26	188	201	208	214	228	207.0	9.5	4.9	---	---
All durations-1993	74	178	198	204	210	235	204.4	11.4	3.4	---	---
Short Grotto I.E.-1993	24	178	194.5	201	205.5	226	200.5	11.1	6.0	---	---
After short Grotto-1993	34	181	199	205.5	212.5	235	206.4	12.4	5.6	---	---
Marathon I.E.-1993	7	199	205	211	212	217	208.7	6.1	6.4	---	---
After marathon-1993	9	196	199	201	206	223	204.3	9.3	8.4	---	---
All intervals-June	34	92.03	98.09	100	102.88	107.23	100.16	3.62	1.63	51	100.59
All intervals-August	123	82	96.09	99.85	102.35	128	99.370	5.750	1.343	224	100.471
All intervals-1992	194	82	96	99.52	102.19	128	99.211	5.373	0.998	326	100.243
Before Oblong (Aug)	20	82	97.79	99.98	103.92	106.03	98.578	4.654	2.230	29	100.178
Across Oblong (Aug)	24	92	96.5	100.25	102.71	107.98	99.907	4.101	2.207	28	99.686
After Oblong (Aug)	21	87.2	96	97.57	101.17	113	98.652	6.418	3.702	26	99.043
Before Riverside (Aug)	21	91	97.73	101.28	102.07	110.3	100.099	4.596	2.652	33	99.896
Across Riverside (Aug)	31	88.17	97	100	102.64	112.08	99.890	5.123	2.413	37	100.029
After Riverside (Aug)	30	87.2	95.55	100.14	101.61	106.03	98.578	4.654	2.230	35	98.851
Short Grotto I.E. (Aug)	22	82	99.35	100.54	101.99	108.32	100.121	5.243	2.952	30	100.489
After short Grotto (Aug)	43	90.5	97	100.33	102.18	106.03	99.450	3.591	1.430	58	100.123
Marathon I.E. (Aug)	20	87.58	94.88	96.18	99.64	117	97.877	6.960	4.120	39	99.749
After marathon (Aug)	32	88	97.78	100.13	103.95	128	101.364	7.585	3.515	44	101.469
All intervals-1993	137	92.97	100.68	103.6	107	134.83	103.256	5.443	1.204	---	---
Short Grotto I.E.-1993	37	93	100.68	103.7	105	115.7	103.256	4.749	2.042	---	---
After short Grotto-1993	55	95.8	101.25	104.5	108	112	104.279	4.173	1.465	---	---
Marathon I.E.-1993	19	92.97	100	102.3	104.34	108	101.962	3.991	2.427	---	---
After marathon-1993	26	97	100.48	103	107.5	134.83	105.68	8.517	4.395	---	---

Table II

Linear Regression Analyses - Daisy Geyser

The linear regression results in Tables II, III, IV, and VII are all presented in the same format. The variables being tested are listed in the form "dependent variable (units) vs. independent variable (units)." The equation is given the the form "y=A+Bx." Two measures of correlation strength are given. The correlation coefficient r ranges from ±1, showing perfect correlation, to zero, showing no correlation. The percentage by which the equation model reduces scatter in the data is also given; perfect correlation is 100%, while any negative number implies no correlation. In cases where data was tested in halves, each half should show a similar or better correlation than the entire set if the correlation is real.

Test # and Description:	Equation	|r|=	Variance:	N:
1. Daisy interval (min) vs. preceding Daisy duration (sec)				
	I=68.191+.1537D	.259	5.6%	84
2. Duration (sec) vs. length of east vent preplay (min)				
	D=195.7+.501P	.164	0.89%	57
2A. First half of data	*D=198.4+.413P*	*.134*	*-1.82%*	*29*
2B. Second half of data	*D=191.9+.673P*	*.228*	*1.57%*	*28*
3. Interval (min) vs. length of preceding east vent preplay (min)				
	I=95.843+.3120P	.175	1.28%	56
3A. First half of data	*I=96.912+.2710P*	*.152*	*-1.43%*	*28*
3B. Second half of data	*I=94.480+.3798P*	*.216*	*0.98%*	*28*
4. East vent preplay (min) vs. length of concurrent interval (min)				
	P=-22.89+.337I	.670	43.9%	56
4A. First half of data	*P=-22.37+.329I*	*.671*	*43.0%*	*28*
4B. Second half of data	*P=-25.03+.362I*	*.691*	*45.8%*	*28*
5. Duration (sec) vs. length of west vent preplay (min)				
	D=204.2-.142P	.049	-5.6%	19
6. Interval (min) vs. length of preceding west vent preplay (min)				
	I=80.55+.917P	.444	14.3%	17
6A. First half of data	*I=55.24+2.060P*	*.606*	*27.7%*	*9*
6B. Second half of data	*I=90.73+.336P*	*.356*	*-1.84%*	*8*
7. West vent preplay (min) vs. length of concurrent interval (min)				
	P=-18.03+.392I	.694	45.0%	18
7A. First half of data	*P=-3.07+.244I*	*.320*	*-2.6%*	*9*
7B. Second half of data	*P=-23.36+.441I*	*.789*	*56.9%*	*9*

Table III
Linear Regression Analyses - Daisy Geyser and Bonita's Sputs

Test # and Description:		Equation	|r|=	Variance:	N:
1.	Daisy interval (min) vs. preceding BS delay (sec)				
		Y=96.521+.0235X	.078	-0.8%	---
2.	Daisy duration (sec) vs. corresponding BS delay (sec)				
		Y=190.2+.0979X	.169	1.6%	---
3.	BS delay (sec) vs. preceding Daisy interval (min)				
		Y=103.7+.197X	.065	-0.9%	---
4.	BS duration (sec) vs. preceding Daisy interval (min)				
		Y=110.1+.805X	.168	0.4%	---
4A.	*First half of data*	*Y=41.0+1.394X*	*.273*	*7.6%*	---
4B.	*Second half of data*	*Y=193.7+.0765X*	*(?)*	*16.5%*	---
5.	BS duration (sec) vs. corresponding Daisy duration (3 min+*x* sec)				
		Y=162.4+1.32X	.402	14.1%	42
5A.	*First half of data*	*Y=122.1+2.81X*	*.666*	*40.8%*	*21*
5B.	*Second half of data*	*Y=189.5+.533X*	*.219*	*22.5%*	*21*
6.	Daisy duration (sec) vs. preceding BS delay (sec)				
		Y=197.6+.0258X	.046	-1.4%	63
7.	Daisy interval (min) vs. preceding BS duration (sec)				
		Y=98.663+.0039X	.022	-2.5%	42
8.	Daisy duration (sec) vs. preceding BS duration (sec)				
		Y=213.03-.0568X	.179	-0.3%	30
9.	BS duration (sec) vs. corresponding BS delay (sec)				
		Y=305.6-.9181X	.590	33%	42
9A.	*First half of data*	*Y=295.9-.8836X*	*.474*	*20%*	*21*
9B.	*Second half of data*	*Y=299.3-.8221X*	*.641*	*47%*	*21*

Table IV
Linear Regression Analyses - Daisy Geyser and Bank Geyser

The following variables are used: U=number of Bank "pulse" cycles in 15 minutes; V=number of "bubble" cycles in 15 minutes; X=number of minor eruptions in 15 minutes; Y=number of major eruptions in 15 minutes; Z=total number of bursts from Bank minor and major eruptions in 15 minutes; I=Daisy interval in minutes; D=Daisy duration in seconds.

Test # and Description:	Equation	|r|=	Variance:
1. Daisy interval vs. number of bursts			
	I=100.71-.00466Z	.016	-5.9%
2. Daisy interval vs. number of eruptions			
	I=100.92-.0447(X+Y)	.035	-5.7%
3. Daisy interval vs. total number of eruptive events			
	I=109.94-.530(U+V+X+Y)	.362	8.0%
3A. First half of data	*I=98.82-.0882(U+V+X+Y)*	*(?)*	*38%*
3B. 2nd half of data	*I=94.70+.608(U+V+X+Y)*	*.232*	*7.2%*
4. Daisy interval vs. proportion of events that were eruptions			
	I=99.77+1.95[(X+Y)/(U+V+X+Y)]	.080	-5.2%
5. Daisy duration vs. number of bursts			
	D=200.9+.0462Z	.111	-4.6%
6. Daisy duration vs. number of eruptions			
	D=201.3+.113(X+Y)	.064	-5.4%
7. Daisy duration vs. total number of eruptive events			
	D=209.0-.391(U+V+X+Y)	.194	-1.9%
8. Daisy duration vs. proportion of events that were eruptions			
	D=200.2+4.77[(X+Y)/(U+V+X+Y)]	.142	-3.7%

Table V
Riverside Geyser - Prediction Accuracy
(Percentage of eruptions within a window of specified size)

A. Predictions based on Mean Interval

Range	Percentage
±5 min	8%
±10 min	48%
±20 min	88%
±30 min	88%
±45 min	100%

B. Calculated using the expression 292.76+1.132*(Daisy Interval)

Range	Percentage
±5 min	28%
±10 min	48%
±20 min	88%
±30 min	92%
±45 min	100%

Table VI
Intervals and Weather Conditions

Interval expressed in minutes; wind speed expressed in arbitrary units, approximately equal to kilometers per hour; cloud cover expressed as a percentage of the sky.

Direction	N	Interval	(Std Dev)	Wind Speed	(Std Dev)	Cloud Cover	(Std Dev)
North	49	97.69	5.13	30	15	25	26
Northeast	18	94.79	4.91	24	12	27	29
East	17	97.89	4.90	22	11	35	27
Southeast	21	99.95	4.73	25	14	29	23
South	58	100.68	4.92	34	15	25	26
Southwest	61	100.65	4.96	34	15	24	26
West	75	100.61	4.71	32	15	25	26
Northwest	74	99.48	5.24	32	15	24	26

Table VII
Correlation between Wind Speed, Cloud Cover, and Interval

(I=Interval, W=Wind Speed, C=Cloud cover, expressed in same units as in Table VI)

Direction	Wind Equation	|r|=	Variance	2nd Equation	|r|=	Variance
North	94.88+.0938W	.26	5.2%	94.94-.00613C+.0970W	.27	3.2%
Northeast	97.06-.0939W	.23	-0.8%	96.17+.0674C-.1330W	.44	9.1%
East	97.15-.0336W	.08	-6.0%	96.83+.0131C+.0280W	.10	-13%
Southeast	94.79+.2045W	.62	35%	94.89-.0041C+.2050W	.62	32%
South	96.71+.1155W	.36	11%	97.09-.0349C+.1299W	.40	13%
Southwest	95.93+.1410W	.43	18%	96.36-.0351C+.1533W	.47	19%
West	97.69+.0900W	.29	7.1%	98.05-.0551C+.1204W	.41	14%
Northwest	96.26+.0996W	.28	6.5%	96.42-.0131C+.1043W	.29	5.6%

Grotto Fountain Geyser -- Grotto's "Indicator"

by

Rocco Paperiello

ABSTRACT: Grotto Fountain Geyser's present activity is apparently not typical for much of its history. This paper chronicles its not well known early history, and its succession of names. A short sketch of related thermal features is also included.

Early History of Grotto Fountain Geyser:

Prior to the 1920's, there are only two references to eruptive activity by Grotto Fountain Geyser. The first is found on a map of the Upper Geyser Basin constructed by Gustavus R. Bechler [1872] from information obtained in 1872. On this map Bechler indicated that today's Grotto Fountain Geyser was a "spouter". Unfortunately no height or description was given.

The next mention of geyser activity for Grotto Fountain is found in Walter Weed's field notebook for 1886.[1] He noted that "the hole in the formation just below Grotto Geyser (and by its overflow channel) was said to spout 30 feet high." [Whittlesey 1988] Apparently this activity was not actually witnessed by Weed himself, but it was "major" in character.

There appears to be no definitive eruptive history (except for very minor action to a foot or so) recorded for Grotto Fountain Geyser from 1886 until about 1922. In an article entitled "Morning Lecture - Old Faithful," written by James D. Landsdowne in about 1923, we read the following:

> Within recent years (1922 - 1923) the INDICATOR (sign removed) has been known to play to a height of one hundred feet for fifteen minutes. (Evidence of ex-temporary rangers Robertson and Alcorn). It has an irregular interval. [Landsdowne circa 1923]

There are specific records of at least 2 "major" eruptions of Grotto Fountain in 1923, 1 in 1926, 1 in 1927, 5 in 1928, 4 in 1930, 9 in 1931, and 5 in 1932. The earliest description of "major" eruptions of both Grotto Fountain and

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1 Some authors have used the following paragraph from General Strong's diary to indicate possible activity for Grotto Fountain Geyser on August 4, 1875:

> A few minutes before 7 o'clock the Secretary, Colonel Gillespie, and myself [General W. E. Strong] walked up the valley to Old Faithful and got to it just in time to see the first jets shoot up, and at the same time the Castle broke out, below our camp, followed quickly by the Grotto Group, further down, and we had a fine view of the three geysers playing simultaneously. Doane was in camp, and said the display made by the Castle was the finest he has yet seen. [Bartlett 1968, p 83]

The group stated that they had gotten to Old Faithful, and from the mound of Old Faithful, eruptions of both Castle and Grotto would be visible. Being able to note three separate vents erupting in the Grotto area from that distance is doubtful. I think it most probable that the "the three geysers playing simultaneously" were exactly as stated, namely, Old Faithful, Castle, and Grotto.

In 1878, A. C. Peale [1883] wrote the following about the Grotto Group:

6 Basin 16 feet diameter in which is a fissure 2 by 4 feet.	176[°F]	Water is 2 feet below the top	These springs are in a basin of hard geyserite, and at times are connected probably	[South Grotto Fountain Geyser]
7 15 by 20 feet.	175[°F]	light-blue funnel spring	after an eruption of the Grotto which sends water to	[Grotto Fountain Geyser]
8 Crater 4 by 3 feet, fissure at base.			No. 7.	[Indicator Spring]

South Grotto Fountain Geysers is found in the August, 1923 *Monthly Report of the Superintendent*:

> During the first week of August[, 1923],... one of the two vents associated with the hot pool near Grotto Geyser, formerly called the Indicator, erupted in true geyser fashion at least twice. ...the active vent was the more northeasterly of the two, that is, the one situated outside the basin of the pool itself. Reports state that the manner of the eruption was somewhat like that of the Grand Geyser, that is, in a series of successive jets. The height of the eruption varies greatly in the different reports, some stating a height of over a hundred feet, some less than fifty. [MRofS August, 1923, p 16]

Most of the known activity of which we have record for 1926, 1927, and 1928 is described in a recently discovered "Memorandum to [Superintendent] Mr. Albright" from Park Naturalist Dorr Yeager in 1928:

> I am making the following report on the geyser which has broken out near the Grotto Geyser in the Old faithful District.
>
> The geyser was first noted and reported by Mr. Ruhle as having played at 4 P.M. on August 15th[, 1928]. He reports an eruption of the fountain type with many rockets rising to a height of 80 feet and over. During the eruption, which lasted 20 minutes, large amounts of sinter and mud were hurled into the air. The crater fills and empties several times before an eruption, forming a pool 60 feet in diameter and 1 foot deep. During the eruption, three small vents due south from the crater [South Grotto Fountain] play to a height of 10 feet. Mr. Marsh observed a similar eruption with a similar period at 10 A.M. on the next day.
>
> The crater, approximately 2½' x 8", is located 150 feet north west by north of Rocket. It formerly acted as an overflow for Grotto and Rocket when they were in eruption.
>
> The "new" geyser erupted for the first time on August 15th playing for 20 minutes. A similar eruption occurred on the 16th and 17th. An eruption occurred early on the morning of the 18th but the period was not observed.
>
> Mr. Martindale tells me that Dr. Van Pelt reported this geyser as playing once in 1926 and Dolliver reports it in 1927. Evidently it comes to life for a few eruptions each season. Mr. Baker says he knows nothing of it and is sure that neither Dr. Allen and Dr. Fenner have heard of it before. [Yeager 1928]

The 1926 activity seen by Dr. Van Pelt, is corroborated by the following excerpt from Ansel F. Hall's late 1926 descriptions of the nature trails and signs in the Upper Geyser Basin:

> Note: At a distance of thirty-five paces from ROCKET GEYSER is a small geyser which was formally labeled as shown by the old post. Nobody seems to know the name. Water from GROTTO drains into its pool during heavy eruptions. Van Pelt has seen this small geyser play. A.F.H. [Hall 1926]

The 1927 eruption occurred on June 30th and was reported to have reached 50 feet high. [MRofS June 1927, p 19]

One additional eruption of Grotto Fountain was seen in 1928 by Ranger Robert M. Baker on November 14th. The geyser, which he called the "Indicator to Grotto and Rocket", erupted

---

[Note: Walter Weed [1883], radically altered the description of #8 to read: "Basin of rather indefinite shape, with a mound in the center 4 inches high, in which the orifice is 2 by 3 feet." This is clearly today's Grotto Fountain Geyser. Thus according to Weed, this would make #7, his "funnel shaped spring of light blue water" today's Indicator Spring. There is a problem, however, with this interpretation of Peale, in that Grotto clearly sends water to Grotto Fountain Geyser (Weed's #8) and not the Indicator (Weed's #7).]

Peale also stated that their "time for the examination of the group was small, and [they] were unable to devote any time for observation of the geysers." Unfortunately there is nothing mentioned which could either confirm or deny possible geyser activity for spring No. 7.

for 29 minutes and reached heights of 20 to 80 feet. Three minutes after the start of Grotto Fountain, the South Grotto Fountain started and erupted for 26 minutes to heights of 8 to 20 feet. Grotto started 10 minutes into the eruption of the Grotto Fountain. [MRofS Nov 1928 p 10, see also Skinner 1932 p 32, and RofND May 1932]

J. Thomas Stewart recorded four eruptions for Grotto Fountain in 1930 and added some interesting information:

> The small vent into which the Grotto and Rocket drain has been seen in eruption four times and we usually think of the eruption as taking place just after the beginning of the short eruption following a long interval. [Stewart 1930, see also RofND July, 1930]

This "long interval" involved what is in today's parlance called a "marathon eruption". This refers to the exceptionally long duration eruptions of Grotto which subsequently become part of an exceptionally long interval. Even today, these "marathon eruptions" are usually followed by one of very short duration. The eruption of one such "long interval" noted in 1930, lasted longer than 11 hours. [Stewart 1930] In his reports of 1931 and 1932, Thomas "Geyser Bill" Ankrom will coincidentally call this "marathon eruption", a "long run". [Ankrom 1931a, 1932a]

In his extensive 1931 geyser notes Thomas Ankrom described the activity of Grotto Fountain for that year:

> [Grotto] Fountain is erratic in its interval, and varies in its period of duration from ten to thirty minutes. The greatest height is about fifty feet. The jet is slender... and feathers toward the top.
>
> South [Grotto] Fountain seldom erupts to any great height, the greatest that I have seen was about fifteen feet, the water being thrown out at an angle to the South-east.
>
> As this group is erratic in their actions, a close check was not made...
>
> After a long run of the Grotto Geyser [synonymous with our term "marathon eruption"], there will be but very little action of the group for as much as 24 hours. The pool to the South-east ["Variable Spring"] will lower as much as 4 feet by the time that one of these long runs has finished, even with the water of the Grotto going into it. This indicates that there is some connection. Have also noticed that when the water in this pool reaches a certain place in this pool, that the Grotto, Rocket, or both would erupt in a short time. [Ankrom 1931a]

During the summer of 1931, there were at least 9 eruptions of the Grotto Fountain recorded. Two of these were joined in eruption by the South Grotto Fountain. Recorded durations were from 6 to 23 minutes. During at least some of these eruptions, Grotto was also reported to erupt. In addition, the South Grotto Fountain was recorded in at least 5 eruptions independent of Grotto Fountain; during every occasion, this was reported as causing a long delay in the eruption of Grotto. [Ankrom 1931a, Crowe 1931, Lystrup 1931]

At least 5 eruptions of Grotto Fountain were recorded in the summer of 1932. Two of these were joined by the South Grotto Fountain. Recorded durations were from 13 to 20 minutes. All eruptions of Grotto Fountain were joined by Grotto. At least 3 independent eruptions of the South Grotto Fountain were also recorded. [Crowe 1932, Ankrom 1932a, Lystrup 1932] One eruption seen in May was described in some detail:

> The GROTTO showed some variation in that one of the drain vents turned into a geyser on the evening of May 22, playing to a maximum of fifty feet, continuing in eruption for seventeen minutes. Its activity was characterized by a steady rush of water and steam, closely resembling the playing of Old Faithful, except to a lesser height and a smaller volume of water... Just before this drain vent ceased to erupt a second drain vent burst forth and erupted [for] two minutes to a height of six feet... [Nine minutes into the eruption,] Grotto and Rocket began to play. [Crowe 1932, see also Skinner 1932, p 32, RofND May, 1932]

It is interesting to note that, although there was some sporadic major activity of Grotto Fountain from at least 1923 through 1930, the relatively frequent and sizable activity seen in 1931 and 1932 was probably unprecedented in the known history of the Park. That this is true can be inferred from what happened to a specific tree which was situated near the vent of Grotto Fountain Geyser. In his 1973 *Inventory...* Marler wrote:

> ...Another tree of interest [near the Grotto Fountain] is a stump about 3 feet in height and 24 inches in diameter which grew within a few feet of the crater which Grotto Fountain's erupting waters have excavated. No doubt because it was dead, having been killed during one of Grotto Fountain's eruptive cycles, some early park administration had this tree felled and removed. The tree was not less than 150 years in age. The fact that it grew within a few feet of Grotto Fountain indicates not only cyclic activity, but that some of its dormant periods were long. [Marler 1973, p 105]

This above report becomes exceptionally significant when we find that this very tree was probably alive in 1931 and was called the "snake tree". The following excerpt from George Crowe's July, 1931 geyser report makes this clear by telling us the date:

> A small geyser on the Nature Trail, which formerly played to a height of one to two and a half feet is now playing to a height of more than a hundred feet and has killed the famous "snake tree". [Crowe 1931, see also RofND July 1931]

One lone eruption of South Grotto Fountain was reported the next year (1933), but no further activity for Grotto Fountain Geyser will have been reported until its major rejuvenation in 1941.[2] [Ankrom 1933a, Marler 1941a]

Concerning the "new" period of activity observed by Marler in 1941 and 1942, he wrote the following:

> That the activity described represents a new cycle of activity is shown from the fact that by the end of 1942, several Lodgepole Pines about 50 feet northwest of the geyser were killed and whitened by the frequent wind-blown water they were subjected to. These trees were from 50 to 75 years in age. These trees could not have grown where they were with Grotto Fountain functioning as it has... [Marler 1973]

Known records indicate that Grotto Fountain Geyser probably remained a relatively consistent performer until the noted decline of activity in the Grotto Group from 1952 through mid-1955. [Marler 1941a, 1942a, 1946a, 1947a, 1947b, 1948a, 1949a, 1949b, 1950a through 1955a, Replogle 1942, Broderick Aug 1943a, 1943b, RofND May, 1945, p 2, Lystrup 1945] This included the dormancy of Grotto Fountain in 1953 and its near dormancy in 1954. [Marler 1953a, 1954a] From 1941, the only year for which we have no specific information on Grotto Fountain Geyser is 1944.

In spite of what Marler stated in his 1973 *Inventory...* [p 104] concerning some 40 to 65 minute durations for Grotto Fountain in 1957, his own 1957 report specifically stated that "at no time was the [Grotto] Fountain's activity observed to last more than 20 minutes." [Marler 1957a] (After the 1959 earthquake, Grotto continued to have numerous "marathon eruptions", one of which lasted for 43 hours. [Marler 1959a])

Nomenclature of the Grotto Fountain Complex:

The name of Grotto's Fountain Geyser was proposed by George Marler [1946a] in 1946 and used by him in the majority of his annual reports since then.[3] Marler wrote the following in a 1947 article entitled "Are the Geysers Declining

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2 Coincidentally, another geyser in the Grotto area made its "modern" debut in 1941. Today it is dubbed "Marathon Pool". See "Unusual Occurrences".

3 That the name of "Grotto's Fountain" was given in 1946 is found in Marler's preliminary typewritten report for that year. In his

in Activity?":

> Due to [the] evident underground connections with the Grotto, and that the drainage from the Grotto helps fill the depressed bowl through which the new comer plays, I have termed this geyser the Grotto's Fountain. [Marler 1947b]

To this explanation Marler added the following in a letter to Jack Haynes in 1949:

> With the water of the Grotto running into the depressed bowl from which the new geyser plays it gives the geyser the appearance of a city fountain, hence the name Grotto's Fountain. [Marler 1949]

Some of the earliest references to Grotto Fountain show that it was long used as an "Indicator" for nearby Grotto Geyser. Probably the earliest record of this appeared in an account of a trip made through the park in 1900 by Charles Taylor. [Whittlesey 1988, p 842, Taylor 1901, p 344].

In a 1911 letter from Jack Haynes to Arnold Hague, detailing geyser activity and geyser tables for that year, we read the following:

> The Grotto has no indicator but a pool one hundred feet north, twenty feet across fills up and recedes again preceding activity of the Grotto. This pool spurts up usually just before the Grotto plays but remains quiet during activity of the Grotto. [Haynes 1911]

Because the above account described the pool "filling and receding" and "spurt[ing] up usually just before the Grotto plays", I have interpreted this "indicator" to be Grotto Fountain Geyser rather the collapse hole we refer to today as "Indicator Spring. In addition, until probably May of 1948, its the dimensions were much smaller. [Marler 1948]

There are a number of additional references of Grotto Fountain being called Grotto's "Indicator", two of which were recounted above. [MRofS August 1923, Landsdowne circa 1923] In the November, 1928 *Monthly Report of the Superintendent*, the location of the "Indicator Spring" was specifically given:

> Indicator to Grotto and Rocket - this opening, so called by Phillips, is 170 feet nearly due north of Rocket...[4] It consists of an irregular shaped orifice 30 x 15 inches in size which normally acts as a drain for the runoff from Rocket Geyser... [MRofS Nov, 1928]

The present "Indicator Spring", namely the collapse pool just west of Grotto Fountain, was not referred to as an "Indicator" for the Grotto Group until Marler's 1958 report, although Marler had taken note of it by 1954. [Marler 1958a, 1973] In his 1958 report Marler wrote:

> During the past few seasons the time of an active period of Grotto Fountain, and the follow-up eruption of Grotto, were readily predictable by the rate of rise of water in the Indicator.

We do not find the specific name of "Indicator Spring" so christened, however, until a September, 1959 report by Marler and Germeraad [1959].

On the map of the Upper Geyser Basin constructed by Bechler [1872] today's Indicator Spring appears to be labeled "Perfect Funnel Spring", although this name may have been meant for Grotto Fountain instead. In 1878, Peale [1883] noted that the crater of this pool measured only "4 by 3 feet".[5] It is much bigger than this today. From a report by Marler in

list of active geysers on the first page, the name Grotto Drain (in typescript) is partially crossed out and the name Grotto's Fountain is inserted. This change (along with a number of others) are in Marler's own handwriting. The name was later simplified to Grotto Fountain Geyser by 1955. [Marler 1946a, 1955a]

4 Grotto Fountain actually lies a little east of due north from Rocket Geyser.

5 An alternate interpretation is that this "4 by 3 feet" spring of Peale is today's Grotto Fountain Geyser, and that his "15 by 20 feet..., light-blue funnel spring" is today's Indicator Spring. This would still not invalidate Marler's 1948 observations concerning the basin of the Indicator Spring.

1948, we find that it was possibly during that year in which the opening of this spring increased in size to its present 11.3 by 6.1 feet:

> ...This lessened activity [of Grotto Fountain] might easily be due to the roof of a cavern which is connected underground, having slumped in during late May of this year. [Marler 1948b]

The first name proposed for today's Grotto Fountain Geyser was made in 1931 by Thomas Ankrom -- or "Geyser Bill" as he liked to call himself. He wrote the following in an unpublished article entitled "Geysers of the Yellowstone National Park":

> This [group] consist of the Grotto, and Rocket Geysers, and two geysers to the North-east of the Rocket which have not been named, these I call the True Fountain, and South True Fountain. There is also a pool South-east of the Grotto, these are in addition to a number of small openings in the Grotto formation... [Ankrom 1931b]

Strangely, Ankrom then added the following:

> I do not believe that the Fountains are direct[ly] connected with the Grotto or Rocket... [Ankrom 1931b]

Thomas Ankrom used these names in his 1931, 1932, & 1933 reports, and they were also used by Herbert Lystrup in 1932 and 1933. [Ankrom 1931a, 1932a, 1933a, Lystrup 1932, 1933]

However, the name "True Fountain" did not survive -- probably because major activity of this geyser was apparently not seen again until 1941.

It was with the revival of Grotto Fountain in 1941 that we first see the name "Grotto Drain Geyser". [Marler 1941a] In spite of what one may infer by reading Marler's 1973 *Inventory...* [p 105], the prior name of "Grotto Drain Geyser" was also his invention. He first used it a 1941 report, and wrote the following in 1942:

> The U. S. Geological Survey refers to this geyser as being one that "plays in the drain from Grotto." Thus I am referring[sic] to it as the Grotto Drain. [Marler 1942a]

The above reference by Marler is puzzling; I have not been able to find any U.S.G.S. publication which made such a reference.

The name of "Strange Geyser" made its debut in 1943. In the log of geyser eruptions kept by Harold Broderick [1943b] in 1943 the names, "Grotto Drain" and "Strange", both appear interchangeably. In his 1945 report, Lystrup [1945] used the name of "Grotto Drain" but further stated that this geyser was locally known as "Strange Geyser". Lystrup continued the use of the name "Strange Geyser" as late as 1947 and 1948. [Bryan 1992]

One final name, that of "Surprise Geyser", involves a somewhat convoluted story. From its first edition in 1890 through that of 1907, the original "Haynes Guides" were actually authored by A. B. Guptill [1890-1907] and published by Frank Haynes. In all of these editions, a geyser was listed in the tables called "Surprise Geyser" which was said to erupt to "100 feet at irregular intervals for 2 minutes". There is no doubt that this geyser was in fact also called "Liberty Geyser", and was located somewhere in the vicinity of present-day Liberty Pool.[6] [Whittlesey 1988]

These guidebooks were later authored by Frank Haynes [1910-1915] from 1910 to 1915, and finally by his son Jack Haynes [1916-1966] starting in 1916. In all these latter editions (after 1910), this "Surprise Geyser" of Guptill was omitted from the geyser tables. In the later editions in the 1930's, the entire geyser tables themselves were omitted for a number of years.

From a letter written by Jack Haynes [1939] to Clyde Max Bauer dated January 30, 1939, it is evident that Jack Haynes did not know of the location of this earlier "Surprise Geyser". He even suggested to Clyde Max Bauer that Bauer

6 There is, in fact, a 1926 reference which stated that "the original Liberty Pool [lay] 150 feet east [of Tardy Geyser], but it has dried up and is now an uninteresting crater..." [Hall 1926] An interesting speculation is that this dead crater -- still dry today -- was the sight of the original Liberty Geyser, especially since the drawing of the crater of "Liberty Geyser" and its depth measurements made by Walter Weed in the 1880's does not very well fit today's Liberty Pool, nor any other active feature in the vicinity. [Whittlesey 1986]

delete this geyser from his soon to be published book *The Story of Yellowstone Geysers*. In his return letter of February 1, 1939, Bauer [1939], likewise stated that he too was not familiar with "Surprise Geyser", and followed this recommendation.

However, in 1939 there was a major revision of the 1939 edition of the *Haynes Guide*, and the geyser tables were again published. Unaccountably, "Surprise Geyser" was again listed with the same data as presented by Guptill four decades earlier. No additional information was given. Note that this was two years before the major rejuvenation of Grotto Fountain Geyser in 1941. This entry remained unchanged until Haynes' 1949 edition, when he replaced the name "Surprise Geyser" with that of Grotto Fountain Geyser; here Haynes stated:

> Grotto Fountain Geyser a 65-foot geyser east[sic] of the Grotto known formerly as Surprise Geyser or Grotto Drain Geyser, erupts every 6 to 12 hours. [Haynes 1949]

This equating of "Grotto Fountain Geyser" with the former "Surprise Geyser" was a mistake; but the mistake was that of George Marler, not Jack Haynes. The following is an excerpt from a letter sent to Jack Haynes by George Marler dated April 28, 1949 just in time for the changes to the 1949 edition of the *Haynes Guide*:

> The Surprise Geyser you have listed is no doubt the one the ranger naturalists at Old Faithful have been calling "Grotto Drain Geyser," and "Grotto Fountain Geyser." Last season we decided to be -- uniform and settled on the latter title, though either one somewhat correctly describes the geyser... The duration of its activity is 17 to 20 minutes, height about 60 feet. It plays one or more times each day. By day I mean daylight hours, or hours of observation. [Marler 1949b]

How Marler had come to the conclusion that Haynes' "Surprise Geyser" was "Grotto Fountain" is not known.

For some reason, in 1959, Marler again started to use the name of "Surprise Geyser" in his annual reports, instead of "Grotto Fountain". This continued throughout the 1960's; in some instances the name of Grotto Fountain Geyser was also parenthetically used. [Marler 1959a-1971a] But by the early 1970's, the naturalist again decided to strictly use the name of Grotto Fountain Geyser instead of "Surprise Geyser". [see Marler 1970a] Thus the name "Surprise Geyser" has also been finally abandoned.

The name of South Grotto Fountain appears to have come into use by at least the late 1960's. Two previous names included "South True Fountain" given by "Geyser Bill" Ankrom [Ankrom 1931b, Lystrup 1932], and "South Surprise" [Marler 1962a-1969a]. By 1970, when Marler [1970a] reverted to using the name of Grotto Fountain, the name South Grotto Fountain also now appeared in his reports. In his 1973 *Inventory...* [p 103], Marler stated that this feature was "sometimes called South Grotto Fountain."

Unusual Occurrences:

ERUPTIONS OF "MARATHON POOL" IN 1941, 1959 & 1960:

"Marathon Pool" is situated on the opposite side of the Firehole River from Riverside Geyser and just south of the paved walkway. (It was called "Connector Pool" by Scott Bryan [1989] in his 1988 report, *GOSA Transactions*, Vol I, 1989). The name of "Marathon Pool" was originally given by Mike Keller in 1988 to a feature now called "Variable Spring". It lies about 115 feet southeast of Grotto Geyser. This name was then moved the next year to its present position by Lynn Stephens because it was felt this pool was more deserving of the name. Keller and other observers concurred. [Keller 1993]

August, 1941

> New Geyser: At the parking area at the Riverside one of the small pool[s] near the southern end of this area erupted at 3:30 P.M. on the 28th [1941]. The eruption was witnessed by Scotty and Stone. They reported the activity lasting for ten minutes and the height of the eruption about six feet. A considerable

amount of water was discharged and not less than a hundred pounds of rocks were blown from the crater. From the time of the eruption until the present writing the water in the pool has been turbid and boiling. [Marler 1941a]

August, 1959

Marler mentions an eruption of a small spring in the "Riverside parking area" the night of the quake. This may have been "Marathon Pool". [Marler 1959a]

February, 1960

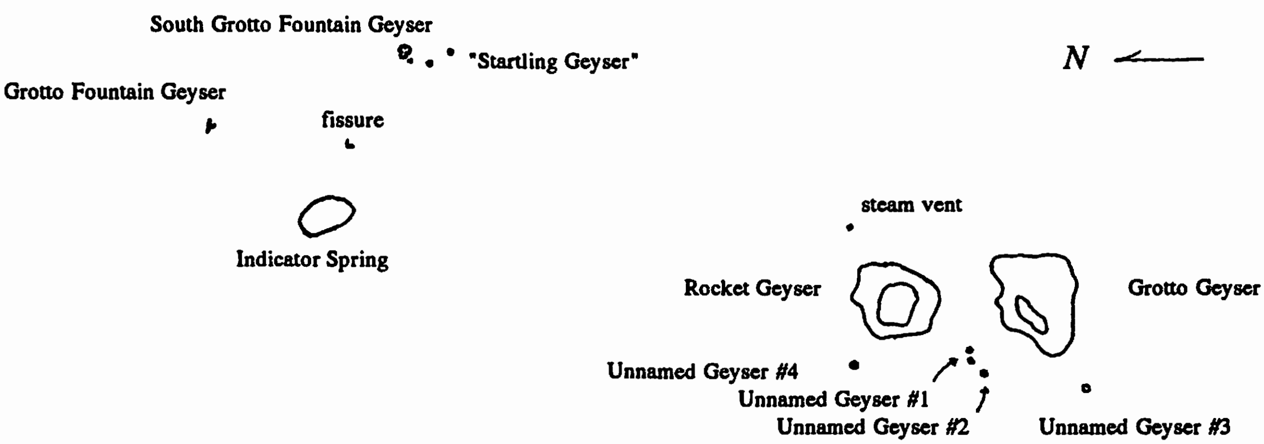
In the Riverside Geyser parking area, an unnamed geyser (small) that has been dormant for several years began erupting in February. The greatly increased discharge over that which was its habit during earlier eruption cycles necessitated closing part of the parking area. Continuous overflow, with lessened activity, continued through the year. [Marler 1960a]

ERUPTION OF INDICATOR SPRING IN 1988:

...on July 27[,1988], Indicator Spring erupted. The play rose above a pool level fully 2½ feet below the rim, yet some of the splashes reached 4 feet above the rim. The play was vigorous and rather violent but also mostly confined by the crater. The roiling water thoroughly stirred the sediment in the bottom of the crater causing the murkiness that was still evident at dark, more than 2 hours later. The duration of the eruption was roughly 4 minutes. The subsequent activity by Grotto Fountain and Grotto did not appear to be altered in any way. [Bryan 1989]

ERUPTION OF "VARIABLE SPRING":

This irregularly shaped spring, so named by Scott Bryan, lies about 120 feet southeast of Grotto. It responds directly to the longer "marathon" eruptions of Grotto Geyser by dropping as much as 3 feet or more by its end. When this spring starts refilling it can have some heavy boiling. In 1989, when some "marathon eruptions" of Grotto were noted to have lasted as much as 24 hours, the activity in this spring was even more pronounced, enough so to describe the subsequent boiling splashes of 3 to 4 feet as an eruption. A number of these were seen this summer by the author and by others. One on June29 reached as high as 4 feet above the level of the pool. [Keller 1993]



MAP OF THE GROTTO & GROTTO FOUNTAIN COMPLEX

Resume of Features in the Grotto & Grotto Fountain Complex:

1 - Unnamed Geyser #1. (Scott Bryan's "Central Vents") This geyser will frequently erupt (from both vents) sometime during an eruption of Grotto; when this occurs, the eruption will usually come toward the beginning of the activity. These eruptions consist of nearly continuous splashing to about 1 to 2 feet. The durations are commonly about 5 to 15 minutes. During the past few years these vents have sometimes started erupting before the start of Grotto (or Grotto Fountain). Usually when this occurs, Grotto (and Grotto Fountain) will follow in about a half hour to 45 minutes, namely, during the next hot period. A few noted exceptions to this have occurred; on these occasions Grotto started erupting while these "central vents" were still going, and without the precursor of Grotto Fountain. (One such occasion reported by Scott Bryan in his report for 1988).

2 - Unnamed Geyser #2. This geyser can either erupt independently, or can erupt along with the two vents of unnamed geyser #1. Maximum height is again from 1 to 2 feet.

3 - Unnamed Geyser #3. I have seen this geyser erupt to over 6 feet with a thin stream of water and sometimes with quite a bit of steam. Every time I've seen it, it has been a few hours into the eruption of Grotto. (See photo below).

4 - Grotto Geyser. In recent years, this geyser has been having frequent "marathon eruptions" of moderate length. In the summer of 1993, there were times when "marathons" occurred every 2 to 3 days. Often, the next eruption of Grotto was initiated without an eruption of Grotto Fountain Geyser.

5 - Rocket Geyser. During the past few years (1990 - 1993) major eruptions of Rocket Geyser have been unusually common. Frequently these eruptions would seem to come about 1½ to 2 hours into the eruption of Grotto. A few spectacular eruptions of this geyser have reached as high as 60 feet and lasted over 10 minutes.

6 - Unnamed Geyser #4. I have seen this geyser erupt on a number of occasions, but much less frequently than the other small vents on the Grotto-Rocket platform. These eruptions invariably occurred well into the eruptions of Grotto. They reached 2 to 3 feet high.

7 - Indicator Spring. The only eruption of this feature that I have been able to substantiate was that reported by Scott Bryan for 1988. (See entry above).

The water level in this pool during most seasons can be a good indicator of an impending eruption of the geysers in this system. While the system is recharging, this pool will very gradually fill. When the level is down about 1 foot, it will usually be about an hour before the Grotto Fountain can erupt. The last couple of inches in the level of the Indicator Spring can fill rather fast when compared to the fill up to that time. Whenever either the Grotto Fountain or the South Grotto Fountain erupt in "minor" fashion during a hot period, this pool will drop several inches. This level can again rapidly rise right before the beginning of the next hot period. During some seasons it has been sometimes observed that Grotto can begin its eruption before this pool completely fills; when this happens, Grotto Fountain will not erupt.

8 - Grotto Fountain Geyser. The terrain about this geyser may be deceptive; this vent becomes a "drain" for Grotto and Rocket well before the Indicator Spring. Its vent is shaped something like a "T". This geyser has been known to erupt as high as 100 feet, although perhaps 50 to 70 feet has been its maximum height during the past decade or so. Known durations have ranged from merely a few seconds to nearly an hour; but those of 5 to 20 minutes are the most common. Eruptive activity in the very early 1980's was not very common; however, by 1984 (and through 1989), activity again was very frequent, preceding most eruptions of Grotto. In 1990 and 1991, eruptions again were not as frequent, nor seemingly as large. By 1993, eruptions were again very common, but perhaps not quite as big as those seen in the mid-1980's. When this geyser erupts, it will invariably presage an eruption of Grotto. Most commonly Grotto will follow in 1 to 5 minutes, although simultaneous starts have been known, and delays of more than 10 minutes have also

GROTTO FOUNTAIN & SOUTH GROTTO FOUNATIN GEYSERS

been recorded. Delays as long as 15 minutes were recorded in 1972. (See photo above).

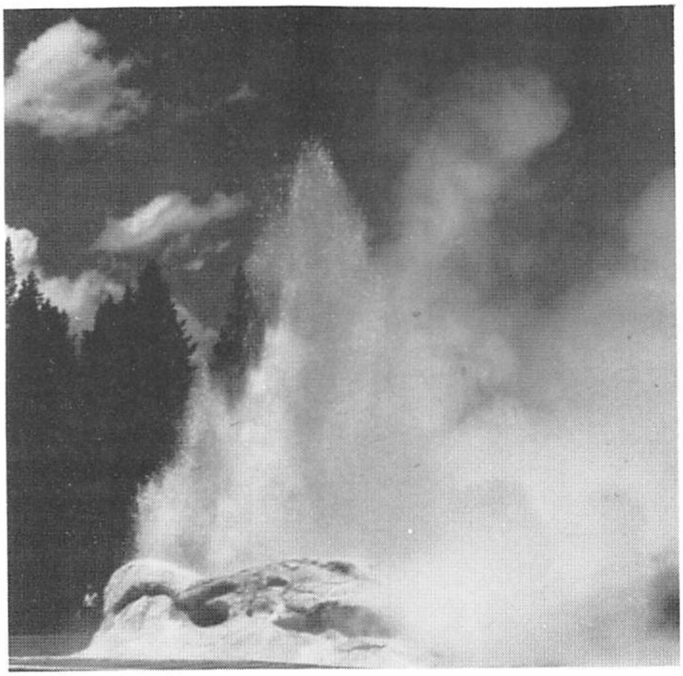
9 - South Grotto Fountain Geyser. This geyser is a smaller edition of Grotto Fountain. It actually has two vents, although eruptions of its secondary vent frequently go unnoticed. It will usually start its eruption a few minutes into an eruption of Grotto Fountain. Maximum heights of 15 to 20 feet have been recorded, but 8 to 15 feet is more usual. This geyser can also erupt alone (during one of the hot periods, and before the start of either Grotto Fountain or Grotto). But these eruptions are usually less vigorous and will frequently stop and start. It has often been reported, (even as long ago as 1931 Ankrom 1931a]), that these independent eruptions of the South Grotto Fountain, which "gets the jump on" the Grotto Fountain (or Grotto itself), can delay the eruptions of these two geysers. Sometimes when this happens, the Grotto Fountain may not erupt at all.

The small secondary vent of this geyser sits in front of the main vent when faced from the road. This vent will usually only play during the stronger eruptions of this geyser, and thus, only when the South Grotto Fountain is playing in tandem with Grotto Fountain. Even then, this secondary vent will only play to a few feet; its water will shoot directly in front of the main vent at an angle to the north.

10 - "Startling Geyser". Scott Bryan has previously referred to this geyser as "South South Grotto Fountain Geyser". The name of "Startling Geyser" was given to this feature in about 1992 by Ann Deutsch. Ann Deutsch, Scott Byran, and Tom Hougham were all awaiting the start of Grotto. "Startling" started playing, and 20 minutes later it played again. Ann said something like (paraphrase): "Wow, that's startling!" And so... [Bryan 1993]

Scott Bryan will be using this unofficial name in the upcoming edition of his book.

This geyser's 2 small vents lie just a few feet south of the South Grotto Fountain Geyser.



GROTTO GEYSER (at start)

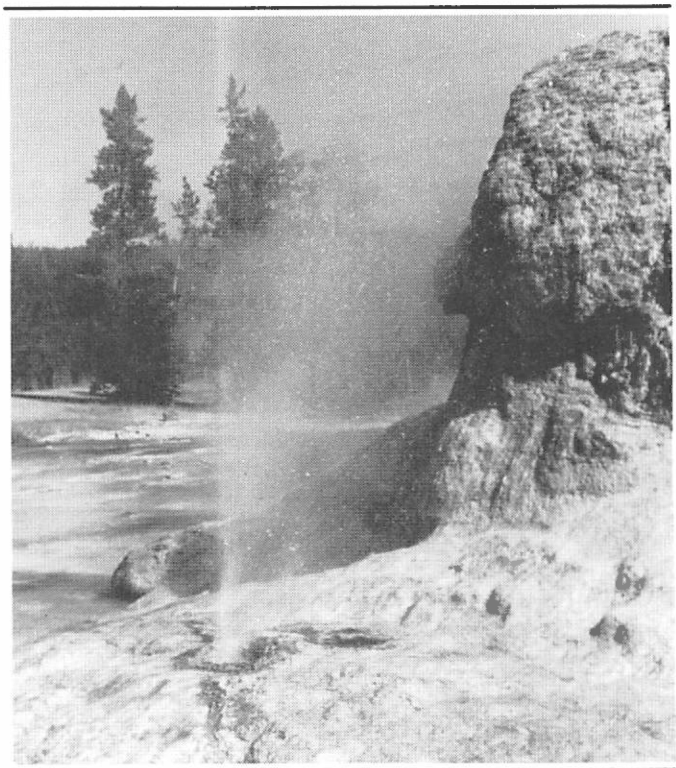
These are actually connected immediately underground. It can infrequently be seen playing with the eruptions of the South Grotto Fountain or even intermittently during Grotto's play. But it can also play independently! These independent eruptions can most often be seen when the "system" is building up for an eruption of Grotto Fountain, and during those hot periods in which there is some minor play of the South Grotto Fountain Geyser. Its maximum height is most commonly only 1 to 3 feet; but on very rare occasions it can even out perform the South Grotto Fountain when it plays in concert with Grotto Fountain. On one occasion I have seen it reach 15 feet high. Although I have not seen any significant play from this vent for the past few years, a couple of these larger eruptions were reported in 1992.

Scott Bryan has also reported that in 1988, this geyser "unfailingly played, to as high as 8 feet, as a precursor to an eruption of Grotto Fountain, leading that play by about an hour. This was a reliable enough indicator to serve as a warning for the impending end of a long-mode interval [of Grotto]. It also preceded the short-mode eruptions. The reliability failed only when there was independent activity by the "Central Vents" [Unnamed Geyser #1].

"South South ["Startling Geyser"] also played consistently to ~15 to 20 feet high throughout the 53+ minute duration by Grotto Fountain on July 5." [Bryan 1989]

Discussion of the Hot Periods of the Grotto Fountain System:

That Fan & Mortar erupt out of a "hot period" has long been recognized. Equally well known are the cyclic hot periods of Riverside Geyser. But less recognized are the hot periods associated with Grotto and the Grotto Fountain Complex.



UNNAMED GEYSER #3

What I had found (in 1984) is that this system too has hot periods; they seemed to occur about every 45 to 50 minutes. In later years I noted some hot periods as short as a half hour. In 1993, those few hot periods which I timed, were all in the 40 to 50 minute range. The Grotto Fountain will only erupt during the peak of one of these hot periods which will last for only 5 to 10 minutes. The "first" hot period will come at about the time that the Indicator Spring first fills.

At the times of these hot periods both the South Grotto Fountain and #10 ("Startling Geyser") may begin their minor play. Grotto Fountain will also have some minor play. Both "Fountains" will overflow into the Indicator Spring. This minor play will coincide with the lowering of the water in the Indicator Spring by several inches. This minor play can last a good portion of the 45 to 50 cycle, but Grotto Fountain, if it erupts, will erupt well toward the beginning of this period. In was my observation both in 1984, and again in 1993, that it was commonly the second hot period during which the Grotto Fountain erupted. But eruptions out of the 1st and 3rd hot periods are not uncommon.

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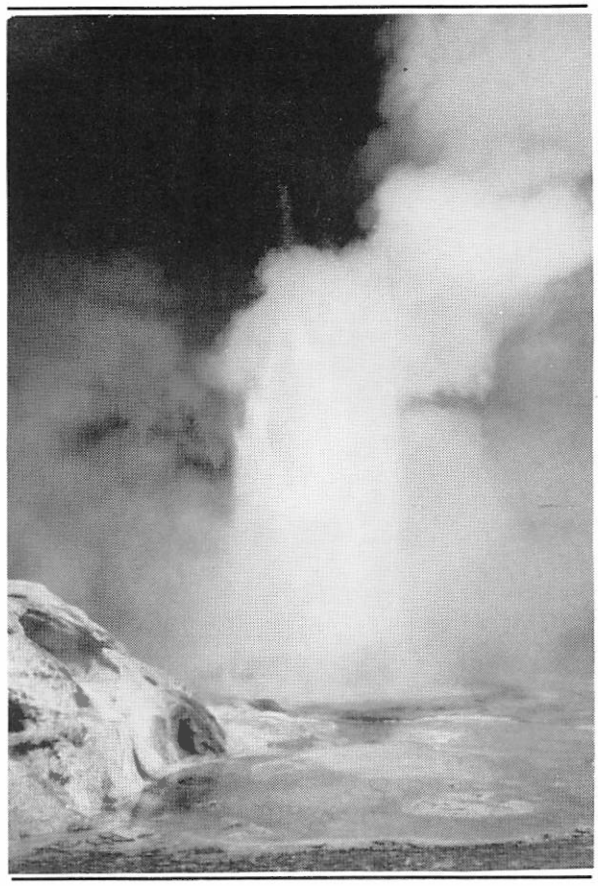

ROCKET GEYSER

FOUNTAIN GEYSER, ACTIVITY DURING SUMMER 1991, LOWER GEYSER BASIN, YELLOWSTONE NATIONAL PARK

Lynn Stephens

ABSTRACT: During June and July 1991, Fountain generally erupted from a nonoverflowing pool with intervals of 7.5 hours and durations of 40 minutes. However, a short time prior to Morning's activity on July 4-5 and in August, Fountain's intervals increased in length and variability, showing a second type of behavior. A third type of behavior occurred on July 4 and 5, and August 9, 28, and 29 when Fountain erupted in concert with Morning Geyser. These concerted eruptions were not earthquake induced. Instead, they seemed to be an aboveground manifestation of an underground exchange of function between Fountain and Morning where the energy was balanced between the two. Following the August 9 concerted eruption, the energy shifted completely to Morning, as evidenced by Morning's solo eruptions and Fountain's dormancy for August 10 through 27. Fountain's behavior from August 29 through early September demonstrated a fourth type of activity in 1991. This paper presents an analysis of Fountain Geyser's activity from late May through early September 1991.

INTRODUCTION

Fountain Geyser, located in the Lower Geyser Basin, is the namesake geyser for the Fountain Complex, which includes two major geysers--Fountain and Morning. Over the years, Fountain has shown a variety of eruptive behavior patterns, including years of dormancy.[1]

One of the reasons for variations in Fountain's behavior has been (in)activity by Morning. Since the 1959 earthquake, when Fountain has been active, Morning has not, and when Morning has been active, Fountain has not. Morning was active in 1973,[2] 1978, 1981, 1982, and 1983. The energy in the Fountain Complex shifted back and forth between Fountain and Morning at various times in those years. The last eruption of Morning recorded prior to 1991 occurred on February 10, 1983.[3] Since 1983, Fountain has most commonly erupted from an overflowing pool with intervals of about 11 hours and durations of about 60 minutes.[4]

During the summer of 1991, Fountain usually erupted from a nonoverflowing pool with intervals of about 7.5 hours and durations of about 40 minutes. This change in behavior was accompanied by a rejuvenation of Morning, and exchanges of function in the Fountain Complex, or shifts of energy between Fountain and Morning. Energy in the Fountain

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[1] See Marler [1973] and Whittlesey [1988] for discussions of Fountain's eruptive history. Rocco Paperiello has located additional historical references in the Yellowstone National Park Library at Mammoth. Now that Marler's papers are available at Brigham Young University, future research may uncover additional changes in the historical record of Fountain's eruptive activity.

[2] Activity listed in Bryan [1991] and Whittlesey [1988] as 1974 is apparently a typographical error since neither lists 1973 as an active year. Records of activity by Morning in 1973 have been located, but no records of activity by Morning in 1974 have been located.

[3] The entry in the geyser log maintained at the Old Faithful Visitor's Center (OFVC) for this eruption contains the notation "probable delayed response to tremors on Sunday 02/06/83." This is the only eruption recorded in 1983.

[4] Any statement about geysers is subject to exceptions. Bryan [1991, p. 144] notes that "...eruptions may last anywhere from 35 to 60 minutes, but the usual duration is just about 50 minutes." About Fountain's intervals, Bryan states "[M]ost of the time they average about 11 hours...but Fountain sometimes...doubles its frequency, maintaining 5-1/2 hour intervals for a few days before lapsing back to the normal....Though uncommon, Fountain will sometimes maintain 4- to 6-hour intervals over an extended period..." In June 1988, Fountain was erupting at comparatively long intervals--sometimes in excess of 20 hours. Generally, Fountain erupted at 11-12 hour intervals during much of 1988, and for 1989 and 1990. Bower [1992, p. 54] noted "[O]ften, Fountain erupted on a regular pattern of 11-12 hour cycles" in 1990.

TABLE 1. Activity of Fountain Geyser May 5, July 4-6, and August 9, 28 and 29

Date	Time	Duration (in minutes)	Interval Before	Comments
5/5	17:23	62	>32 hrs	Solo
		Interval after unknown		
7/4	14:40	95	unknown	Concerted
7/4	22:26	50	7h 46m	Solo
7/5	13:43	81	15h 17m	Concerted
7/6	13:22	40	23h 39m	Solo
7/6	21:56	unk.	8h 43m	Solo
		Double interval after 12h 50m		
8/9	19:23	122	9h 19m	Concerted
8/28	18:53	140	18d23h30m	Concerted
8/29	12:14	98	17h 21m	Concerted
8/29	21:02	unk.	8h 47m	Solo
		Interval after 11h 0m		

Complex made a complete shift from Fountain to Morning sometime before 09:38 on May 4. Between 00:45 and 17:23 on May 5, the energy shifted from Morning back to Fountain. The energy made another complete shift from Fountain to Morning again overnight on August 9-10, and stayed with Morning until August 28, when it started a shift back to Fountain. This shift was completed by the evening of August 29.[5]

This paper describes and analyzes behavior patterns exhibited by Fountain Geyser during the summer of 1991. The first section briefly reviews Fountain's behavior during the energy shifts: May 5 when the energy shifted from Morning to Fountain; July 4-6 when the energy attempted to shift from Fountain to Morning but failed to complete the transition; August 9 when the energy shifted from Fountain to Morning; and August 28, and 29, when the energy shifted from Morning back to Fountain. The second section discusses Fountain's behavior for May 26 to July 3 and July 7 to August 9. The activity of Fountain Geyser during this time frame is termed "Fountain Mode". The third section discusses Fountain's behavior from August 29 through early September. This activity is termed "Recovery Mode" because (1) it occurred after Fountain's dormancy while Morning was active, and (2) Fountain's behavior pattern was different from the behavior in Fountain Mode.

MAY 5; JULY 4-6, AUGUST 9, AND AUGUST 28 AND 29--EXCHANGES OF FUNCTION BETWEEN FOUNTAIN AND MORNING

Table 1 summarizes Fountain's activity in 1991 during exchanges of function between Fountain and Morning.

Morning was active on May 4 and 5, erupting from a nonoverflowing pool at 3 to 5 hour intervals. Sometime following an eruption of Morning that started at 00:25 on May 5, the energy shifted back to Fountain. Fountain erupted at 17:30 (d=62m, I>32h) on May 5. The Fountain interval succeeding this eruption is not known.

This exchange of function is termed "complete" exchange of function. The energy shift was accomplished without an intermediate equilibrium point where the energy was balanced between Fountain and Morning enabling the two geysers to erupt in concert.

Prior to 1991 the only observed concerted eruption of Fountain and Morning occurred on August 17-18, 1959. The Hebgen Lake, earthquake clearly induced this concerted

[5]See Stephens [1992a] for discussion of activity by Morning Geyser and other geysers in the Fountain Complex on May 4 and 5, 1991. The first observed eruption of Morning's May activity was sighted at 09:38ie on May 4. R. Hutchinson, Park Geologist, stated this was probably not the first eruption of Morning in this series, based on his observations of the clarity of the water and erosion in the runoff channels. Also, see Stephens [1992b] for a discussion of activity in the Fountain Complex on July 4-6, 1991, and Stephens [1992c] for activity in the Fountain Complex on August 8, 28, and 29, 1991.

eruption.[6] The July 4 and 5, and August 9, 28, and 29, 1991, concerted eruptions of Fountain and Morning were historically unprecedented in that none was earthquake induced. These exchanges are termed "partial exchanges" because there was an intermediate equilibrium point where neither Fountain nor Morning completely captured the energy away from the other, but instead the two erupted simultaneously.

Following the May 5 energy shift, Fountain retained the energy until sometime July 3-4. At 14:40 on July 4, Fountain erupted (d=95m, I unknown). Morning started 14:42 (d=31m, I=60d14h17m). Apparently, the energy attempted to shift to Morning but failed to complete the shift. The solo Fountain eruption at 22:26 on July 4 (d=50m, I=7h46m) seemed to indicate the energy was back with Fountain. However, there was another partial energy shift on July 5 when Fountain (13:43, d=81m, I=15h17m[7]) and Morning (13:45, d=21m, I=23h3m) erupted in concert again. Again the attempted energy shift failed. On July 6 Fountain erupted solo at 13:22 (d=40m, I=23h39m), and again at 21:56 (d unknown, I=8h34m). Fountain retained the energy August 9.

Another partial exchange occurred on August 9. Sometime between 10:04, when Fountain erupted solo, and 19:23 (d=122m, I=9h19m) when Fountain erupted in concert with Morning (19:24, d=38.5m, I=34d5h38m), the energy again moved away from Fountain toward Morning. This time, after the concerted eruption, the energy shift continued, completing the shift to Morning. The shift took less than 10 hours. Morning erupted solo at 0:516 on August 10.[8] Morning was active from August 10 through August 28 and Fountain was dormant.

Morning's last solo eruption of 1991 occurred at 11:38 on August 28. Sometime between the end of that eruption and 18:53 another partial energy shift took place. Fountain erupted at 18:53 (d=140m, I=18d23h30m) and Morning joined in within a minute (d=36m, I=7h15m).

This time the partial energy shift lasted much longer, allowing another concerted eruption at 12:14 on August 29 (Fountain 12:14, d=98m, I=17h21m; Morning 12:15, d=27m25s, I=17h22m). Fountain initiated this concerted eruption, just as it had initiated the other four concerted eruptions. After this concerted eruption, the shift of energy toward Fountain continued. Fountain erupted solo at 21:01 on August 29 (d unknown, I=8h47m). Fountain was not yet back to 1991 "normal", as will be discussed in the section on "Recovery Mode". However, Fountain had recaptured the energy, and as of early March 1993, has retained it.

Fountain's duration on May 5 was not unusually long compared to Bryan's [1991] 35-60 minute range. The only information I have located about Fountain's durations for initial eruptions after an active period by Morning indicates that the 62 minute duration could be considered short. Hutchinson [1982] reported that on July 15, 1982, Grover Schrayer and David Scheel witnessed what was apparently an initial eruption of Fountain following an active period by Morning. They saw the eruption at 20:43, within three minutes of the start. The eruption had not ended when they

[6]See Marler [1964 and 1973] for discussion of the effects the earthquake had on geysers in the Fountain Complex. Technically, the 1959 and 1991 eruptions were concerted eruptions of Fountain, Morning, and Clepsydra. Since Clepsydra erupts constantly except for pauses sometimes following Fountain's eruptions, and on rare occasions between eruptions of Morning, Clepsydra is generally ignored when the concerted eruptions of Fountain and Morning are discussed.

[7]Although no marker was placed on Fountain after the 22:26 eruption on July 4 ended, observations of the water level in Fountain's crater at 06:00 on July 5, lack of water around Fountain's crater at that time, and activity by other geysers in the Fountain Complex indicated that Fountain had not erupted.

[8]I did not place a marker on Morning after the August 9 concerted eruption ended so it is possible that Morning could have erupted before the 05:16 eruption. Also, as Ralph Taylor has pointed out, length of time between aboveground events may not indicate the amount of time required for any of the energy shifts. For example, the energy could have shifted to Morning immediately after the end of Fountain's portion of the August 9 concerted eruption but did not manifest itself aboveground until Morning's first solo eruption.

left at 00:52, a duration exceeding 4 hours. Compared to the duration of this eruption, the 62 minute duration on May 5 was relatively short. Indeed, Fountain's durations for the concerted eruptions on August 28 (140m) and 29 (98m) when the energy was switching from Morning back to Fountain also appear comparatively short.

On May 5 the interval between Morning's last eruption and Fountain's first eruption was 16 hours 58 minutes. This interval is similar to intervals between Morning and Fountain observed in 1982.

During the summer of 1982, Fountain and Morning alternated periods of activity. Data from the OFVC geyser log shows Fountain active through at least May 26. The next entry about these two geysers is an eruption of Morning on June 16. Morning remained active through an eruption recorded "early am" on July 15. The eruption of Fountain that Schrayer and Scheel witnessed followed this eruption of Morning. If "early am" is interpreted conservatively (00:01), at most the interval between Morning and Fountain was about 20 hours 40 minutes.

The next eruption of Morning listed is 13:45 on July 28, 1982. The energy returned to Fountain on July 31, with an interval of 13 hours 37 minutes between Morning and Fountain eruptions. The next Morning eruption shown is on August 14, followed by a Fountain eruption 19 hours 46 minutes later.

The next entry is a Fountain eruption on August 18, then Morning on August 22, 23, 25, 26, and 27. The August 27 eruption of Morning was followed by an eruption of Fountain at 22:58, an interval of 13 hours 56 minutes. Even though Morning was erupting at longer intervals, from an overflowing pool, and with longer durations in 1982 than it did in 1991, the 1991 interval between Morning and Fountain eruptions was similar to 1982 intervals.

MAY 26 TO JULY 3 AND JULY 7 TO AUGUST 9--FOUNTAIN MODE

Two sources provided data on Fountain's activity during this time. The OFVC geyser log provided data for eruptions of Fountain Geyser for May 26 to July 3 and July 7 to 20. The log lists 61 eruptions during those times. Since these are scattered over 50 days, there are very few recorded consecutive eruptions. Six exact durations are noted. I began a study of the Fountain Complex on July 21. Between July 22 and August 9, 42 eruptions of Fountain were recorded. Markers were used to verify 12 additional eruptions. Exact durations were obtained for 32 eruptions.

The first part of this section discusses Fountain's durations. Analysis of recorded times for Fountain's durations during Fountain Mode showed very little variability in the data across time, so the only analysis presented here is an overall analysis.

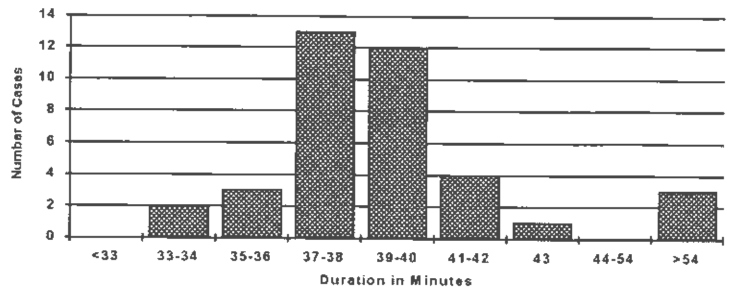
The second part of this section discusses Fountain's intervals. Examination of the data on Fountain's intervals showed distinct discontinuities, or sub periods. Results of the analysis are presented for the complete period and for sub periods.

DURATIONS: Figure 2 shows the distribution of the 38 durations used in this analysis.[9] The durations range from a minimum of 34 minutes to a maximum of 58 minutes. The durations have a median of 38 minutes and a mean of 40.0 minutes, with a standard deviation of 8.0 minutes. Sixty-six percent of the durations are 37 to 40 minutes in length, and 84% are 37 to 42 minutes long.

There are no recorded durations between 44 and 54 minutes. The three durations exceeding 54 minutes were 55 minutes for the 08:56 eruption on July 21, 58 minutes for the 01:02 eruption on July 28, and 59 minutes for the 09:41 August 5 eruption. Excluding the times when Fountain erupted in concert with Morning, the solo eruption of Fountain on July 4 between the July 4 and 5 concerted eruptions, and the 17:23 eruption of Fountain

[9]One duration shown in the OFVC geyser log on July 2 as ">40m" was not used in this analysis.

FIGURE 1. Fountain's Durations May 26-July 3 and July 7-August 9

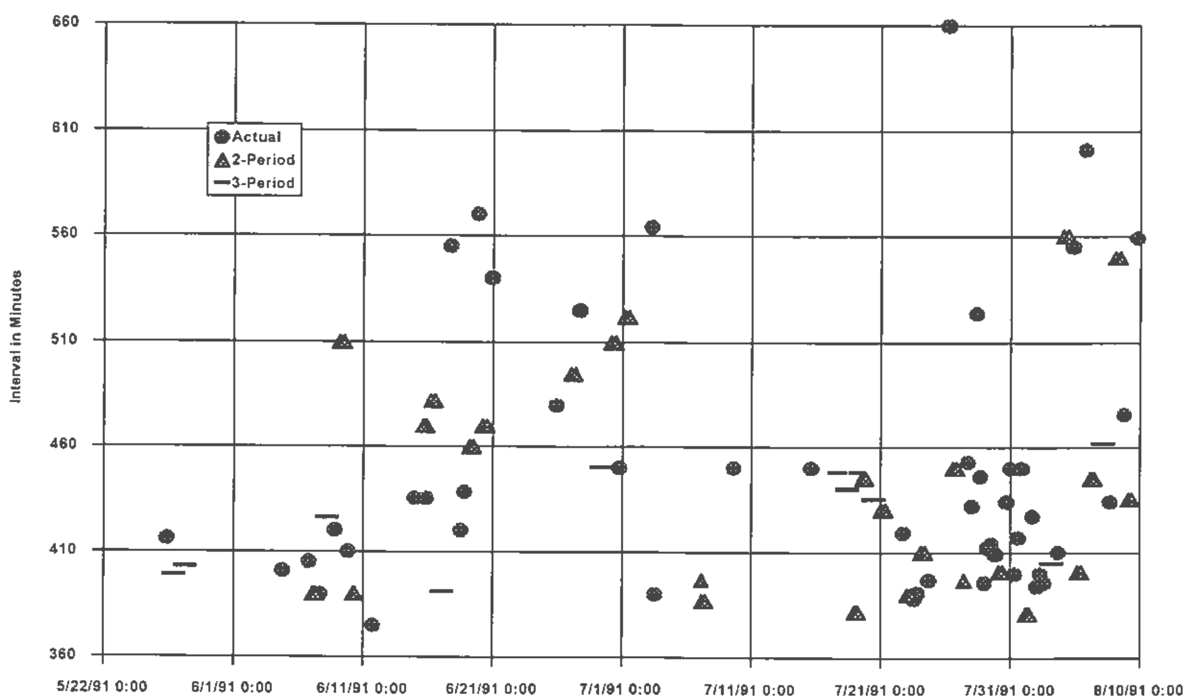


on May 5 after Morning had ceased activity, these are the only known Fountain durations exceeding 45 minutes during the summer of 1991.

Neither the interval preceding nor the interval succeeding the July 21 eruption is known. The interval preceding the 01:02 eruption on July 28 was 7h15m, and the succeeding interval was 8h45m. The interval preceding the 09:41 August 5 eruption is not known, but the average for the two intervals preceding it was 6h40m. The succeeding interval was 10 hours. In both cases where the preceding interval is known, or can be estimated, the preceding interval appeared to be normal Fountain Mode. But in both cases where the succeeding interval is known, durations exceeding 54 minutes were followed by a interval much longer than the 1991 Fountain Mode average interval of 7h30m.

INTERVALS: Figure 2 shows Fountain's intervals for May 26 to August 9, excluding July 4-6. Intervals used in this figure include actual intervals, approximated intervals from "ns" and "ie" times, and average intervals for two and three interval averages where averages could be estimated. Visual examination of the intervals for May 26-July 3 shows intervals in late May and early June had less variation and were shorter than intervals in mid to late June. Examination of the actual and

FIGURE 2. Fountain Intervals May 26-July 3 and July 6-August 9



Note: The interval overnight on July 25-26 that exceeded 16 hours is shown on the graph as 11 hours (660 minutes).

approximated intervals showed the first known closed interval exceeding 450 minutes occurred on June 17. Therefore, the period May 26-July 3 was divided into two sub periods of May 26-June 16 and June 17-July 3.

After the concerted eruptions of Fountain and Morning on July 4 and 5, Fountain's intervals appear to be relatively stable until July 25-26, when Fountain had an interval known to exceed 16 hours. Then, the intervals appear to stabilize again until sometime on August 3. Between August 4 and the concerted eruption of Fountain and Morning on August 9, the pattern shown by the intervals looks more like the June 17 to July 3 pattern than the July 7 to August 3 pattern.

Results of analysis are presented for each time frame analyzed separately: (a) overall period May 26 to August 9; (b) May 26 to July 3 combined, with sub periods May 26-June 16 and June 17-July 3; and (c) July 7 to August 9 combined, with sub periods July 7-to August 3 and August 4-9. Then results are presented for May 26 to June 17 combined with July 7 to August 3 (termed "Fountain Mode A") compared with June 17 to July 3 combined with August 3 to August 9 ("termed "Fountain Mode B").

Computation of Intervals: Table 2 shows the number of intervals used in various segments of the analysis. From May 26 through July 20 many of the observations listed in the OFVC geyser log are shown as "ns" or "ie". A few of the July 21 to August 9 eruptions are also recorded as "ns" or "ie". Near start times were treated as actual start times for computing intervals. For observations listed "ie", the difference between listed times was rounded to the nearest 15 minutes.

TABLE 2. Computation of Intervals

	5/26-6/16	6/17-7/3	7/7-8/3*	8/4-8/9	Total
Single Intervals:					
Actual	3	2	19	4	28
Actual/IE	6	7	5	1	20
IE/IE	-	1	-	-	1
Total	9	10	24	5	48
2-Interval Averages	10	10	20	10	50
3-Interval Averages	9	6	12	3	30
Total	28	26	56	18	128
Anomalies	1	2	1		

	5/26-7/3	7/7-8/9*	5/26-6/16 & 7/3-8/3*	6/17-7/3 & 8/4-8/9
Single Intervals:				
Actual	5	23	22	6
Actual/IE	13	6	12	8
IE/IE	1	-	-	1
Total	19	29	34	15
2-Interval Avg.	20	30	29	20
3-Interval Avg.	15	15	21	9
Total	54	74	84	44

*Excludes the >16 hour interval overnight on July 25-26.

Although computing double and triple interval averages for Fountain during the summer of 1991 is dangerous because of the known interval exceeding 16 hours on July 25-26, estimates were made to determine other possible anomalies and to assess the impact the estimates would have on computations of averages. I made no estimates for cases where elapsed time between reported eruptions was less than 12 hours 30 minutes or more than 24 hours. When elapsed time between reported eruptions was from 12 hours 30 minutes to 18 hours 30 minutes, I assumed this represented a double interval. Twice the longest actual interval would have been 19 hours and three times the shortest actual interval would have been 18 hours 45 minutes, but I decided the two cases of 18 hours 30 minutes were too close to make an estimate. I assumed elapsed times between reported eruptions ranging from 19 hours 30 minutes to 22 hours 30 minutes represented two missed eruptions, or triple intervals.

Overall Fountain Mode--May 26 to August 9: Table 3 shows results of the analysis for May 26 to August 9, excluding July 4-6 and overnight July 25-26.

Seventy-two percent of the intervals are between 6h15m and 7h30m, although the range is from 6h15m to 10h. The overall median is 7h15m, and the mean is 7h25m. The stability of the results is due in part to the fact that if, for example, three consecutive intervals of 8h30m had occurred with an elapsed time of 25h30m, no attempt to evaluate elapsed times that long was made.

No matter which data set is used, the statement that Fountain was erupting on average at 7.5 hour intervals for the summer of 1991 while the Fountain Complex was operating on Fountain Mode is supported by the data. But this overall analysis obscures separate patterns of activity within this overall Fountain Mode.

TABLE 3. Distribution of Intervals for May 26-August 9+

Length (in minutes)	Single Intervals (A)		2-Interval Averages (B)	(A+B)		3-Interval Averages (C)	Total (A+B+C)	
361-390	4	8.3%	12	16	16.3%	-	16	12.5%
391-420	19	39.6	8	27	27.6	12	39	30.5
421-450	13	27.1	10	23	23.5	15	38	29.7
451-480	3	6.3	6	9	9.2	3	12	9.4
481-510	-	-	8	8	8.2	-	8	8.2
511-540	3	6.3	2	5	5.1	-	5	3.9
541-570	5	10.4	4	9	9.2	-	9	7.0
>570	1	2.1	-	1	1.0	-	1	0.8
Total	48	100.1%*	50	98	100.1%*	30	128	100.1%*
Minimum	375			375			375	
Maximum	601			601			601	
Median	429.5			435			435	
Mean	446			446			441	
Standard Deviation	57.5			55.7			50.8	

+Excludes the >16 hour interval on July 25-26.
*Does not add to 100.0% due to rounding.

TABLE 4. Intervals for May 26-June 16 (Fountain Mode A)

Length (in minutes)	Single Intervals (A)		2-Interval Averages (B)	(A+B)		3-Interval Averages (C)	Total (A+B+C)	
<361	-	-	-	-	-	-	-	-
361-390	2	22.2%	4	6	31.6%	-	6	21.4%
391-420	5	55.6	-	5	26.3	6	11	39.3
421-450	2	22.2	-	2	10.5	3	5	17.9
451-480	-	-	2	2	10.5	-	2	7.1
481-510	-	-	4	4	21.2	-	4	14.3
511-540	-	-	-	-	-	-	-	-
541-570	-	-	-	-	-	-	-	-
>570	-	-	-	-	-	-	-	-
Total	9	100.0%	10	19	100.0%	9	28	100.0%
Minimum	375			375			375	
Maximum	435			510			510	
Median	410			416			407.5	
Mean	410			430			423	
Standard Deviation	18.6			42.7			37.1	

May 26-June 16: Table 4 shows results for May 26 through June 16.

Twenty-three eruptions of Fountain are listed in the OFVC geyser log for May 26 through June 16. Eight of the times listed are start times; seven are "ns"; and eight are "ie". Three single intervals were computed using consecutive eruptions with actual and "ns" times. Six single intervals were estimated using consecutive eruptions where one observation was either start or "ns" and the other observation was "ie". There were no consecutive eruptions where both times were listed "ie".

There are nine single interval observations. They range from a minimum of 6h15m to a maximum of 7h15m, have both a median and a mean of 6h50m, and a standard deviation of 18.6m.

There are five cases where elapsed time between observations was 13 to 17 hours. Assuming that these represent one missed eruption, 2-interval averages were computed. The 2-interval average is higher than the single interval. Two of the five cases yield an average of 6h30m; one case results in a 7h50m average; one case has an 8h average, and the fifth case has an 8h30m average. When these intervals are added to the single intervals, the median increases by 6 minutes to 6h56m. The mean increases by 20 minutes to 7h10m, and the standard deviation increases to 42.7m.

Elapsed time between observations is 20-22 hours in three cases. Assuming that these represent two missed eruptions, 3-interval averages were computed, with resulting averages of 6h39m, 6h43m, and 7h6m. If these are combined with the closed intervals and 2-interval averages, the median decreases by 8.5 minutes to 6h47.5m, the mean decreases by 7 minutes to 7h3m, and the standard deviation decreases to 37.1m.

There is one case where elapsed time between observations was 27h23m. No attempt was made to estimate the number of intervals for this case.

TABLE 5. Intervals for June 17-July 3 (Fountain Mode B)

Length (in Minutes)	Single Intervals (A)		2-Interval Averages (B)	(A+B)		3-Interval Averages (C)	Total (A+B+C)	
361-390	1	10.0%	-	1	5.0%	-	-	3.8%
391-420	1	10.0	-	1	5.0	3	4	15.4
421-450	2	20.0	-	2	10.0	3	5	19.2
451-480	1	10.0	4	5	25.0	-	5	19.2
481-510	-	-	4	4	20.0	-	4	15.4
511-540	2	20.0	2	4	20.0	-	4	15.4
541-570	3	30.0	-	3	15.0	-	3	11.5
Total	10	100.0%	10	20	100.0%	6	26	100.0%
Minimum	390			390			390	
Maximum	570			570			570	
Median	512.5			495			470	
Mean	493			492			476	
Standard Deviation	62.5			47.2			53.2	

There is one case where elapsed time between observations does not seem to clearly fit either a 2- or 3-interval average. On May 28-29 elapsed time between an actual start at 13:02 on May 28 and an eruption recorded 07:28ie on May 29 was 18h26m. Assuming a 1991 average duration of 40 minutes and that the "ie" was at the very end of the eruption, the time between starts would have been 17h46m--a 2-interval average of 8h53m, or a 3-interval average of 5h55m. Assuming that the "ie" was at the very beginning of the eruption, elapsed time would have been 18h26m--a 2-interval average of 9h13m, or a 3-interval average of 6h13m. The only one of these averages outside the range of observed single intervals during the 1991 season is the 5h55m average, but consecutive intervals with these numbers were seldom observed. Of course, either one of these cases could actually have been a closed interval, in light of the July 25-26 closed interval exceeding 16 hours.

June 17-July 3: Table 5 shows results for June 17-July 3. Twenty-two eruptions are listed in the OFVC geyser log for June 17-July 3. Eight are shown as starts, four as "ns", nine as "ie", and for one observation an end time is listed. Two intervals were computed using consecutive eruptions with actual and "ns" times. Seven single intervals were estimated using consecutive eruptions where one observation was either start or "ns" and the other observation was "ie". One interval was computed using two consecutive eruptions where both times were listed "ie".

This provided 10 single interval observations. The 10 intervals range from a minimum of 6h30m to a maximum of 9h30m; have a median of 8h32.5m, a mean of 8h13m, and standard deviation of 62.5m.

There are five cases where elapsed time between observations was 15h15m to 17h30m. Assuming that these represent one missed eruption, 2-interval averages were computed. Listed chronologically, the averages were 7h40m, 7h50m, 8h15m, 8h30m, and 8h45m. When these intervals are added to the single intervals, the median drops by 17.5 minutes to 8h15m. The mean only decreases by one minute to 8h12m. Standard deviation decreases to 47.2m.

There are two cases where elapsed time between observations indicate that probably two eruptions were missed. Overnight June

TABLE 6. Intervals for May 26-July 3

Length (in Minutes)	Single Intervals (A)		2-Interval Averages (B)	(A+B)		3-Interval Averages (C)	Total (A+B+C)	
361-390	3	15.8%	4	7	17.9%	-	7	13.0%
391-420	6	31.6	-	6	15.4	9	15	27.8
421-450	4	21.1	-	4	10.3	6	10	18.5
451-480	1	5.3	6	7	17.9	-	7	13.0
481-510	-	-	8	8	20.5	-	8	14.8
511-540	2	10.5	2	4	10.3	-	4	7.4
541-570	3	15.8	-	3	7.7	-	3	5.6
Total	19	100.1%*	20	39	100.0%	15	54	100.1%*
Minimum	375			375			375	
Maximum	570			570			570	
Median	435			470			436.5	
Mean	454			462			449	
Standard Deviation	62.9			54.8			52.5	

*Does not add to 100.0% due to rounding.

16-17, time between observations was 19h30m, a 3-interval average of 6h30m. On June 29, time between observations was 22h30m, a 3-interval average of 7h30m. When these six estimated intervals are added to the other intervals, the median decreases another 25 minutes to 7h50m, the mean decreases by 16 minutes to 7h56m, and standard deviation increases to 53.2m.

No attempt at estimating the number of intervals involved was made for two cases with elapsed times between observations of 26h50m and 32h40m.

There are two cases where elapsed time between observations doesn't seem to fit Fountain's 1991 normal behavior, although both probably fit Fountain Mode B activity. One case where elapsed time didn't lend itself to estimating average intervals was on June 25-26 when elapsed time between observations was 18h30m. The 2-interval average would have been 9h15m; 3-interval average would have been 6h10m. The 2-interval average of 9h15m doesn't conflict with Fountain Mode B activity. Three consecutive intervals of 6h10m is at the very low end of Fountain Mode A activity. Either is possible, so neither was used in computing any statistics.

The other case occurred on June 17-18 when a single interval of 9h15m was followed by elapsed time of 11h55m, from 18:30 "ns" on June 17 to 06:40ie on June 18 (end 07:03). Assuming the 06:40ie/07:03end had an average 1991 duration of 40 minutes, it would have started about 06:25. In my opinion, the 2-interval average of just under 6 hours is much less likely than a single interval of 11h55m. The closed interval of 9h15m that preceded this 11h55m elapsed time was one reason for splitting the May 26-July 3 time frame into subperiods of May 26-June 16 and June 17-July 3. This possible 11h55m interval, or two consecutive 6 hour intervals adds support to the conclusion that something happened in the Complex on June 17.

May 26-July 3: Table 6 shows results for May 26-July 3. An overall analysis for this period is presented because it represents Fountain's activity between Morning's activity in May and Morning's next activity on July 4 and 5.

The 19 single interval observations for May 26-July 3 range from a minimum of 6h15m to a maximum of 9h30m, with a median of 7h15m, a mean of 7h34m, and a standard deviation of 62.9m. When the 2-interval averages are added to the single interval observations, the 39 observations have the same range, but the median increases by 35 minutes to 7h50m. The mean only increases by eight minutes to 7h42m, and standard deviation decreases to 54.8m. When the 3-interval averages are added, the 54 observations have the same range. The median drops 34 minutes to 7h16m. The mean drops 13 minutes to 7h29m, and the standard deviation is 52.5m.

July 7-August 3: Data on Fountain eruptions for July 7 to 20 was extracted from the OFVC geyser log. Twelve eruptions are listed--six with actual starts, five "ie", and one is shown "ie" with an end time also noted. One additional notation of a "posteruption" time confirmed a missed eruption for computation of a 2-interval average. From July 21 through the 16:23 eruption on August 3, 32 eruptions were observed. For three of these, observation of the eruption was "ie". Seven additional eruptions were verified through the use of markers.

Fountain had a very long interval July 25-26, possibly indicating an attempted exchange of function between Fountain and Morning. I was not at the Complex during the day on July 25. Observers at Great Fountain during the day on July 25 did not see a steam cloud from Fountain, although they indicated they were watching for one. Using the 1991 average interval, I estimated a Fountain eruption for early evening on July 25. The average for July 21-24 had been 6h40m. Four 6h30m intervals would have put Fountain's eruption at about 18:30 on July 25. When I arrived at 19:30, the water level in Fountain had risen enough to cover all the rocks inside the inner crater and was nearing the point where it would start up the ramp leading to overflow. This indicated that Fountain had not erupted for several hours. Fountain was under observation until 01:00 on July 26, and still had not erupted.

Fountain was in eruption when I returned at 06:09 on July 26, an interval exceeding 16 hours--the 10.5 hours between 19:30 July 25 and ~~06~~:00 July 26 plus 5.5 hours for the water level to reach the point where all the rocks in the inner crater were covered. The eruption ended at 06:49, a duration exceeding 40 minutes. A marker was placed on Fountain after this eruption ended.

When I returned at 14:30, Fountain had already finished an eruption, as indicated by the missing marker. Assuming a 1991 average duration of 40 minutes, the eruption started before 13:50. Fountain was back to 1991 Fountain Mode. The >16 hour interval is not included in the analysis of the July 7 to August 3 intervals.

Table 7 shows results of the analysis of intervals for July 7 to August 3. Nineteen single intervals were computed using consecutive actual starts. Five more were estimated using an actual start combined with an "ie" observations, for a total of 24 single interval observations. The closed intervals range from a minimum of 6h28m to a maximum of 8h44m. The median is 6h55m, and the mean is 7h3m, with a standard deviation of 30.0m.

Missed eruptions were assumed when elapsed time between recorded observations was 17h44m on July 18-19 (6h22m average) and 14h21m on July 21 (7h10m average). On July 19, the notation in the OFVC geyser log indicating "1439 posteruption" confirms a missed eruption between two observations, for a 7h30m average. Markers were used overnight July 6-7 to conirm a missed eruption with a 6h27m average, July 22-23 for a 6h30m average, July 23-24 for a 6h50m average, July 26-27 for a 6h37m average, July 29-30 for a 6h41m average, and July 31-August 1 for a 6h21m average. As previously noted, a marker combined with observation of the water level was used on July 26 to confirm a missed eruption for an average of 7h30m.

When the 20 2-interval averages are combined with the single interval observations, the statistics are not significantly affected. The range changes slightly, with the minimum decreasing by 7 minutes to 6h21m. The median decreases 5.5 minutes to 6h50m, and the mean decreases 7 minutes to 6h56m, with a standard deviation of 28.7m.

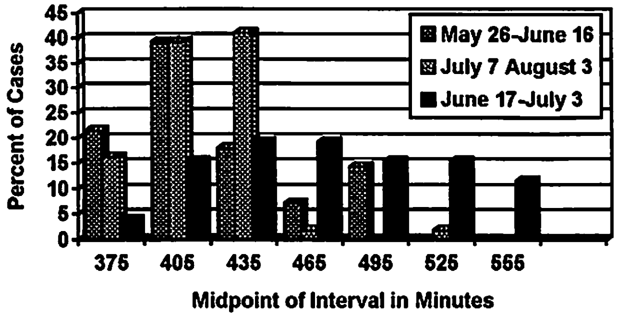
TABLE 7. Intervals for July 7-August 3+ (Fountain Mode A)

Length (in Minutes)	Single Intervals (A)		2-Interval Averages (B)	(A+B)		3-Interval Averages (C)	Total (A+B+C)	
361-390	1	4.2%	8	9	20.5%	-	9	16.1%
391-420	13	54.2	6	19	43.2	3	22	39.3
421-450	8	33.3	6	14	31.8	9	23	41.1
451-480	1	4.2	-	1	2.3	-	1	1.8
481-510	-	-	-	-	-	-	-	-
511-540	1	4.2	-	1	2.3	-	1	1.8
541-570	-	-	-	-	-	-	- -	-
Total	24	100.1%*	20	44	100.1%*	12	56	100.1%*
Minimum	388			381			381	
Maximum	524			524			524	
Median	415.5			410			413	
Mean	423			416			419	
Standard Deviation	30.0			28.7			27.4	

+Excludes the >16 hour interval on July 25-26.
*Does not add to 100.0% due to rounding.

Twelve 3-interval averages were computed from elapsed time between observations of 22 hours 23 minutes (7h28m average) on July 16-17, 22 hours (7h20m average) on July 17-18, 21 hour 45 minutes (7h15m average) on July 19-20, and 20h15m (6h45m average) on August 2-3. No attempt was made to estimate number of intervals for elapsed times of 29h30m, 24h, 29h25m, and 26h21m.

FIGURE 3. Comparison of Intervals May 26-June 16, June 17-July 3, and July 7 - August 3



Adding the 12 3-interval averages also does not significantly change the results. The median increases 3 minutes to 6h53m, and the mean also increases 3 minutes, to 6h59m, with a standard deviation of 27.4m.

A comparison of the distribution of the total intervals for May 26-June 16, June 17-July 3, and July 7-August 3 (Figure 3) shows that behavior for July 7-August 3 is similar to that of May 26-June 16, while June 17-July 3 is different from the other two time frames. Means and medians for May 26-June 16 (Table 4) and July 7-August 3 (Table 7) are also similar, while those for June 17-July 3 (Table 5) are dissimilar. These differences are explored further in the section "Fountain Mode A versus Fountain Mode B".

August 4-9: Beginning with the eruption at 11:04 on August 4 and ending with the 10:04 eruption on August 9, ten eruptions of Fountain were observed. Only four exact intervals were observed. One interval was estimated between two consecutive eruptions for which times

TABLE 8. Intervals for August 4-9 (Fountain Mode B)

Length (in Minutes)	Single Intervals (A)		2-Interval Averages (B)	(A+B)		3-Interval Averages (C)	Total (A+B+C)	
361-390	-	-	-	-	- -	-	-	-
391-420	-	-	2	2	13.3%	-	2	11.1%
421-450	1	20.0%	4	5	33.3	-	5	27.8
451-480	1	20.0	-	1	6.7	3	4	22.2
481-510	-	-	-	-	-	-	-	-
511-540	-	-	-	-	-	-	-	-
541-570	2	40.0	4	6	40.0	-	6	33.3
>570	1	20.0	-	1	6.7	-	1	5.6
Total	5	100.0%	10	15	100.0%	3	18	100.0%
Minimum	434			401			401	
Maximum	601			601			601	
Median	555			476			469	
Mean	525			494			489	
Standard Deviation	60.9			67.0			62.3	

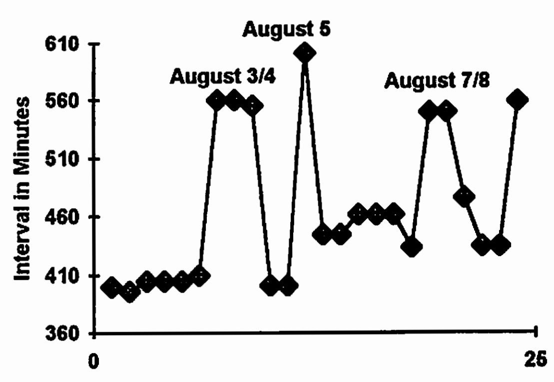
were recorded "ie", providing a total of five single interval observations for use in the analysis. Thirteen additional intervals were estimated by taking the time between known eruptions and dividing by the number of intervals in that time frame. Ten of these were 2-interval averages where missed eruptions were confirmed by missing markers and/or observations of the water level in Fountain's crater. Three were computed from an assumed triple interval. This resulted in 18 intervals for use in the analysis, including the 9 hour 19 interval between the August 9 10:04 solo eruption of Fountain and the 19:23 concerted eruption of Fountain and Morning.

Table 8 shows the intervals. The intervals fall into two distinct groups--intervals that were 6.5 to 8 hours long and intervals that were greater than 9 hours.

The intervals are arranged chronologically in Figure 4. An examination of this figure shows that long intervals were interspersed with short intervals. The pattern indicates that there might have been two or three attempts at an energy shift from Fountain to Morning before the evidence of the energy shift appeared aboveground in the form of the concerted eruption of Fountain and Morning on August 9.

Overnight August 2-3 the average for 3-intervals was 6h45m. This was followed by a closed interval of 6h50m. Overnight August 3-4 the average for 2-intervals was 9h20m. Total time between observed eruptions was 18h40m. Use of a marker confirmed that at least one eruption occurred, but doesn't tell when two or more eruptions might have

FIGURE 4. Intervals August 2-9



happened. If this had been for two missed eruptions, the average would have been 6h13m. Given other observed intervals for Fountain, it is very doubtful that there were three consecutive 6h13m intervals, particularly while Fountain was operating on Fountain Mode B. This was followed by a closed interval of 9h15m. Attempted energy shift #1?

Overnight August 4-5 the average for 2-intervals was 6h41m, back to 1991 average. The missed eruption occurred between 02:00 and 05:00. The next observed eruption occurred at 09:41 on August 5, lasted 59 minutes, and was followed by a 10h1m interval. Attempted energy shift #2?

Use of markers confirmed that an eruption was missed overnight August 5-6. The 2-interval average was 7h42m, followed by a closed interval of 7h14m.

Overnight August 7-8 the 2-interval average was 9h10m. Total time between observed eruptions was 18h20m. If this had been for three intervals, the average would have been 6h6m--well below any other three consecutive intervals observed even when Fountain was operating on Fountain Mode A. This was followed by an interval of 7h55m. Attempted energy shift #3?

Overnight August 8-9 a missed eruption was again confirmed through the use of markers, for an average interval of 7h15m. This was followed by the 9h19m interval that concluded with the 19:23 concerted eruption of Fountain with Morning. Energy shift now in progress!

By 05:16 on August 10 the energy had completely shifted to Morning, when the first observed solo eruption of Morning was recorded. The energy stayed with Morning through a solo eruption of Morning at 11:38 on August 28. Fountain did not erupt for 18 days. Then the energy started to shift back to Fountain, as evidenced by the concerted eruption of Fountain with Morning at 18:53 on August 28, discussed in the first section of this paper.

Table 8 also shows the ranges and averages for the August 4-9 intervals. The single intervals range from a minimum of 7h14m hours to a maximum of 10h1m, have a median of 9h15m, and a mean of 8h45m with a standard deviation of 60.9m. Adding the 2-interval averages reduces the minimum to 6h41m. The median drops 79 minutes to 7h56m. The mean drops 31 minutes to 8h14m, with a standard deviation of 67.0m. When the 3-interval averages are included, the median drops 9 minutes to 7h49m. The mean drops 5 minutes to 8h9m, with a standard deviation of 62.3m. Because of the small sample size, the median and mean are quite sensitive and show large changes when the 2-interval averages are included in the analysis.

July 7-August 9: Table 9 shows results for the combined period July 7 to August 9. Although there appear to be two different types of behavior within this time frame, an overall analysis is presented because it represents Fountain's activity between Morning's activity on July 4-5 and Morning's next activity in August.

The intervals are dispersed from 6h15m to 10h; however, 82% of them are between 6h15m and 7h30m. The 29 single interval observations range from a minimum of 6h30m to a maximum of 10h. The medians go from 7h7m for single intervals, to 6h59m when 2-interval averages are added, and to 7h13m when 3-interval averages are added. The means are all within minutes of 7 hours 20 minutes, with a standard deviation between 48m and 54m.

These statistics are very similar to the numbers for the overall period May 26 to July 3 for Fountain's activity between Morning's May and July active episodes. However, the overall statistics hide the fact that Fountain actually appeared to have two different patterns of behavior in the cycle between Morning's active spells.

Fountain Mode A (May 26-June 16 and July 7-August 3) versus Fountain Mode B (June 17-July 3 and August 4-9): As noted at various places in this paper, Fountain's behavior while on Fountain Mode seemed to consist of two different types of behavior--one of post-Morning behavior where Fountain had sole possession of the energy (May 26-June 16 and July 7-August 3), and one of pre-Morning

TABLE 9. Intervals for July 7 - August 9+

Length (in Minutes)	Single Intervals (A)		2-Interval Averages (B)	(A+B)		3-Interval Averages (C)	Total (A+B+C)	
361-390	1	3.5%	8	9	15.3%	-	9	12.2%
391-420	13	44.8	8	21	35.6	-	24	32.4
421-450	9	31.0	10	19	32.2	3	28	37.8
451-480	2	6.9	-	2	3.4	9	5	6.8
481-510	-	-	-	-	-	3	-	-
511-540	1	3.5	-	1	1.7	-	1	1.4
541-570	2	6.9	4	6	10.2	-	6	8.1
>570	1	3.5	-	1	1.7	-	1	1.4
Total	29	100.1%*	30	59	100.1%*	15	74	100.1%*
Minimum	388			381			381	
Maximum	601			601			601	
Median	427			419			433	
Mean	441			436			436	
Standard Deviation	53.5			53.9			48.9	

+Excludes the >16 hour interval on July 25-26.
*Does not add to 100.0% due to rounding.

behavior where the energy was shifting toward Morning (June 17-July 3 and August 4-9). Rather than showing a consistent pattern of intervals from one active episode of Morning until the next episode of Morning, Fountain started with intervals ranging from 6.25 to 8 hours with an average of about 7 hours, then, prior to Morning's next activity, made a shift to much longer intervals averaging 8 hours. At some point prior to start of Morning's activity, Fountain's behavior changed to reflect the shift in energy that was taking place. In other words, the samples represent two populations, one of post-Morning behavior (Fountain Mode A) and one of pre-Morning behavior (Fountain Mode B).

Statistical Analysis: Initial research hypotheses were formulated as:

1. Activity by Fountain while the Fountain Complex was operating on Fountain Mode during the summer of 1991 consisted of two types of behavior--post-Morning (Fountain Mode A) and pre-Morning (Fountain Mode B).

H_1: (May 26 to June 16 and July 7 to August 3) is different from (June 17 to July 3 and August 4 to August 9)

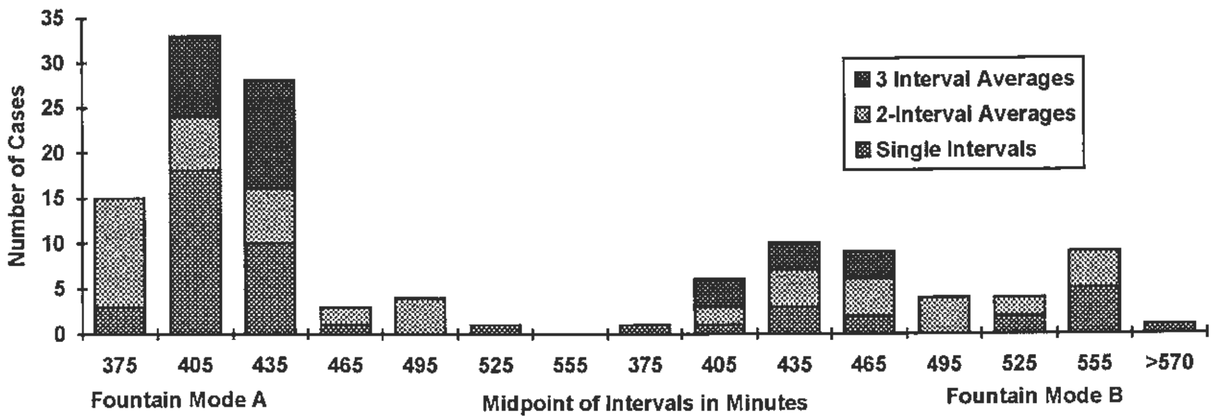
2. Fountain's different post-Morning and pre-Morning behaviors were evident prior to each activity of Morning.

H_{2A}: (May 26-June 16) is different from (June 17-July 3)

H_{2B}: (July 7-August 3) is different from (August 4-August 9)

A two-sample t-test was used to test each hypothesis. Statistical tests use variance as part of the computation to measure the probability of whether observed sample differences are statistically significant or whether they are due to random chance. Using 2- and 3-interval averages understates the variance. Since the degree of understatement is unknown and may vary for each sample, single interval observations were used to test the hypotheses.

FIGURE 5. Fountain Intervals Fountain Mode A (May 26-June 16 and July 7-August 3*) and Fountain Mode B (June 17-July 3 and August 4-9)



+Excludes July 25-26 interval that exceeded 16 hours.

Standard deviation figures reported in Tables 3, 4, 5, 6, 7, 8, and 9 were computed using the formula for population variance. Variance figures were recomputed using the formula for sample variance for use in this analysis.

An F-test was first performed to determine if the variance values for the two groups are equal. When group variance is similar, a t-test for groups of equal variance is used, but when group variance is not similar it is necessary to use a t-test for groups of unequal variance. Probability levels were set at .10 for the tests of variance and .05 for the tests of means. In other words, if the F values exceed a certain amount (with the amount varying depending upon the degrees of freedom), the null hypothesis of equal variance can be rejected at a 90% confidence level that rejection is the correct choice. If the t values exceed a certain amount (varying depending upon the degrees of freedom), the null hypothesis that the groups are the same can be rejected at a 95% confidence level that rejection is the correct choice and the behavior patterns are different.

Results--Hypothesis 1 (Fountain Mode A vs Fountain Mode B): Data for May 26-June 16 was grouped with data from July 7-August 3, and data for June 17-July 3 was grouped with data from August 4-9. Figure 5 and Table 10 show the intervals for these groupings.

The distribution tables reflect the lower averages for length of intervals during Fountain Mode A. Ninety percent of the intervals for Fountain Mode A is between 6h15m and 7h30m. However, less than 40% of the intervals for Fountain Mode B is in that range. The intervals for Fountain Mode B are spread across more categories, which is reflected in the higher standard deviation.

The closed interval means show a difference of 84 minutes. When the 2- and 3-interval estimates are included, the difference declines to 73 minutes, and then to 60 minutes--still a difference of an hour.

The F-test to test whether the samples of single interval observations were taken from populations of equal variance showed variance between the two groups was significantly different ($F=5.356$, df 14/32, $p<.001$). The t-test for groups with unequal variance applied to the single interval observations also showed that the group means were significantly different ($t=4.748$, df 16, $p<.005$).

Fountain's activity while the Fountain Complex was operating on Fountain mode during the summer of 1991 was different *before* the July and August activity of Morning than it had been *after* the May and July activity of Morning.

TABLE 10. Distribution of Intervals for Fountain Mode A (May 26-June 16 and July 7-August 3+) and Fountain Mode B (June 17-July 3 and August 4-9)

Length (in Minutes)	Single Intervals (A)		2-Interval Averages (B)	(A+B)		3-Interval Averages (C)	Total (A+B+C)	
Fountain Mode A								
361-390	3	9.1%	12	15	23.8%	-	15	17.9%
391-420	18	54.5	6	24	38.1	9	33	39.3
421-450	10	30.3	6	16	25.4	12	28	33.3
451-480	1	3.0	2	3	4.8	-	3	3.6
481-510	-	-	4	4	6.3	-	4	4.8
511-540	1	3.0	-	1	1.6	-	1	1.2
541-570	-	-	-	-	-	-	-	-
>570	-	-	-	-	-	-	-	-
Total	33	99.9%*	30	63	100.0%	21	84	100.0%
Minimum	375			375			375	
Maximum	524			524			524	
Median	414			410			412	
Mean	420			420			421	
Standard Deviation	28.5			34.5			31.2	
Fountain Mode B:								
361-390	1	6.7%	-	1	2.9%	-	1	2.3%
391-420	1	6.7	2	3	8.6	3	6	13.6
421-450	3	20.0	4	7	20.0	3	10	22.7
451-480	2	13.3	4	6	17.1	3	9	20.5
481-510	-	-	4	4	11.4	-	4	9.1
511-540	2	13.3	2	4	11.4	-	4	9.1
541-570	5	33.3	4	9	25.7	-	9	20.5
>570	1	6.7	-	1	2.9	-	1	2.3
Total	15	100.0%	20	35	100.0%	9	44	100.1%*
Minimum	390			390			390	
Maximum	601			601			601	
Median	525			495			462	
Mean	504			493			481	
Standard Deviation	59.5			57.3			58.1	

+Excludes the >16 hour interval on July 25-26.
*Does not add to 100.0% due to rounding.

Results--Hypothesis 2A (May 26-June 16 vs June 17-July 3): Distributions of the intervals for May 26-June 16 (Table 4) and those for June 17-July 3 (Table 6) are shown in Figure 6. The observations for June 17-July 3 are much more widely dispersed than those for

TABLE 11. Comparison of May 26-June 16 with June 17-July 3 Range, Median and Mean of Intervals (in Minutes)

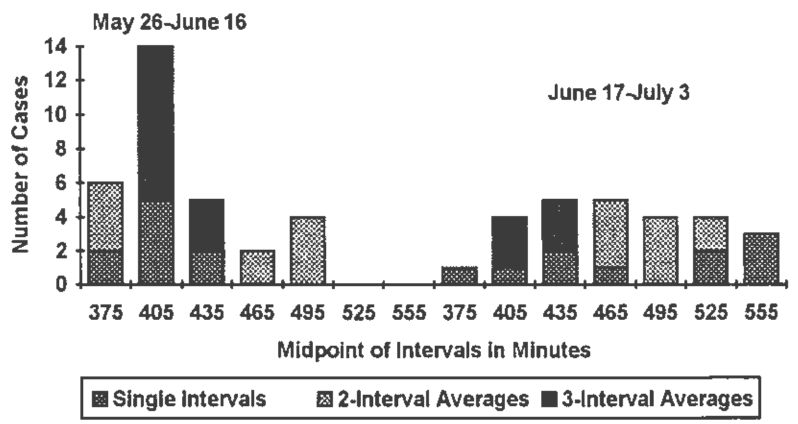
	Minimum	Maximum	Median	Mean
Single Intervals:				
5/26 - 6/16	375	435	410	410
6/17 - 7/3	390	570	512.5	493
Single Intervals and 2-interval averages:				
5/26 - 6/16	375	510	416	430
6/17 - 7/3	390	570	495	492
Single Interval, 2-interval averages, and 3-interval averages:				
5/26 - 6/16	375	510	407.5	423
6/17 - 7/3	390	570	470	476

May 26-June 16. Table 11 shows a comparison of the ranges, medians, and means for May 26-June 16 with those for June 17-July 3. The intervals for May 26-June 16 have much lower ranges, medians, and means than those for June 17-July 3. While the average for May 26-June 16 was close to 7 hours, the average for June 17-July 3 was close to 8 hours.

A test of variance showed that the variability within each of the groups was different ($F=11.13$, df 9/8, $p<.005$). A t-test adjusted for groups with unequal variance showed that the means of the two groups were also different ($t=3.824$, df 11, $p<.005$). Fountain's behavior pattern was different June 17-July 3 than it was for May 26-June 16. In other words, Fountain's behavior changed at least two weeks prior to the aboveground evidence of the energy shift.

<u>**Results--Hypothesis 2B (July 7 - August 3 vs August 4-9):**</u> Distribution of the intervals for July 7 - August 3 (Table 7) and those for August 4-9 (Table 8) are shown in Figure 7.

FIGURE 6. Fountain Intervals May 26-June 16 (Fountain Mode A) and June 17-July 3 (Fountain Mode B)



The observations for August 4-9 are bimodal with half the intervals exceeding 9 hours. Almost all the intervals for July 7 to August 3 are 6h15m to 7h30m. A comparison of the ranges and averages (shown in Table 12) shows that the bimodality of the August 4-9 intervals is reflected in the higher standard deviation. The means and medians for August 4-9 are much higher than those for July 7-August 3. The distributions and statistics for August 4-9 are more similar to those for June 17-July 3 than they are to those of July 7-August 3.

TABLE 12. Comparison of July 7-August 3 with August 4-9 Range, Median and Mean of Intervals (in Minutes)

	Minimum	Maximum	Median	Mean
Single Intervals:				
7/7 - 8/3	388	524	415.5	423
8/4 - 8/9	434	601	555	525
Single Intervals and 2-interval averages:				
7/7 - 8/3	381	524	410	416
8/4 - 8/9	401	601	476	494
Single Interval, 2-interval averages, and 3-interval averages:				
7/7 - 8/3	381	524	413	419
8/4 - 8/9	401	601	469	489

The test of variance showed that the two groups do not have equal variance ($F=4.914$, df 4/23, $p<.01$). The t-test for groups with unequal variance also showed that the difference between means of the two groups is statistically significant ($t=3.28$, df 4, $p<.025$). Fountain's intervals for five days prior to the August rejuvenation of Morning were different from what they had been between July 7 and August 3.

Partial Energy Shift versus Complete Energy Shift: Because there were two types of energy shifts, a partial energy shift in July and a complete exchange of function in August and May, it could be argued that May 26-June 16 represented a post-complete exchange of function following the May activity of Morning and July 7-August 3 represented a post-partial exchange, and that June 17-July 3 represented a pre-partial exchange of function prior to the July 4-5 activity of Morning and August 4-9 represented a pre-complete exchange of function, resulting in four groups rather than two. If the two concerted eruptions in July not followed by solo eruptions of Morning represented a partial exchange of function and the solo activity of Morning in August represented a complete exchange of function, two different underground events, would aboveground evidence of this appear with Fountain's intervals showing different behavior?

Table 13 shows the four groups with their respective cell means (single-interval observations), sizes, and sample variances. Visual examination of the column means for the partial energy shift versus the complete energy shift show no significant difference (7 minutes).

FIGURE 7. Fountain Intervals July 7 - August 3 (Fountain Mode A) and August 4-9 (Fountain Mode B

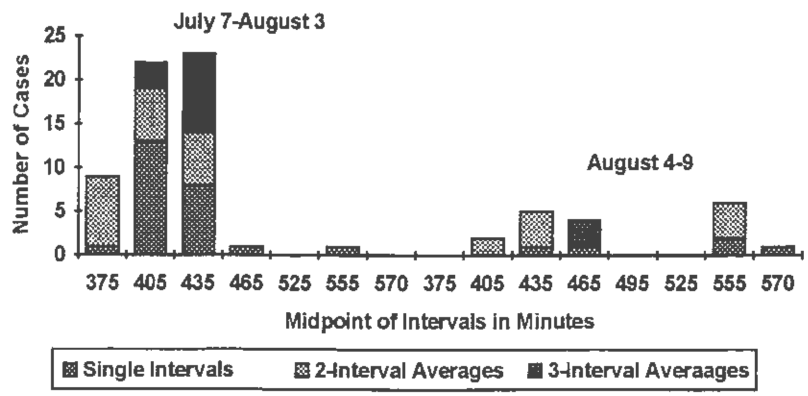
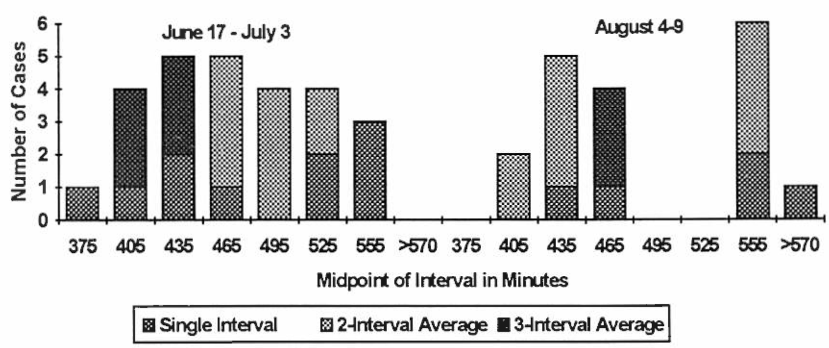


TABLE 13. Comparison of Type of Energy Shift and Pre-and Post- Morning Time Frames

	Type of Energy Shift Partial	Complete	Row Total
Pre-Morning	6/17-7/3	8/4-8/9	
mean	493.2	525	503.8
variance	4340.28	4636.01	3542.41
cell size	10	5	15
Post-Morning	7/7-8/3	5/26-6/16	
mean	423.3	409.7	419.6
variance	939.13	389.205	814.285
cell size	24	9	33
Column Total			Grand Total
mean	443.9	450.9	445.9
variance	2884.492	4292.38	3376.60
cell size	34	14	48

FIGURE 8. Fountain's Intervals June 17-July 3 (Pre Partial) and August 4-9 (Pre-Complete)



Visual examination of the cells for the two pre-Morning intervals indicated that there might be a difference between June 17 - July 3 (pre-partial) and August 4-9 (pre-complete).

Distributions of the intervals for June 17-July 3 (Table 5) and those for August 4-9 (Table 8) are shown in Figure 6. The distribution for August 4-9 shows more bimodality than does the distribution for June 17-July 3. The intervals are spread fairly evenly across the categories for June 17-July 3. August 4-9 has a higher percentage of intervals in the above 8.5 hour range. Table 14 shows a comparison of the ranges, medians, and means for the two time frames. The range, median, and mean of the single interval observations for June 17 to July 3 (before the partial energy shift) are about 30 minutes below those for August 4-9 (before the complete energy shift).

<u>Statistical Analysis:</u> There are two factors involved in this model, the nature of the energy shift (partial and complete) and the location of the energy (post-Morning period where the energy was with Fountain and pre-Morning period when the energy was shifting from Fountain to Morning). Research hypotheses were formulated as:

3. Fountain's activity before and after a partial energy shift to Morning was different from Fountain's activity before a complete energy shift to Morning.

H_3: (June 17-July 3 and July 7 - August 3) is different from (August 4-9 and May 26-June 16))

4. Fountain's pre-Morning activity before a partial energy shift to Morning was different from Fountain's pre-Morning activity before a complete energy shift to Morning.

H_4: (June 17-July 3) is different from (August 4-August 9)

TABLE 14. Comparison of June 17-July 3 with August 4-9 Range, Median and Mean of Intervals (in Minutes)

	Minimum	Maximum	Median	Mean
Single Intervals:				
6/17 - 7/3	390	570	512.5	493
8/4 - 8/9	434	601	555	525
Single Intervals and 2-interval averages:				
6/17 - 7/3	390	570	495	492
8/4 - 8/9	401	601	476	494
Single Interval, 2-interval averages, and 3-interval averages:				
6/17 - 8/3	390	570	470	476
8/4 - 8/9	401	601	469	489

A two-way ANOVA for unequal cell sizes was used for the statistical analysis, using a regression approach. In the unequal cell size situation, there are alternative orders in which the effects (row, column, or interaction) can be entered. The approach used in this analysis was the most widely recommended approach, which is to enter the interaction first, then test for the significance of one main effect controlling for the remaining main effect.

<u>Results--Hypothesis 3 and 4:</u> None of the tests for the nature of the energy shift showed any statistically significant difference. The test of interaction between the two factors shows no statistically significant difference (F=2.436, df 1/44, .10<p<.25). In other words, Fountain's behavior did not depend on the combined effect of the nature of the energy shift to Morning and whether the behavior occurred before or after the activity by Morning. Hypothesis 4 was not supported. The intervals from June 17-July 3 were not significantly different from those for August 4-9. These results are consistent with the results from a t-test for the sample means. A test of variance for these two cells showed that the groups have equal variance (F=1.067, df 3/8, 2.92 critical value for p<.10). The t-test for groups with equal variance indicated that means of the groups are not different (t=.873, df 13, .15<p< .20).

One reason for no statistically significant differences may be that the time periods involved were not of equal length. However, visual examination of the graphs shows that the 6-day interval June 28-July 3 looks even more like the August 4-9 time period.

Another reason for the finding may be the small sample sizes involved. If more single interval observations had been taken, these might have shown a difference.

The tests for main effects of the nature of the shift also show no statistical significance (F=.015, df 1/46, p>.25), confirming the visual examination of the data that showed a difference of only 7 minutes between the means of the two columns.

The test for main effects of the pre- and post-Morning interval was significant (F=37.654, df 1/46, p<.001), confirming the t-test results for the sample means.

The test for overall significance of the model shows that there is a statistically significant difference among the four time frames (F=13.851, df 3/44, p<.001). As the tests for interaction and main effects demonstrate, the difference results from the difference between the pre- and post-Morning behavior, and not from any effect due to the nature of the energy shift.

Summary: Fountain's intervals did change prior to Morning's activity, providing aboveground evidence of the underground exchange of function that was occurring. This happened prior to both the July and August activity of Morning. The data did not support the hypotheses that Fountain's activity was different prior to the partial energy shift that failed to materialize into a complete energy shift than it was prior to the complete energy shift that was both preceded and succeeded by a partial energy shift. One person has suggested that instead of characterizing the concerted eruptions of Fountain and Morning as partial energy shifts, I should accept the fact that the concerted eruptions of Fountain and Morning were something unique. Rejection of the hypotheses that there was a difference between Fountain's pre-Morning behavior before the July and August activity of Morning lends credence to his view.

RECOVERY MODE--AUGUST 29-EARLY SEPTEMBER

Following the three week dormancy that started on August 9 after Fountain concluded a concerted eruption with Morning and ended when Fountain had concerted eruptions with Morning on August 28 and 29, Fountain exhibited yet another type of behavior. Fountain erupted with shorter durations and shorter intervals, indicating that it had not yet fully recovered from Morning's activity. It was hypothesized that the three weeks of activity by Morning had had a significant impact on Fountain.

DURATIONS: Fourteen durations were observed from August 30 to September 6. One of these, noted ">31m" was not used in the analysis. Table 15 shows the distribution of the durations.
The durations range from a minimum of 26 minutes to a maximum of 42.5 minutes (since this duration exceeds 42 minutes, it is shown in Table 15 in the 43-44 range), with a median of 35 minutes. The average (mean) is 35 minutes, with a standard deviation of 4.3. The median and mean are both well below the median of 39 minutes and mean of 40 minutes for the rest of the summer of 1991.

On the basis of the theory that the three weeks of activity by Morning had hàd a significant impact on Fountain, the research hypothesis that Fountain's durations had been affected was formulated and tested. Durations for August 30 to September 6 were tested against those for May 26 to August 9 (excluding the concerted eruptions). The test of variance shows no statistically significant difference for the variance of the groups ($F=1.502$, df 37/12, $.10<p<.25$). The t-test for groups with equal variance shows that the difference in the durations after Morning's August activity versus the rest of the summer is statistically significant ($t=2.987$, df 49, $p<.005$). Fountain's durations were significantly shorter in the recovery period.

INTERVALS: Ten closed intervals were recorded from August 29 to September 5, beginning with the interval between the concerted eruption with Morning that started at 1214 on August 29 and the first solo Fountain eruption at 2102 on August 29. The 10 intervals range from a minimum of 4 hours 22 minutes to a maximum of 11 hours, have a median of 6 hours 50 minutes, a mean of 6 hours 57

TABLE 15. Distribution of Fountain's Durations August 30 - September 6

Duration (in Minutes)	Number	Percent
<31	2	15.4%
31-32	2	15.4
33-34	1	7.7
35-36	4	30.8
37-38	1	7.7
39-40	1	7.7
41-42	1	7.7
43-44	1	7.7
>44	-	-
Total	13	100.1%*

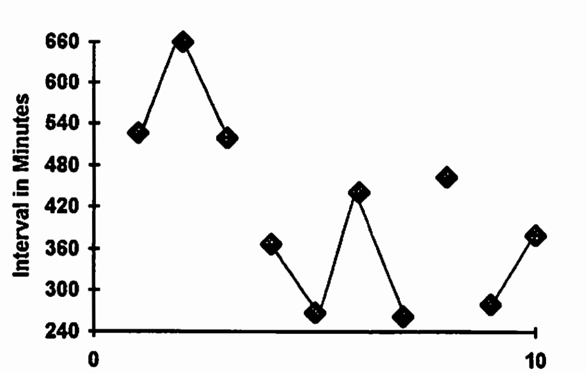
*Total does not equal 100% due to rounding.

minutes, and a standard deviation of 123.7. Because the closed intervals showed extreme variability, no attempt was made to estimate 2- or 3-interval averages.

Figure 9 shows the intervals. Examination of that figure shows that the first three intervals after the concerted were all long compared to Fountain's 1991 average. Then Fountain's intervals dropped to very short times (for 1991). Three intervals between September 1 and 4 were less than 5 hours long--the only closed intervals less than 6h15m that had been recorded during the entire summer. It would be tempting to remove the three intervals on August 29-30 and consider them part of the partial energy shift, but they did occur after activity in Morning had ceased. Furthermore, examination of the portacorder strip on August 30 showed that the "noise" from steam bubbles collapsing underground that was evident when Morning was erupting solo during August and was still being recorded between the last solo eruption of Morning and the concerted eruption with Fountain on August 28 had disappeared sometime between August 29 and 30.

Because Fountain's durations throughout the summer of 1991 had been relatively constant, it was possible to test durations in the recovery period against observations for the rest of the summer. If intervals were to be tested though, the question arose of which group of intervals should the recovery period be tested against. Since the recovery period occurred after Morning's activity, then the only theoretically defensible decision would be to test the recovery period against either May 26-June 16 or July 7-August 3. The mean interval for the recovery period was 417 minutes and the means for May 26-June 16 and July 7-August 3 were 410 and 423 minutes, respectively. The difference is not large enough to be significant.

FIGURE 9. Intervals August 29 - September 4



CONCLUSION

Activity in the Fountain Complex was certainly interesting during 1991, with Fountain and Morning each erupting at various times, and sometimes in concert. And even when Morning was not erupting, the possibility that it might rejuvenate generated more interest in Fountain by geyser gazers than had been evident in previous years.

Throughout late July and early August I had speculated that Fountain needed to "stall" (have a long interval) before Morning would erupt. Fountain had a major stall overnight on July 25-26 with an interval exceeding 16 hours and Morning didn't erupt. What I didn't take into account at the time was that it wasn't a single major stall that was needed in 1991, but rather a series of "stutters".

Knowing that the differences in Fountain's intervals during the summer of 1991 were statistically significant, could these patterns have been used to predict Morning's activity in August? Or, can these patterns be used to predict Morning in the future? The answer to both of these questions is no. No prediction model built on limited observations (one "partial" rejuvenation of Morning on July 4-5 and one "complete" rejuvenation of Morning for August 9-29) has much chance of success. However, if Fountain is erupting from a nonoverflowing pool with durations of about 40 minutes and intervals of about 7 hours, and then Fountain starts erupting from a nonoverflowing pool with durations of about 40 minutes and intervals of about 8 hours or longer for three or four days, it *might* be worth your time to visit the Fountain Complex.

ACKNOWLEDGMENTS

Without the data from the OFVC geyser log, half this article wouldn't exist because I wasn't

in Yellowstone May 26 to July 20, except for July 4-6. Everyone who took the time to write down an observation about Fountain and then made certain that it got entered into the OFVC geyser log contributed to this article. Thank you all, but particular thanks to the members of the Naturalist staff and volunteers monitoring Great Fountain who made special efforts to watch for indications of activity by Fountain.

I would also like to thank Ralph Tyalor for his comments and suggestions and help in editing all the 1991 articles about activity in the Fountain Complex.

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JET GEYSER, ACTIVITY IN 1991
LOWER GEYSER BASIN, YELLOWSTONE NATIONAL PARK, WYOMING

Lynn Stephens

ABSTRACT: The exchange of function between Fountain and Morning in 1991 affected Jet's cycle. Regardless of whether Fountain or Morning was active, UNNG-FTN-2 demonstrated control over Jet's cycle. The exchange of function also significantly affected Jet's durations. Both variability and length of durations increased when Morning was active. This paper describes Jet's behavior patterns during 1991.

INTRODUCTION

Jet Geyser is located south of the boardwalk that passes between it and Fountain Geyser. Jet erupts from at least 6 vents in an elongated cone that appears to have developed along an old fracture in the sinter. During the summer of 1991, Jet exhibited several different types of behavior, and, like other geysers in the Fountain Complex, was affected by shifts of energy between Fountain and Morning. This paper describes the different types of activity exhibited by Jet. The first section provides a brief history of Jet's activity over the years. The second section describes Jet's cycles when Fountain was active. The third section presents a description of Jet's activity when Morning was active. The fourth section contains a review of Jet's behavior during the periods the energy was shifting between Fountain and Morning. The final section describes Jet's durations.

JET'S HISTORICAL PATTERNS OF ACTIVITY

The name "Jet" was originally given to the geyser now known as Spasm. There is little early history for Jet. This is partly due to name confusion and maybe also because Jet was in a period of dormancy. Whittlesey [1988, p. 869] noted that "By 1939 Jet Geyser was listed as erupting 10-15 feet high for 19-30 minute periods at unrecorded intervals."

Marler [1973, p. 334] stated: "Prior to the rejuvenation of Fountain and Morning Geysers in the late 1940s Jet erupted with marked regularity, the intervals being from 4 to 5 minutes; the duration less than a minute. Following Morning's rejuvenation for the entire duration of its eruption, which sometimes would last for an hour, Jet would be dormant. From the time of cessation of play in Morning until Fountain erupted there was infrequent and feeble activity of Jet, however, as soon as Fountain began erupting, and for the duration of its activity, about 45 minutes, Jet would play with old time frequency and vigor."

Lewis reported his 1957 observations of Jet as follows: "This geyser was quite variable as far as its interval went. Some days it hardly played at all, while at other times it erupted every few minutes. On days when neither Morning or Fountain played it was more active than when they had. While Fountain was playing, Jet also played about every 4 or 5 minutes and put on its wildest display at this time. When Fountain quit, Jet also quit and was inactive for a long, but undetermined period [p. 54]."

Marler [1973, p. 334] stated: "Following the 1959 earthquake, which resulted in the dormancy of Morning and Fountain, Jet also became dormant. Its rejuvenation occurred simultaneously with that of Fountain." Lewis [1963, p. 3] reported that this rejuvenation occurred in October 1962. During 1963, Lewis observed 72 intervals of Jet, ranging from a minimum of 7 minutes to a maximum of 54 minutes with an average of 21 minutes. Marler continued Jet's history: "In late 1964 when Fountain again became dormant Jet did likewise, rejuvenating in 1968 along with recurrence of eruptions of Fountain. Since the above season Jet's most pronounced activity has been during eruptions of Fountain, at which time Jet played about every 4 to 5 minutes [1973, p. 334]."

Martinez commented on Jet's 1978 behavior: "Eruptions occurred at 7 to 12 minute intervals with occasional long quiet periods, due to the activity of a near-by frying pan geyser. During the quiet phase Jet would sometimes growl or roar for a few seconds. No changes in activity as a result of Morning's eruptions were observed, but I wasn't in the area long enough to judge all the influences of Morning fairly [1978, p. 78-4]."

In the 1979 edition of *The Geysers of Yellowstone*, Bryan listed Jet's interval as 2 to 5 minutes, and duration as 20 seconds. Bryan also noted that periods of dormancy occur and stated that Jet is most active when Fountain is playing and inactive when Morning is active. In the 1986 and 1991 editions, Bryan listed Jet's interval as 1 to 20 minutes and duration as seconds.

Whittlesey [1988, p. 869] stated "In recent years Jet's most powerful eruptions have come when nearby Morning Geyser was active...Intervals are from two to five minutes with the eruptions often lasting no more than twenty seconds. Periods of dormancy are common."[1]

Bower [1992] described cycles exhibited by Jet in 1990 when Fountain was active. Bower noted that Jet was quiet for several hours following an eruption of Fountain. When Jet resumed erupting, it erupted at irregular intervals. Both Fountain and UNNG-FTN-2 affected Jet's cycles in 1990.

During 1991, both Fountain and Morning were active, so Jet demonstrated aspects of all the descriptions, with the exception of long periods of dormancy associated with dormancy of Fountain and Morning. Intervals ranged from 1 minute to hours, depending on whether or not Fountain and/or UNNG-FTN-2 ("Super Frying Pan") had just erupted. Because the Fountain Complex was under observation both when it was operating on Fountain function and when it was on Morning function, the impact on Jet's behavior caused by the exchange of function in 1991 was observed.

[1]This statement should probably read that Jet is most active when Fountain is active. All other sources agree that Jet is most active when Fountain is active rather than when Morning is active. In 1991 Jet was definitely more active when Fountain was active than when Morning was active.

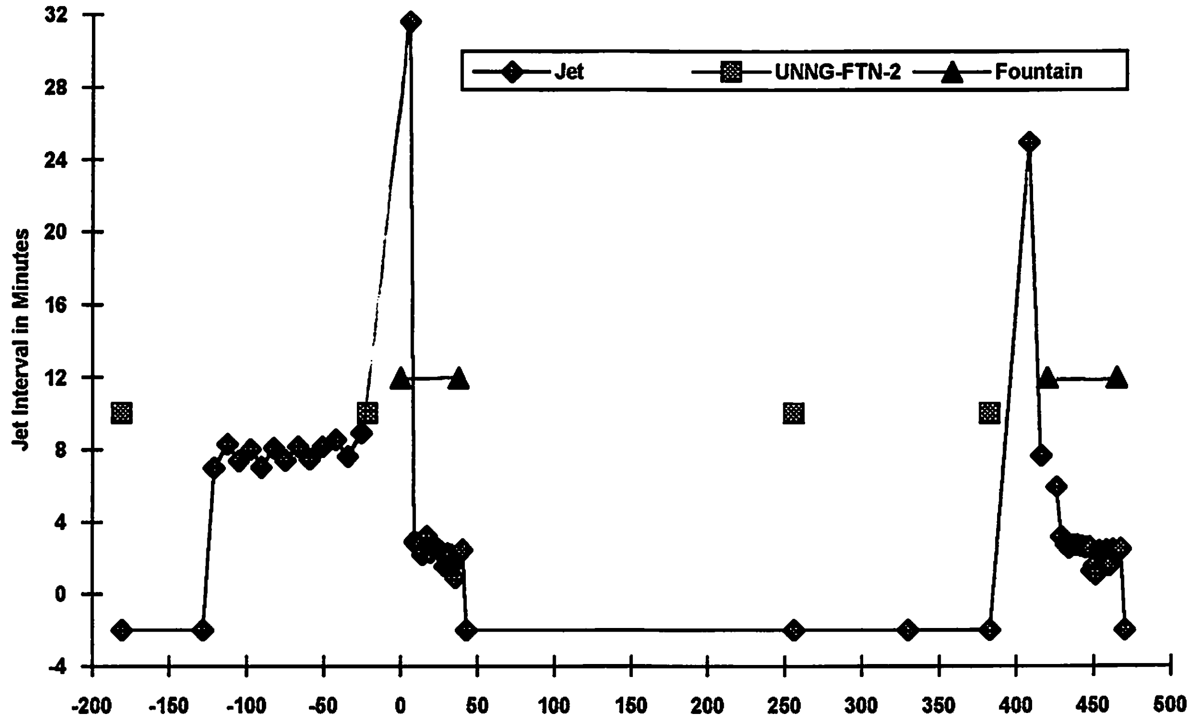
JET'S ACTIVITY WHEN FOUNTAIN WAS ACTIVE--JULY 21-AUGUST 9

When Fountain was active, Jet's general cycle from Fountain eruption to Fountain eruption consisted of (1) 1 to 4 minute intervals during Fountain's eruption, (2) a period of quiet after Fountain's eruption, (3) intervals of 8 to 10 minutes decreasing to about 6 minutes prior to the next Fountain eruption, and (4) periods of quiet after an eruption of UNNG-FTN-2. Following an eruption of UNNG-FTN-2, Jet would be quiet for 30 to 60 minutes. Figure 1 shows a typical Jet cycle.

The first Jet quiet period shown represents a quiet interval in excess of 159 minutes. The first Jet eruption shown was the first eruption after the preceding Fountain eruption (exact time of the Fountain eruption overnight is not known). That Jet interval also involved an eruption of UNNG-FTN-2. Following the eruption of UNNG-FTN-2, Jet was quiet for 53 minutes. Jet then began having intervals of about 8 minutes. These intervals decreased to 7 minutes, before rising to 9 minutes just before the next eruption of UNNG-FTN-2. Following the eruption of UNNG-FTN-2, Jet was quiet for 31 minutes. In the meantime, Fountain started an eruption. Jet was quiet for 6 minutes after the start of Fountain's eruption, apparently still recovering from the UNNG-FTN-2 eruption. Then Jet started erupting at 2.5 minute intervals. Jet continued to erupt at 1 to 2.5 minute intervals until Fountain stopped.

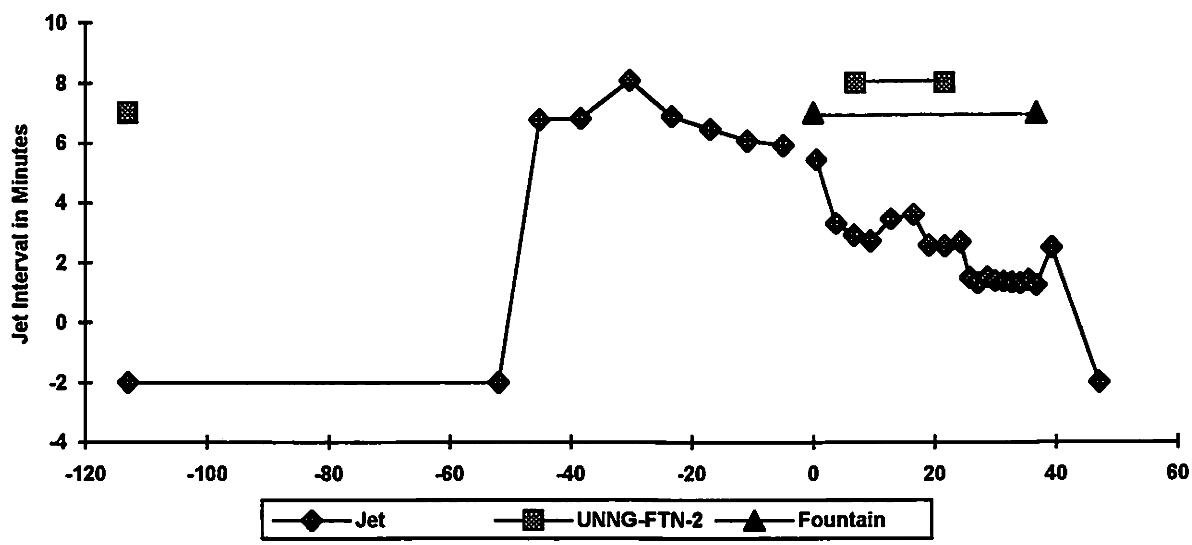
After the stop of this Fountain eruption, Jet was quiet until 12 minutes before the next Fountain eruption. Jet's one interval prior to the Fountain eruption was 7.7 minutes. The next interval for Jet overlapped the start of the Fountain eruption and was 6.0 minutes. This was a typical response by Jet. It often appeared that Jet's plumbing system was not affected by the start of the Fountain eruption until the first Jet interval that overlapped with Fountain's eruption, or the interval where both Jet eruptions occurred after the start of Fountain's eruption. Then Jet started erupting at 2.5 minute intervals for 8 intervals, before dropping to 1 to 1.5 minute intervals. Jet had one eruption after Fountain stopped. Then Jet started its long post-Fountain quiet period.

FIGURE 1. Sample Jet Cycles, Fountain Function,July 22, 1991



Inactivity by Jet is indicated by -2.

FIGURE 2. Sample Jet Cycle With UNNG-FTN-2 Starting an Eruption During Fountain's Eruption



Jet activity shown as -2 represents post-Fountain quiet period by Jet that exceeded several hours.

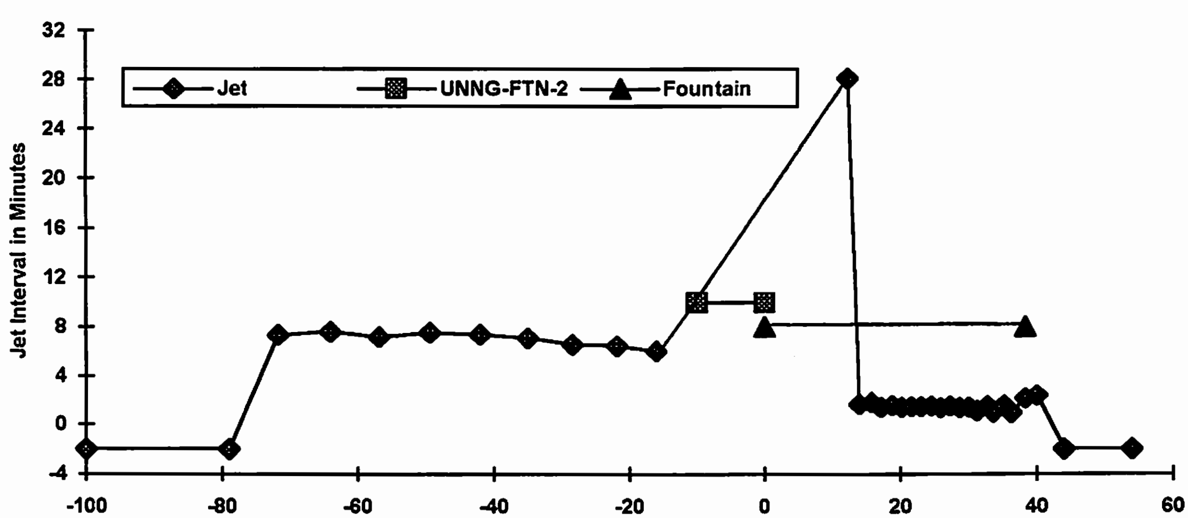
When Fountain started an eruption first, and then UNNG-FTN-2 erupted during Fountain's eruption, UNNG-FTN-2's ability to completely suppress eruptions by Jet was negated by the fact that Fountain was in eruption. Figure 2 shows a typical cycle of this type.

In this cycle, the quiet period shown for Jet was actually an hours' long interval after the preceding Fountain. Jet started erupting at 6.8 minute intervals, had one 8.1 minute interval, then gradually dropped to 5.9 minutes just prior to Fountain's eruption. The first interval overlapping Fountain's eruption was 5.5 minutes, again demonstrating the one interval lag between the start of Fountain's eruption and Jet's response to the fact that Fountain was erupting. UNNG-FTN-2 started 7 minutes after the start of Fountain. Jet's intervals were 2.5 to 3.5 minutes while UNNG-FTN-2 was erupting. After UNNG-FTN-2 stopped erupting, Jet's intervals dropped to 1.5 minutes. Jet had one eruption after Fountain ended, then went into its long post-Fountain quiet period. UNNG-FTN-2 retained some ability to suppress Jet eruptions, as demonstrated by the decrease in Jet's intervals after UNNG-FTN-2 stopped while Fountain was still in eruption.

If UNNG-FTN-2 erupted and Jet was still in a post-UNNG-FTN-2 quiet period when Fountain erupted, UNNG-FTN-2 retained its ability to suppress Jet's eruptions during the Fountain eruption until the normal post-UNNG-FTN-2 quiet period ended. Figure 3 contains a sample cycle illustrating this case 3.

For this cycle, observations began when Jet was in a post-UNNG-FTN-2 quiet period where the Jet interval exceeded 30 minutes. After Jet recovered from the post-UNNG-FTN-2 quiet period, Jet's intervals started at about 7.5 minutes and declined to 6 minutes just prior to the next UNNG-FTN-2 eruption. UNNG-FTN-2 erupted 10 minutes before Fountain started, so there was an overlap of about 6 minutes between the start of Fountain's eruption and the end of UNNG-FTN-2's eruption. In this case, Jet was quiet for 28.1 minutes after UNNG-FTN-2 started erupting. In other words, Jet was quiet until 12 minutes

FIGURE 3. Sample Jet Cycle, Fountain Eruption Starts While Jet Is Still in Quiet Period After UNNG-FTN-2's Eruption



Jet activity shown as -2 represents quiet period by Jet. The first quiet period was a post-UNNG-FTN-2 quiet period where the interval exceeded 30 minutes. The second quiet period was the beginning of a long post-Fountain quiet period.

after the start of Fountain. Jet immediately began having intervals of 1 to 1.5 minutes during Fountain's eruption. Jet had one eruption after the end of Fountain's eruption before entering its post-Fountain quiet period.

This cycle also demonstrates one other characteristic Jet often exhibited. Just prior to the end of Fountain's eruption, Jet's final interval increased to 2 to 2.5 minutes. This type of increase often alerted me to the fact that Fountain would end within the next 1 to 2 minutes.

Three other facets of Jet's behavior when Fountain was active deserve mention. First, as Martinez [1978] noted, Jet's growling and roaring was often heard during either the post-UNNG-FTN-2 quiet period or the post-Fountain quiet period. This growling was noted for as long as an hour before Jet resumed eruptive activity.

Second, Jet had minor as well as major eruptions. Major eruptions lasted 40 seconds to just over a minute. Minor eruptions lasted 5 to 10 seconds. Minor eruptions were distinguished both by their short duration and the fact that water barely cleared the top of the sinter mound and generally only emerged from one or two vents. These minor eruptions usually occurred near the end of Fountain's eruption, and served as a second type that Fountain's eruption was nearing its end. Jet's durations appear to be correlated with Jet intervals. The first Jet eruption after a post-UNNG-FTN-2 quiet period would have a duration slightly in excess of 1 minute. Most other durations, excluding minor eruptions, were generally 30 to 50 seconds long.

Third, Jet's interval just prior to an eruption of either UNNG-FTN-2 or Fountain usually showed an increase over the preceding interval. If Jet's intervals had already dropped to 6 minutes, this increase served as an indicator that either UNNG-FTN-2 or Fountain would erupt before the next eruption of Jet.

JET'S ACTIVITY WHEN MORNING WAS ACTIVE--AUGUST 10-28

When the energy in the Fountain Complex shifted from Fountain to Morning, Jet's behavior changed in several ways. Once Jet and UNNG-FTN-2 had adapted to the exchange of function, Jet's long quiet periods of 4 to 5 hours disappeared, although Jet still had post-UNNG-FTN-2 periods of quiet, lasting from 30 minutes to about 2 hours. Jet also sometime had an eruption during UNNG-FTN-2's eruption. Jet might erupt once or twice during Morning's eruption. Most Jet intervals that overlapped Morning's eruption were 10 to 12 minutes. Following an eruption of Morning, Jet immediately started erupting at 4 to 5 minute intervals, with the intervals gradually increasing to about 6 to 6.5 minutes prior to the next eruption of Morning.

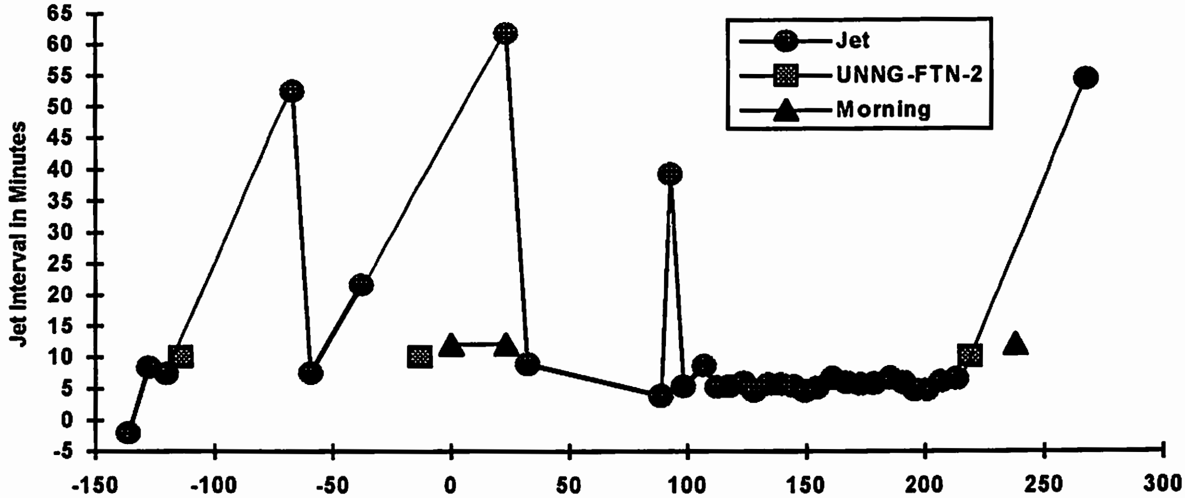
Eight of the first nine August eruptions of Morning (for which activity by Jet and UNNG-FTN-2 was observed prior to the Morning eruption) were preceded by an eruption of UNNG-FTN-2, then the eruption of Morning, with no intervening eruption by Jet. Figure 4 shows a sample cycle.

This figure contains observations made between 07:00 and 14:00 on August 10, with a break in the data between 07:30 and 08:15. Jet was active prior to an eruption of UNNG-FTN-2 at 07:31. Two intervals of Jet were recorded prior to this eruption, one of 8.5 minutes and one of 7.4 minutes. Following UNNG-FTN-2's eruption, Jet was quiet for 52.5 minutes, then had one interval of 7.5 minutes and one of 21.7 minutes before the next UNNG-FTN-2 eruption at 09:12.

Morning erupted at 09:25. Jet did not erupt during Morning's eruption. Jet did not resume eruptions until 09:48, an interval of 61.7 minutes attributable to the post-UNNG-FTN-2 quiet period. Jet's intervals started at 4 minutes and gradually increased to 6.6 minutes just prior to the next UNNG-FTN-2 eruption at 13:04.

Morning erupted again at 13:23. Again, Jet did not erupt during Morning's eruption. Jet resumed eruptive activity at 13:52, 29 minutes after Morning started. The interval of 54.4 minutes is attributable to the post-UNNG-FTN-2 quiet period. The first Jet eruption during an eruption of Morning was not observed until the 18:07 eruption of Morning on August 10.

FIGURE 4. Sample Jet Cycle, Morning Function, August 10, 1991

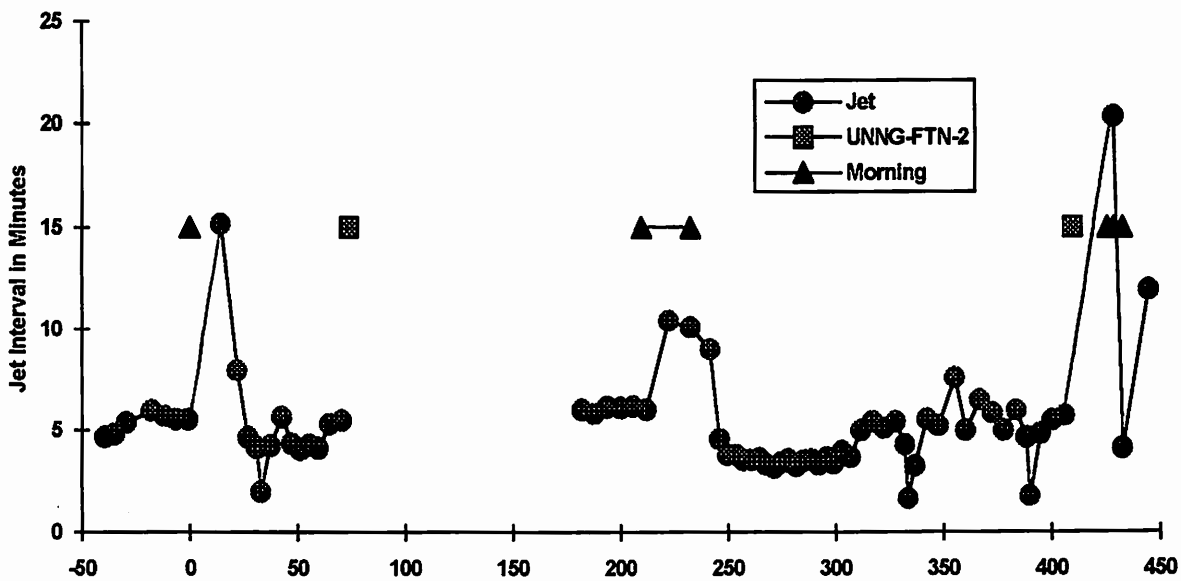


Jet activity shown as -2 represents start of observation period.

Figure 5 shows a sample cycle where Jet erupted during an eruption of Morning. These observations were made on August 12 between 05:00 and 13:15, with a break in data between 07:15 and 08:45. As shown by the breaks after the UNNG-FTN-2 eruptions, Jet continued to have post-UNNG-FTN-2 periods of quiet.

Prior to an eruption of Morning at 05:53, Jet erupted at 4.7 to 5.5 minute intervals. No Jet eruption occurred during the Morning eruption at 05:53. The interval between the Jet eruptions before and after the Morning eruption was 15.8 minutes. This interval was followed by an 8.0 minute interval. Jet's intervals then dropped to 4.5 minutes and continued dropping to 4.1 minutes before increasing to 5.3

FIGURE 5. Sample Jet Cycle Showing Jet Erupting During Morning's Eruption



and 5.5 minutes just prior to the UNNG-FTN-2 eruption at 07:07. Jet's post-UNNG-FTN-2 quiet period is not known.

Data collection resumed at 08:45. At that time Jet was erupting at intervals near 6.1 minutes. Morning erupted at 09:23. Jet had three eruptions during Morning's eruption. The first occurred at an interval of 6.0 minutes. Again, Jet's behavior indicates its system took one interval before responding to an eruption of the active major geyser. Jet's next two intervals during the Morning eruption were 10.4 and 10.1 minutes. Morning stopped, and Jet's first eruption after Morning ended occurred at a 9 minute interval, demonstrating the one-interval lag again.

Jet's intervals then dropped to 3.5 minutes and stayed there until shortly after 11:00. Jet had a minor eruption at 11:25, 2 hours 2 minutes after the preceding Morning eruption, or 1 hour 37 minutes before the next Morning eruption. Jet's intervals then began fluctuating between 4 and 6 minutes until UNNG-FTN-2 erupted at 12:46. Morning erupted at 13:02, before Jet had resumed activity. Jet erupted 30 seconds after the start of Morning, an interval of 20.4 minutes attributable to the post-UNNG-FTN-2 quiet period. Jet erupted once more during Morning's eruption at a 4.1 minute interval. The next Jet eruption occurred after a 12 minute interval. This eruption occurred after Morning ended. The one-interval lag before Jet reacted to Morning's eruption and the one-interval lag before Jet reacted to the end of Morning's eruption are also demonstrated in this cycle.

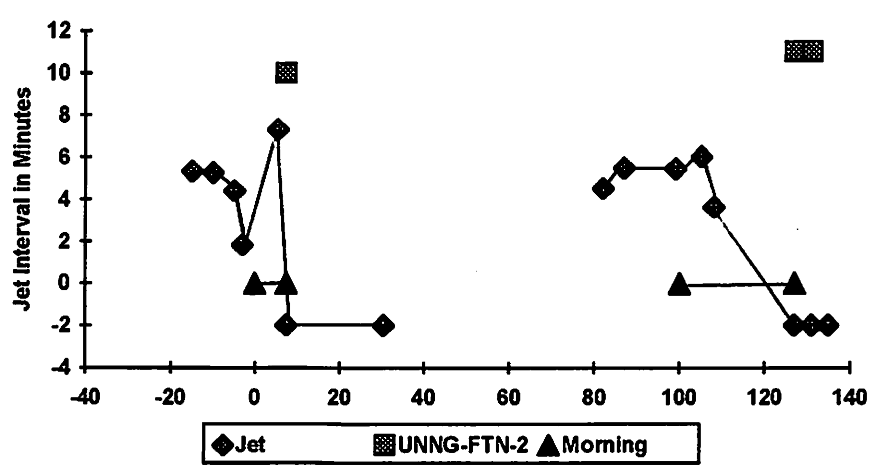
Figure 6 shows typical Jet cycles when Morning started and then UNNG-FTN-2 erupted while Morning was still in eruption. Jet was erupting at 5.5 minute intervals prior to Morning's eruption. In one cycle, Jet had a minor eruption just before Morning's eruption, which sometimes happened prior to either an eruption of Morning or of UNNG-FTN-2, just as it had happened prior to an eruption of Fountain or of UNNG-FTN-2 when the Complex was on Fountain function.

In the first case, Jet had one eruption after Morning started but before UNNG-FTN-2 started. The interval between the last Jet eruption prior to the Morning eruption and the eruption during Morning's eruption was 7.3 minutes. After UNNG-FTN-2 erupted, Jet went into a post-UNNG-FTN-2 quiet period, which lasted more than 23 minutes.

In the second case, Jet erupted two times during Morning's eruptions, for intervals of 6 and 3.5 minutes. After UNNG-FTN-2 erupted, Jet went into a post-UNNG-FTN-2 quiet period that lasted more than 30 minutes.

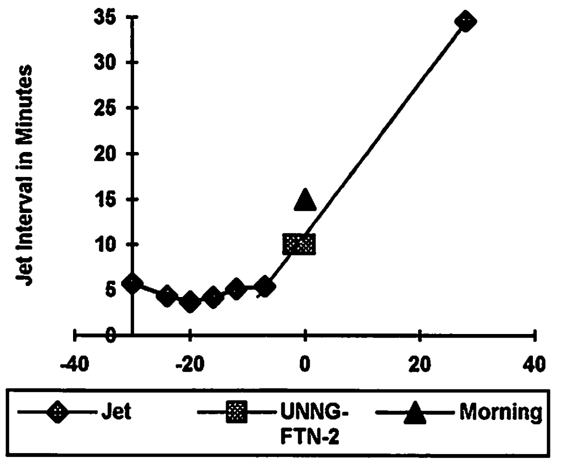
Visual examination of the data indicates that the longer Morning's duration was, the greater chance there was that Jet would have two or three eruptions during Morning's eruption. Since Jet's intervals when one Jet occurred

FIGURE 6. Sample Jet Cycles When UNNG-FTN-2 Started An Eruption During Morning's Eruption



Times for Morning eruptions set at 0 and 100 on the vertical axis.
−2 on the Jet interval axis indicates Jet was quiet but the end of the quiet period was not determined

FIGURE 7. Sample Jet Cycle When Morning Erupted During UNNG-FTN-2's Eruption



during a Morning eruption and one Jet occurred outside a Morning eruption were about 10-15 minutes long, it would be logical that for a short Morning duration, Jet would only erupt once, or not at all. On the other hand, when Morning's duration was about 25 minutes, there was a greater chance that two or three Jet eruptions would occur during Morning's eruption.

Figure 7 shows Jet's cycle when UNNG-FTN-2 erupted and Morning erupted during UNNG-FTN-2's eruption while Jet was in a post-UNNG-FTN-2 quiet period.

In this case, Jet was erupting at 5 to 6 minute intervals. Just prior to UNNG-FTN-2's eruption, Jet had a minor eruption. UNNG-FTN-2 erupted and Jet entered a quiet period. Morning erupted two minutes after the start of UNNG-FTN-2's eruption. Jet remained quiet until sometime after Morning had finished, an interval exceeding 28 minutes.

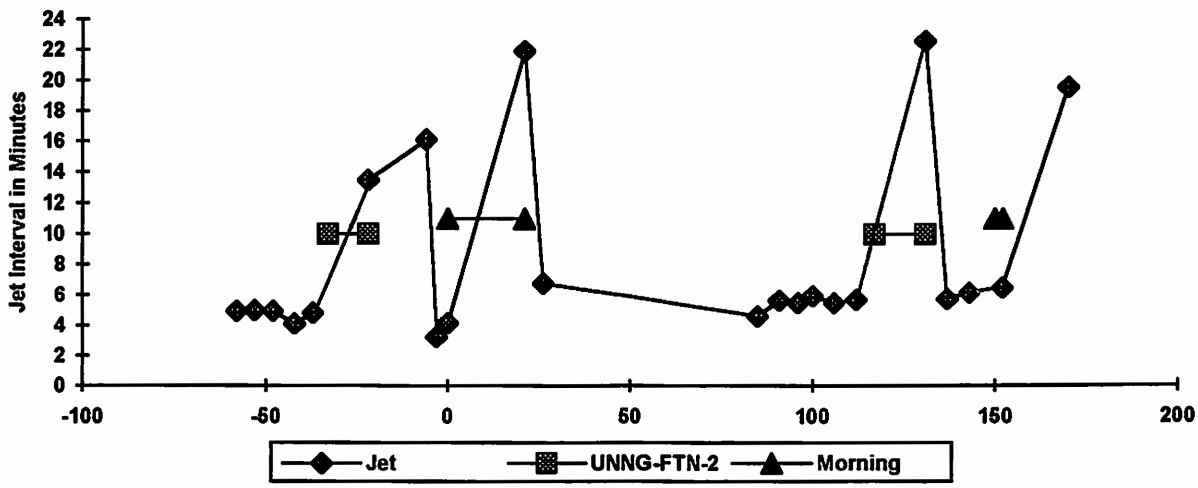
Although there were several cases where Morning started an eruption during UNNG-FTN-2's eruption, no observations were collected on the first Jet eruption following the end of the Morning eruption. Observations ranged from "greater than 16 minutes" to "greater than 31 minutes".
Jet exhibited one other type of activity while Morning was active in August. Jet occasionally had an eruption during UNNG-FTN-2's eruption. The first such case was observed on the morning of August 13, but the Jet interval before the eruption that occurred during UNNG-FTN-2's eruption was not recorded. Figure 8 shows two typical cycles where Jet erupted during an eruption of UNNG-FTN-2.

Observations on August 15 provided data for the first case. Jet was erupting at about 5 minute intervals. UNNG-FTN-2 erupted and Jet had one eruption during UNNG-FTN-2's eruption. The Jet interval preceding UNNG-FTN-2 was 4.8 minutes. The interval during which the UNNG-FTN-2 start occurred was 13.5 minutes and the interval during which UNNG-FTN-2 ended was 16.2 minutes. Then Jet went back to 3 to 4 minute intervals before increasing prior to Morning's next eruption.

Data for the second sample was taken from observations on August 22. Jet intervals were fluctuating around 5.5 to 6 minutes. Then UNNG-FTN-2 erupted four minutes after a Jet eruption. Jet remained quiet for 19 minutes after the start of UNNG-FTN-2, a total interval of 22.6 minutes. UNNG-FTN-2 stopped erupting about a minute after the Jet eruption. Jet erupted just slightly less than 5 minutes later, an interval of 5.8 minutes. Jet had one additional eruption with a 6.4 minute interval before Morning started erupting. Jet's only eruption during Morning's eruption occurred 1.5 minutes after Morning started. The interval that ended with this eruption was 6.5 minutes. Jet's next eruption occurred after an interval of 19.6 minutes.

These two cases, where the two Jet intervals surrounding UNNG-FTN-2's eruption total about 30 minutes, demonstrate another common feature of Jet's behavior while Morning was active. When there was a Jet eruption during an eruption of UNNG-FTN-2, it seemed like the 30-minute post-UNNG-FTN-2 quiet period had been split, or interrupted by an eruption of Jet. This Jet eruption was usually a minor eruption.

FIGURE 8. Sample Cycles Showing Jet Eruptions During Eruptions of UNNG-FTN-2



Occasionally, Jet had a very long quiet period. On August 13, a post-UNNG-FTN-2 quiet period lasted over 219 minutes. On August 15 there was one exceeding 168 minutes; on August 18, one exceeded 66 minutes; and, on August 21, one exceeded 120 minutes. In two of these cases, activity of Morning and Jet preceding the start of the long quiet period is not known. In one case, Jet was erupting, then UNNG-FTN-2 erupted, then Morning erupted, and then UNNG-FTN-2 erupted again, still without an eruption of Jet. In the other case, Jet was erupting, then Morning erupted and UNNG-FTN-2 erupted while Morning was still erupting, and Jet had not resumed eruptions when data collection ended. Because of the limited number of observations and the lack of knowledge about what other geysers were doing at both ends of the interval, it is not possible to determine whether these long quiet periods were attributable to UNNG-FTN-2, Morning, or a conjunction of eruptions by the two.

Following an eruption of UNNG-FTN-2, Jet was completely quiet for a time. Then Jet would periodically growl or roar until it resumed eruptions. This behavior was similar to behavior Jet exhibited when Fountain was active.

Jet's durations of major eruptions ranged from 30 seconds to 2 minutes when the Complex was operating on Morning function. Again, durations appear to be correlated with intervals, with longer durations occurring after longer intervals and before shorter intervals. Jet still occasionally had minor eruptions, but not as frequently as it did when Fountain was active. Most minor eruptions occurred just before or after an eruption of UNNG-FTN-2 or during an eruption of Morning.

JET'S ACTIVITY DURING PERIODS OF EXCHANGE OF FUNCTION BETWEEN FOUNTAIN AND MORNING AND SOME SPECULATIONS

On May 4, while Morning was active, Jet's intervals ranged from 6 to 9 minutes. Exceptions were the two intervals (16 and 11 minutes) preceding the UNNG-FTN-2 eruption that preceded Morning's final May eruption. No concurrent eruptions of Jet and UNNG-FTN-2 were seen on May 4 and 5. Jet's behavior after the 09:38ie eruption on May 4 is not known. However, no 3.5 to 5 minute intervals occurred after an eruption of Morning for the next four eruptions of Morning. This Jet behavior was similar to behavior that was seen on August 10 when Morning again reactivated with solo eruptions. Although we will never know just when Morning reactivated in late April or early May, Jet's behavior may indicate that Morning had not been active for very long before it was observed in eruption on May 4.

The Dunns and Benders reported that Jet erupted at 13:42 and 13:49 on July 4. UNNG-FTN-2 erupted from 13:43 to 14:06. Jet next erupted at 14:28 and 14:34 prior to the July 4 concerted eruption of Fountain and Morning that started at 14:42. This behavior is consistent with Fountain function Jet behavior. Aboveground evidence of the energy shift that was taking place underground was not present in Jet's behavior.

On July 5, Jet's intervals within a series ranged from 6 to 8 minutes, again consistent with Fountain function, and again providing no aboveground evidence of the underground energy shift.

The only concurrent Jet/UNNG-FTN-2 eruptions observed July 4-6 occurred during the concerted eruptions of Morning and Fountain. On July 4, one concurrent Jet/UNNG-FTN-2 eruption occurred after Morning had finished erupting. On July 5, one concurrent Jet/UNNG-FTN-2 eruption occurred while Morning was still erupting.

In summary, there was a lack of short Jet intervals and lack of concurrent JET/UNNG-FTN-2 eruptions except during the concerted eruptions of Fountain and Morning for the period July 4-6. This provides additional evidence that the July 4 and 5 concerted eruptions of Morning and Fountain were indeed a partial energy shift.

On August 9, the Fountain Complex was under observation for just under three hours prior to the 19:23 concerted eruption of Fountain and Morning. Jet's intervals started at 7 minutes when I first began collecting data, then fluctuated between 5 and 6 minutes for the next 2.5 hours. These intervals are consistent with either pre-Fountain or pre-Morning Jet intervals. However, one eruption of UNNG-FTN-2 occurred at 18:15, 68 minutes before Fountain started the concerted eruption. Jet did not erupt during this eruption of UNNG-FTN-2. Jet had an interval of 37.6 minutes between the last Jet eruption prior to the UNNG-FTN-2 eruption and the first Jet after UNNG-FTN-2 stopped. Again, there is a lack of aboveground Jet evidence of the underground shift of energy that was taking place.

The first solo eruption of Morning that was observed occurred at 05:25 on August 10. I left immediately after the eruption, without waiting to see what Jet did. Following the 09:48 eruption of Morning, Jet had intervals of less than 4 minutes an hour after Morning's eruption. After the 13:23 eruption of Morning, Jet was quiet (probably a continuation of a post-UNNG-FTN-2 quiet period that started before Morning erupted). Jet had three intervals exceeding 5 minutes when it resumed activity. The intervals then decreased to less than 5 minutes, and stayed there until 15:14, almost 2 hours after the preceding eruption of Morning had started. The first concurrent Jet/UNNG-FTN-2 eruption wasn't seen until 07:02 on August 13.

Part of Jet's response to the complete shift of energy, intervals under 5 minutes, was evident no later than 10:48 on August 10, 15 hours after the concerted eruption of Fountain and Morning. However, another part of Jet's reaction, concurrent Jet/UNNG-FTN-2 eruptions, was not witnessed for 3 1/2 days. Presence of intervals under 5 minutes within 15 hours of the concerted eruptions may again indicate that Morning had not been active for days prior to the 09:38ie May 4 eruption.

Morning's final solo eruption of 1991 occurred at 11:38 on August 28. Data collection stopped at 11:50 while Jet was still in a post-UNNG-FTN-2 quiet period. Data collection resumed at 14:18, 4 hours 35 minutes before the concerted eruption of Fountain and Morning at 18:53. However, data was not collected between 17:44 and 18:53, the last 69 minutes prior to the concerted eruption.

Between 14:18 and an eruption of UNNG-FTN-2 at 15:37, Jet's intervals fluctuated between 4.5 and 6 minutes. These intervals were consistent with pre-Morning Jet intervals. Jet erupted once during the UNNG-FTN-2 eruption that started at 15:37. The two Jet intervals containing the UNNG-FTN-2 eruption were 13.5 and 15.3 minutes, again consistent with Morning function. When Jet resumed activity, intervals fluctuated between 5.8 and 6.9 minutes, again consistent with

Morning function. Thus, Jet exhibited Morning function type behavior to within at least 69 minutes prior to the concerted eruption of Fountain and Morning. Again, Jet's behavior aboveground did not reflect what was happening underground.

An alternative explanation for the lack of aboveground evidence from Jet may be that the underground shift of energy didn't take a very long period of time. Examination of the portacorder strip for August 28 indicated that "noise" from steam bubbles collapsing underground that normally preceded Morning's eruptions was present several hours prior to the 1853 concerted eruption. The noise started about the same time prior to a Morning eruption that it had with solo eruptions of Morning. This, combined with a lack of warning signs by other geysers in the Fountain Complex that the energy was starting to shift back toward Fountain, may indicate that it took no more than five hours for the energy to shift sufficiently from Morning toward Fountain to allow the concerted eruption to happen. Certainly it took less than 8 hours 15 minutes, the interval between the last solo eruption of Morning and the concerted eruption with Fountain.

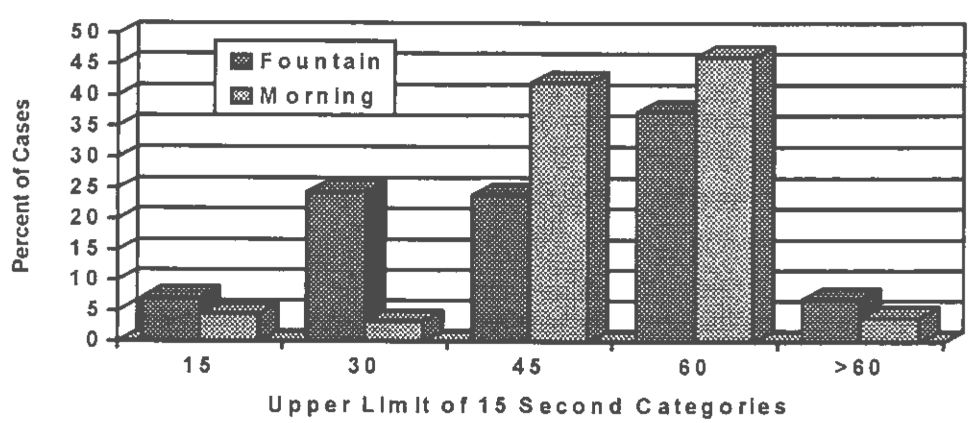
DURATIONS

Figure 9 shows the distribution of Jet's durations from July 21 to August 28. From July 21 to August 9 when Fountain was active, 540 durations were recorded. The durations range from a minimum of 5 seconds to a maximum of 70 seconds, and have a mean of 40 seconds with a standard deviation of 15.8 seconds. Bower [1992] observed an overall mean for Jet's durations of 47.2 seconds with a standard deviation of 17.1 seconds. From August 10-28 when Morning was active, 1076 durations were recorded. These durations range from a minimum of 5 seconds to a maximum of 120 seconds, and have an average of 45 seconds with a standard deviation of 11.25 seconds.

Jet's intervals were much shorter when Jet was erupting during Fountain's eruption than they were when Fountain was quiet, which probably accounts for the shorter durations observed in 1991 when the Fountain Complex was on Fountain function. Bower [1992] computed a mean duration for Jet eruptions of 25.2 seconds when Fountain was on and 58.1 seconds when Fountain was off. Probably because Jet was not erupting at 1.5 to 2 minute intervals while Morning was active, Jet's durations while Morning was active were longer.

The difference in variability between the Fountain function and Morning function durations is statistically significant ($F=1.97$, df 539/1075, $p<.001$). The greater variability of the Fountain function durations is probably attributable to minor eruptions of Jet. Jet had more minor eruptions when Fountain was active. Visual

FIGURE 9. Comparison of Jet's Durations for July 21-August 9 and August 10-28



examination of the data indicated that durations of Jet's eruptions during Fountain's eruptions were about 2/3 the length of Jet's durations when Jet was not erupting concurrently with Fountain.

The difference in means between the two distributions is also statistically significant ($t=5.53$, df 450, $p<.0005$). The Morning function durations were significantly longer. Again, this is probably attributable to the lack of 1.5 to 2.5 minute intervals and minor eruptions that occurred during Fountain's eruptions.

CONCLUSION

During 1991, Jet exhibited cyclic behavior. When Fountain was active, Jet erupted every 1.5 to 4 minutes during Fountain's eruption. After Fountain ended, Jet had a period of quiet lasting hours. When Jet resumed eruptions, intervals usually started at 8 to 10 minutes. Intervals gradually decreased to about 6 minutes prior to the next Fountain's eruption. Following an eruption of UNNG-FTN-2, Jet had periods of quiet ranging from 30 to 60 minutes.

When Morning became active, Jet's cycle with respect to the cycle of the active major geyser in the Fountain Complex reversed. During Morning's eruption, Jet had one or two eruptions, erupting at about 10 to 12 minute intervals. Following Morning's eruption, Jet's intervals dropped to 3 to 4.5 minutes, then gradually increased to about 6 minutes before the next Morning eruption. Following an eruption of UNNG-FTN-2, Jet still had periods of quiet ranging from 30 minutes to hours. Occasionally Jet would have an eruption during UNNG-FTN-2's eruption, resulting in 10 to 12 minute intervals.

Due to the cyclic nature of Jet's activity, calculating an average interval is meaningless. Jet's average interval in different portions of the cycle was anywhere from 1.5 minutes to hours. Jet had minor eruptions when Fountain was active, but not when Morning was active. Thus, durations were shorter and more variable when Fountain was active than when Morning was active.

UNNG-FTN-2 exhibited control over Jet both when Fountain was active and when Morning was active. Eruptions of UNNG-FTN-2 suppressed Jet's eruptions. The report on UNNG-FTN-2's activity in 1991 more fully discusses UNNG-FTN-2's control over Jet.

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UNNG-FTN-2 ("SUPER FRYING PAN") ACTIVITY IN 1991, LOWER GEYSER BASIN, YELLOWSTONE NATIONAL PARK

by Lynn Stephens

ABSTRACT: This paper describes UNNG-FTN-2's activity from July 22 - August 31, 1991. UNNG-FTN-2's average interval and duration increased when the Fountain Complex switched from Fountain function to Morning function. The exchange of energy also weakened UNNG-FTN-2's control over Jet.

INTRODUCTION

UNNG-FTN-2 is located about 12 meters northwest of Jet Geyser and erupts from several fractures in the sinter. The history of this feature is somewhat unclear. Bryan [1991, p. 143] notes that "This geyser is a rather recent development, first showing signs of its existence during 1966 but not breaking out in distinct form until 1975." Sam Martinez [1978, p. 78-8] stated "...it first popped out of the sinter in 1974." Marler [1973, p. 335] reported that it developed "during the past 6 years". However, William Lewis apparently observed this feature in 1963. Lewis described it as follows: "Stegner's Crack--On July 7, at 3:10 p.m. as Mr. Stegner was inspecting the interpretive activity on the Fountain mound, water was seen boiling up an inch or so along a 4 foot crack between Jet and Clepsydra Geyser. The crack runs in a direction 90° to Jet. This was the first time this action was observed. It continued active all summer. A duration of 20 minutes was recorded on July 13. The boiling along the crack has removed the eroded sinter about it [1963, p. 3]."

There has been some dissension about a name for this geyser, which has the informal name "Super Frying Pan". Several other names have been suggested, but none have become common usage. Because I used the designation UNNG-FTN-2 in other reports, I will continue to use it in this report.

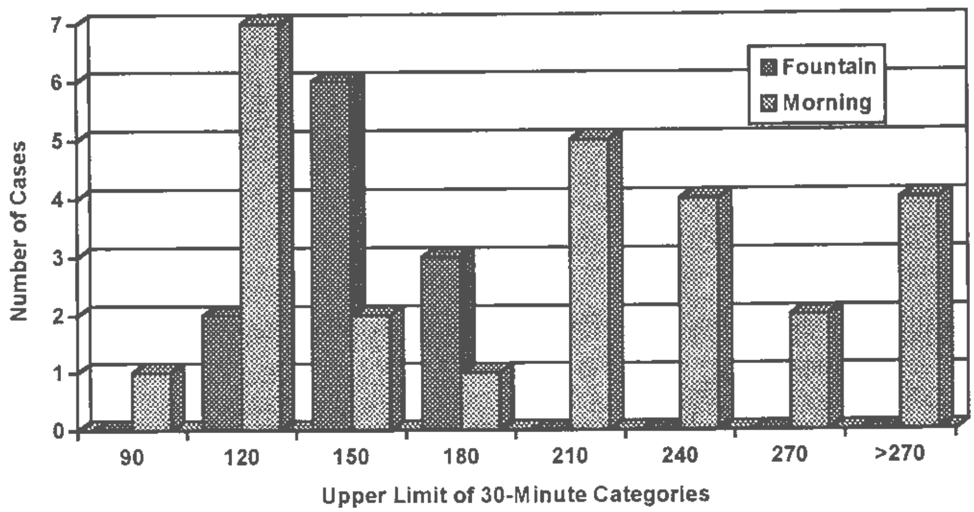
This report describes activity by UNNG-FTN-2 July 22 - August 9, 1991, when Fountain was active, August 10-28, when Morning was active, and times when the energy was shifting between Fountain and Morning. The first section discusses intervals. The second section discusses durations. Each of these sections presents a comparison of 1991 observations with reported observations for prior years. The third section contains a discussion of the interaction between intervals and durations. The fourth section presents a discussion of UNNG-FTN-2's relationships with Jet, Fountain, and Morning. The final section reviews activity of UNNG-FTN-2 during the times energy was shifting between Fountain and Morning--May 5, July 4-7, August 9, and August 28-29--and during Fountain's recovery on August 30-September 1.

INTERVALS

Figure 1 shows UNNG-FTN-2's intervals, stratified into 30 minute segments. Eleven intervals for UNNG-FTN-2 were observed from July 22 through August 8. The intervals range from a minimum of 1 hour 55 minutes to a maximum of 2 hours 44 minutes, and have an average of 1 hour 18 minutes, with a standard deviation of 16.7 minutes. From August 10 through August 27, when Morning was active, 26 intervals of UNNG-FTN-2 were observed. These intervals range from a minimum of 1 hour 20 minutes to a maximum of 5 hours 39 minutes, and have an average of 3 hours 6 minutes with a standard deviation of 77 minutes.

The distribution of intervals for Fountain function (July 22-August 8) appears quite different from the distribution of intervals for Morning function (August 10-28). Differences for both variability ($F=21.27$, df 25/10, $p<.001$) and means ($t=3.02$, df 30, $p<.005$) are statistically significant. UNNG-FTN-2 responded to the energy shift from Fountain to Morning with longer, more variable intervals.

FIGURE 1. UNNG-FTN-2 Intervals July 22-August 8 and August 10-28



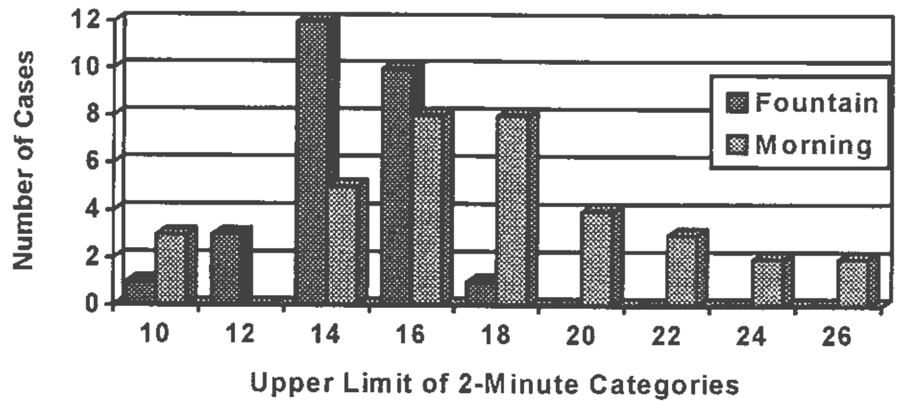
How do the 1991 observed intervals compare with other reported intervals? Marler [1973, p. 335] noted that eruptions of UNNG-FTN-2 were "...periodic in action, however, their frequency and duration have not been determined." Bryan [1991, p. 147] lists the interval as 1-3 hours. For July 22 - August 28, 1991, UNGFTN2's intervals ranged from a minimum of 1 hour 18 minutes to a maximum of 5 hours 39 minutes, with an average of 2 hours 18 minutes when Fountain was active and an average of 3 hours 6 minutes when Morning was active. Both Fountain function and Morning function 1991 intervals were longer than Bryan's range, with the average interval for Morning function exceeding the upper limit of Bryan's listed range.

Morning was periodically active during 1982. Hutchinson [1982, pp. 52-53] listed the following statistics for UNNG-FTN-2: interval (based on 16 observations)--average 1 hour 19 minutes 40 seconds, standard deviation 17 minutes 9 seconds, minimum 53 minutes 20 seconds, and maximum 2 hours 1 minute 29 seconds. I do not know whether Hutchinson's 1982 statistics include observations of UNNG-FTN-2 both for times when Morning was active and times when Fountain was active or during an active period of only Morning. In any case, the intervals 1991 for both Fountain and Morning function were longer than those reported in 1982. The average interval for 1991 when Fountain was active equals the maximum reported by Hutchinson for 1982, and exceeded the 1982 average by 59 minutes, an increase of 75%. The 1991 Morning function average interval is 1 hour 47 minutes longer than the 1982 average, an increase of 135%. The 1982 standard deviation of 17 minutes 9 seconds is larger than the 1991 Fountain function standard deviation of 16.7 minutes, but much shorter than the 1991 Morning function standard deviation of 77 minutes.

Bower [1992] recorded 13 intervals in 1990 when Fountain was active, but Morning was not. The 1990 intervals averaged 1 hour 38 minutes 52 seconds, and ranged from 1 hour 19 minutes 10 seconds to 1 hour 53 minutes 20 seconds, with a standard deviation of 9 minutes 55 seconds. The 1991 average Fountain function interval was 40 minutes longer than the 1990 average, an increase of 40%. Again, 1991 measures of standard deviation exceeded 1990 statistics.

In all cases, UNNG-FTN-2 erupted at longer intervals in 1991 than it had in earlier years.

FIGURE 2. UNNG-FTN-2's Durations July 22-August 8 and August 10-28



Bower's 1990 statistics exceeded Hutchinson's 1982 statistics but were within the range listed by Bryan, so it is not possible to determine whether 1991 represented an unusual year for UNNG-FTN-2 or whether UNNG-FTN-2's intervals have lengthened in the last decade.

DURATIONS

Figure 2 shows UNNG-FTN-2's durations, grouped in 2-minute categories, for Fountain function (July 22 through August 8) and Morning function (August 10-28).

Twenty-seven (27) durations were recorded for Fountain function. These range from a minimum of 10 minutes to a maximum of 17 minutes, and have an average of 13.6 minutes with a standard deviation of 1.6 minutes. From August 10 through noon on August 28, when Morning was active, 35 durations were recorded. These durations range from a minimum of 8 minutes to a maximum of 24 minutes 15 seconds, and have an average of 16.75 minutes with a standard deviation of 4.2 minutes.

Examination of the data indicates that, as with intervals, UNNG-FTN-2's durations while Morning was active were both longer and more variable than they had been when Fountain was active. The differences in both variability (F=7.17, df 34/26, p<.001) and means (t=4.09, df 45, p<.0005) are statistically significant.

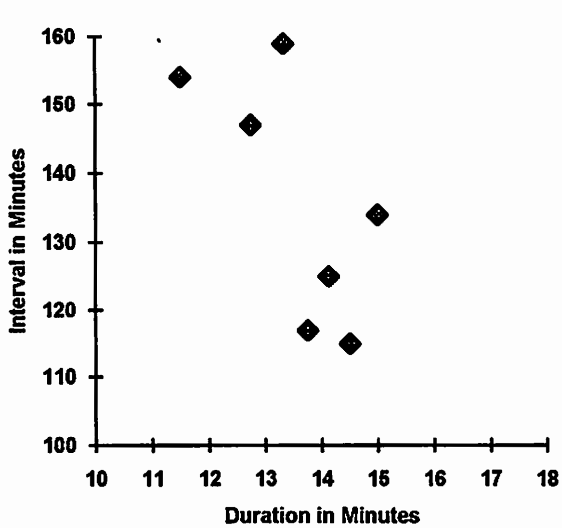
The 1991 range for durations from a minimum of 8 minutes to a maximum of 24 minutes is within the limits of 8 to 29 minutes listed by Bryan [1991]. Hutchinson [1982, p. 53] reported statistics for durations (based on 21 observations) as minimum 11 minutes 56 seconds, maximum 33 minutes, average 17 minutes 25 seconds, and standard deviation 5 minutes 27 seconds. The 1991 observed durations appear to be lower than Hutchinson's observations. The 1991 lower limit of 8 minutes is below Hutchinson's minimum of 11 minutes 56 seconds, a difference of almost 50% using 1991 lower limit as the denominator. The 1991 upper limit of 24 minutes is 9 minutes below Hutchinson's upper limit of 33 minutes, a factor of 37.5% using 1991 as the base. Both the 1991 Fountain function average of 13.7 minutes and the 1991 Morning function average of 16.75 minutes are shorter than Hutchinson's 1982 average of 17.42 minutes. The 1982 standard deviation of 5 minutes 27 seconds is greater than either the 1991 Fountain function standard deviation of 1.6 minutes or the Morning function standard deviation of 4.2 minutes.

Bower observed shorter durations in 1990, when Fountain was active, than were observed in 1991. Bower reported a total of 18 observations that averaged 12 minutes 16 seconds and ranged from a minimum of 10 minutes 35 seconds to a maximum of 17 minutes 10 seconds, with a standard deviation of 1 minute 36 seconds. The 1990 average is about 12% less than 1991 Fountain function average. The 1990 average showed less variability than was observed in either 1982 or 1991.

These comparisons, for both intervals and durations, should be used with caution. Morning was active in both 1991 and 1982, but the nature of its activity was very different. In 1991, Morning erupted from a nonoverflowing pool at much shorter intervals than it had in previous active periods. In 1982, Morning erupted from an overflowing pool at intervals that were longer than those in 1991 and, therefore, more consistent with Morning's intervals during other times of activity by Morning. So, it is possible that the nature of Morning's behavior pattern may account for part of the difference between the 1982 and 1991 observations.

Also, 9 years elapsed between the 1982 and 1991 observations. The difference may be due to a change in UNNG-FTN-2's behavior pattern due to a change over time rather than to a change associated with the nature of Morning's activity. Or perhaps, the difference is due to a combination of these two factors.

FIGURE 3. UNNG-FTN-2 Duration and Succeeding Interval July 22-28



INTERACTION BETWEEN INTERVAL AND DURATION FOR UNNG-FTN-2

There is a relationship between duration and interval for many geysers. Old Faithful is the best known example. The prediction formula for Old Faithful is a function of duration, where duration has a positive correlation with succeeding interval. Generally, the longer the duration of the current eruption, the longer the quiet period before the next eruption, so the longer the predicted interval. The system takes longer to recharge when more water has been expelled.

For July 22 through July 28, there were 7 observations where duration and succeeding interval for UNNG-FTN-2 were observed (Figure 3).

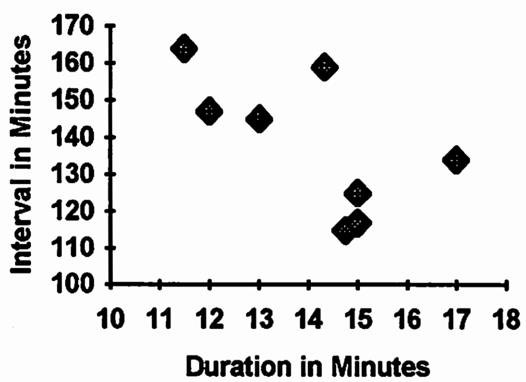
Examination of the cases matching duration and succeeding interval shows that rather than a positive correlation between duration and succeeding interval, there is a negative correlation for these cases. Longer durations occurred in conjunction with shorter succeeding intervals. A least-squares regression model applied to the cases showed an r^2 of .45. The relationship is statistically significant at a probability level of .10 but not at .05 (t=2.01, df 5).

An alternative explanation of geyser mechanics could be that the preceding interval affects duration. A long quiet period results in a higher energy level in the system. This results in a longer duration because the higher energy level supports expulsion of more water in the ensuing eruption.

For July 22-28 there were 8 cases where preceding interval and duration could be matched (Figure 4). Visual examination of these cases also shows a negative correlation between duration and intervals. A least-squares regression model applied to the cases resulted in an r^2 = .39. The relationship is statistically significant at a probability level of .05 but not at .025 (t=1.96, df 6).

There are several possible reasons why these cases show negative correlation between duration and both preceding and succeeding interval. The sample sizes are small. The

FIGURE 4. UNNG-FTN-2 Duration and Preceding Interval July 22-28



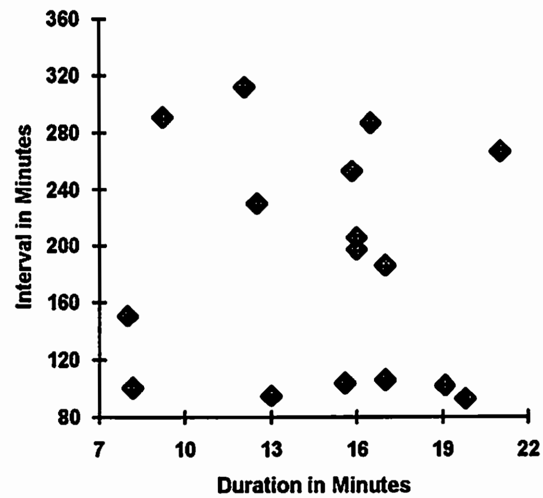
cases do not constitute consecutive observations. UNNG-FTN-2's relationship between intervals and durations may not be linear.

There may be interaction between the point in Fountain's interval at which UNNG-FTN-2's eruption occurs, or there may be interaction between UNNG-FTN-2's cycle and Jet's eruptive cycle. Examination of the 7 "succeeding interval" cases showed that none of the cases involved a situation where UNNG-FTN-2 and Fountain were erupting concurrently. However, 5 of the 8 "preceding interval" cases involved concurrent eruptions of UNNG-FTN-2 and Fountain. Four of the 5 concurrent eruption cases appear in the "long duration, short interval" category. Examination of the cases for "succeeding intervals" showed that 5 of the 8 cases occurred when Jet had not resumed eruptive activity following an eruption of Fountain; in 3 of the cases Jet had resumed activity. Two of the 3 cases where Jet had resumed activity are in the "long duration, short interval" group.

Between August 10 and August 28, 16 cases of UNNG-FTN-2's duration and succeeding interval were recorded (Figure 5). Most of the observations were collected before August 16.

Visual examination of the data shows no linear correlation between duration and succeeding

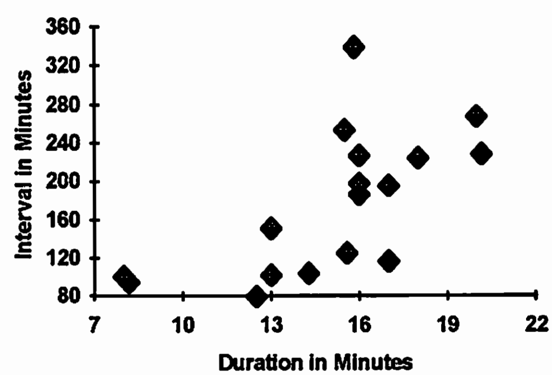
FIGURE 5. UNNG-FTN-2 Duration and Succeeding Interval August 10-28



interval. There appear to be two groups of cases, a set of 90-110 minute intervals and a set of 180-300 minute intervals. In both sets, durations are scattered throughout the short to long range of durations.

The 17 cases matching duration with preceding interval (Figure 6) do show a linear relationship. These cases show a positive relationship between duration and preceding

FIGURE 6. UNNG-FTN-2 Duration and Preceding Interval August 10-28



interval. In other words, longer preceding intervals resulted in longer durations. The relationship is statistically significant (t=3.25, df 15, .0005<p<.005).

Two problems associated with the UNNG-FTN-2 data for July may not be present in the August data. Because Morning's intervals were shorter than Fountain's and because UNNG-FTN-2's intervals were longer when Morning was active, the confounding factor of the point in the "major" geyser's cycle at which UNNG-FTN-2's eruption occurred may have been eliminated. Also, generally, Jet did not have long quiet periods that could be attributed to an eruption of Morning. Instead, Jet's intervals following a Morning eruption were short, gradually increasing until the next Morning eruption, except Jet had a quiet period due to an eruption of UNNG-FTN-2. So the confounding factor of whether or not Jet was in the eruptive portion of its cycle that occurred with the July data was not present in the August data.

Results for a straight-line relationship between duration and interval for UNNG-FTN-2 when Fountain was active were inconclusive (only marginal statistical significance) and inconsistent. Results for a straight-line relationship between duration and interval for UNNG-FTN-2 when Morning was active were statistically significant. A possible explanation for the positive correlation between duration and preceding interval is that the longer quiet spell preceding an eruption results in a better "recharge" of the system, enabling the succeeding duration to be longer.

Although the results for duration and preceding interval are statistically significant for the period Morning was active, these results must be used with caution. Although the sample size is larger, there is still the problem of non-consecutive observations.

RELATIONSHIPS BETWEEN UNNG-FTN-2 AND FOUNTAIN, MORNING, AND JET

UNNG-FTN-2's behavior changed when the Fountain Complex switched from Fountain to Morning function during 1991. This indicates that UNNG-FTN-2 has connections with Fountain and Morning. UNNG-FTN-2 also demonstrated control over Jet regardless of whether Fountain or Morning was active.

UNNG-FTN-2 and Fountain: Between July 22 and noon on August 9, UNNG-FTN-2 and Fountain eruptions overlapped in 16 cases. In 8 of the cases (50%), UNNG-FTN-2 started first; in the other 8, Fountain started first. There is no evidence that Fountain caused UNNG-FTN-2's eruptions to shorten. For the 8 cases where Fountain started first, average duration of UNNG-FTN-2 is 15.03 minutes, and durations range from a minimum of 12 minutes to a maximum of 17 minutes. The average for these 8 durations is slightly longer than the overall average duration of 13.6 minutes. There were 2 cases where UNNG-FTN-2 started an eruption less than 10 minutes after Fountain ended an eruption. There is no evidence that an eruption by Fountain interfered with UNNG-FTN-2's cycle in 1991.

UNNG-FTN-2 and Morning: There is also no evidence that an eruption by Morning interfered with UNNG-FTN-2's cycle. There were 16 observations of overlapping eruptions of Morning and UNNG-FTN-2. UNNG-FTN-2 started during Morning's eruption for 8 (50%) of the cases. Morning started during UNNG-FTN-2's eruption in 8 (50%) of the cases. Again, UNNG-FTN-2 starts were observed shortly after Morning ended, and there was no evidence that UNNG-FTN-2's durations were shorter if an eruption coincided with an eruption of Morning.

UNNG-FTN-2 is interconnected with Morning and Fountain, as evidenced by the statistically significant longer intervals and durations when Morning was active. However, eruptions by either of the major geysers did not appear to affect either UNNG-FTN-2's ability to erupt or the length of its durations in 1991.

UNNG-FTN-2 and Jet: Martinez [1978, p. 78-4] noted that UNNG-FTN-2 had an impact on Jet geyser, and observed that long quiet periods of Jet were "due to the activity of a nearby frying pan geyser." Hutchinson [1982, p. 53] stated "The most significant aspect of its [UNNG-FTN-2's] behavior was its tendency to stop or lengthen Jet Geyser's intervals by a factor of 2 to 6 while active." Bower

[1992] observed that Jet and UNNG-FTN-2 never erupted in concert except during Fountain's eruptions, and Jet's activity increased after an eruption of UNNG-FTN-2.

Observations during 1991 showed that UNNG-FTN-2's activity in 1991 was consistent with activity observed by Martinez and Hutchinson. UNNG-FTN22 exhibited clear evidence of control over Jet Geyser while the Fountain Complex was operating on Fountain function. UNNG-FTN22 retained some control over Jet when the Complex switched to Morning function. However, an eruption of UNNG-FTN-2 did not completely suppress Jet's activity during an UNNG-FTN-2 eruption. Also, Jet's quiet periods caused by an eruption of UNNG-FTN-2 decreased in length.

Between July 22 and August 9, there were 25 cases where the first Jet eruption following an eruption of UNNG-FTN-2 was recorded when no Fountain eruption was involved. Eight of the cases occurred when Jet had not resumed activity after the preceding Fountain eruption. In 6 cases UNNG-FTN-2's start time was recorded "ie", so the time of the last Jet eruption preceding UNNG-FTN-2's eruption was not known. This left 11 cases where Jet's interval with an intervening UNNG-FTN-2 eruption was determined. For these 11 cases, the minimum interval for Jet was 30.08 minutes and the maximum interval was 44.47 minutes, with an average of 36.31 minutes and a standard deviation of 4.43 minutes.

There were 8 cases where UNNG-FTN-2 erupted and then Fountain erupted before Jet had resumed activity. In 1 case, Jet's interval is not known. For the remaining 7 cases, Jet's interval ranges from a minimum of 27.45 minutes to a maximum of 41.4 minutes, with an average of 31.83 minutes and standard deviation of 4.23 minutes.

There were 8 cases where Fountain erupted and then UNNG-FTN-2 erupted. These cases demonstrate that Fountain's control over Jet was stronger than UNNG-FTN-2's control over Jet, but also demonstrate that UNNG-FTN-2 did retain some control over Jet even when Fountain started erupting first. When Fountain erupted but UNNG-FTN-2 did not, Jet's intervals during Fountain's eruption were about 1.5 minutes. However, when UNNG-FTN-2 erupted during Fountain's eruption, Jet's intervals were 2.5 to 4 minutes while UNNG-FTN-2 was also erupting, then dropped to 1.5 minutes immediately after UNNG-FTN-2 stopped.

During the first two days Morning was active, UNNG-FTN-2 showed the same type of control over Jet that it had when Fountain was active. On August 10 and 11, Jet's quiet intervals following an eruption of UNNG-FTN-2 ranged from ">48 minutes" to ">61 minutes". Three exact intervals were observed on August 10, with an average of 54 minutes. Beginning on August 15, a pattern emerged where Jet would erupt once during UNNG-FTN-2's eruption. Jet would be erupting at 3 to 5 minute intervals. The Jet interval preceding the eruption of Jet during UNNG-FTN-2's eruption and the interval succeeding this eruption totalled 28-32 minutes. Then Jet would go back to its 3-5 minute intervals. There were still times when Jet would not erupt during UNNG-FTN-2's eruption and would be quiet for a period following UNNG-FTN-2's eruption. In these cases, Jet's interval containing the UNNG-FTN-2 eruption would be 25-35 minutes long. It was as if the Fountain function Jet interval caused by an eruption of UNNG-FTN-2 had been split by the single eruption of Jet that occurred during UNNG-FTN-2's eruption. UNNG-FTN-2 no longer had the power to completely suppress Jet, but Jet could manage at most one eruption during the period UNNG-FTN-2 had control.

Jet's intervals were clearly dependent on the amount of time that had elapsed since the last Fountain or Morning eruption. Computing a precise factor by which UNNG-FTN-2 stopped or lengthened Jet's intervals is not possible because there was such a variety of Jet intervals. When Fountain was active, if Fountain started first and then UNNG-FTN-2 erupted, UNNG-FTN-2 lengthened Jet's intervals only by a factor of 2. If Fountain was quiet or UNNG-FTN-2 started before Fountain, Jet's interval was about 30 minutes, a factor of 3 times the 10 minute intervals Jet usually had when it first resumed eruptive activity after the preceding Fountain eruption, or a factor of 5 times the 6 minute intervals Jet usually had for a short time prior to the next Fountain eruption. On August 10, 50-minute Jet intervals represent a factor of 10-12 times the 3-5 minute intervals Jet exhibited following the preceding Morning eruption and prior to the eruption of UNNG-FTN-2. After Jet started having an eruption during UNNG-FTN-2's eruption, the factor was 2 to 3 when the 15 minute Jet intervals around the UNNG-FTN-2 eruption are divided by the 3-5 minute intervals Jet showed when UNNG-FTN-2 was not erupting.

Martinez [1978], Hutchinson [1982], and Bower [1992] concluded UNNG-FTN-2 had an impact on Jet. Bower [1992, p. 57] also stated UNNG-FTN-2 "...was a controlling influence upon Fountain, and, therefore the entire complex." In sharp contrast, Bryan [1991, p. 144] states that UNNG-FTN-2's "[E]ruptions, [are] clearly controlled to some extent by the activity of Fountain and Jet Geysers..." Observations in 1991 supported the conclusion that UNNG-FTN-2 exerts control over Jet rather than vice versa. The independence UNNG-FTN-2 exhibited from Fountain and Morning could also be construed to support Bower's contention that UNNG-FTN-2 is the dominant geyser in the Fountain Complex.

ACTIVITY OF UNNG-FTN-2 ON MAY 4 AND 5, JULY 4-7, AUGUST 9, AND AUGUST 28-31

On May 4-5, when Morning was active, three consecutive eruptions of Morning were observed, with intervals between the eruptions of 3 hours 58 minutes and 3 hours 29 minutes. In each case, Jet was erupting at 7-9 minute intervals. Then UNNG-FTN-2 erupted and Jet had intervals of 59, 68, and 54 minutes. Also in each case, Jet had not resumed eruptive activity after UNNG-FTN-2's eruption before Morning erupted. The similarity between this activity and relationships among UNNG-FTN-2, Jet, and Morning on August 10 may indicate that Morning had not been active very long before the 09:38ie eruption on May 4.

After the final May eruption of Morning at 00:25 on May 5, intervals for UNNG-FTN-2 decreased to 2 hours 48 minutes, 2 hours 44 minutes, 2 hours 19 minutes, 2 hours 25 minutes, 3 hours 7 minutes, and 2 hours 28 minutes, consecutively, before the Fountain eruption at 17:23. This pattern of longer intervals while Morning was active is consistent with the July-August pattern when UNNG-FTN-2's intervals were shorter when Fountain was active.

On July 4, following the concerted eruption of Fountain and Morning, the first interval for UNNG-FTN-2 was 3 hours 38 minutes. The next two intervals were 1 hour 58 minutes and 1 hour 35 minutes. These short intervals occurred between the concerted eruption and Fountain's solo eruption, but also occurred when Jet was in a noneruptive status for almost 5 hours. On July 5, prior to the concerted eruption, two intervals of 2 hours 41 minutes and 2 hours 30 minutes were observed. On the morning of July 6, intervals of 3 hours 2 minutes, 3 hours 12 minutes, and 2 hours 44 minutes occurred prior to the 13:22 solo eruption of Fountain. On the morning of July 7, one interval of 2 hours 15 minutes was recorded. The longer intervals on the morning of July 6 may indicate that the energy had not completely shifted back to Fountain.

On August 9, two intervals for UNNG-FTN-2 were observed. Both intervals overlapped the concerted eruption of Morning and Fountain. The first was 100 minutes, and the second was 78 minutes. The 78 minute interval was the second shortest recorded for 1991.

On the afternoon of August 28, when the energy started shifting back from Morning to Fountain no closed intervals were recorded. An interval of 80 minutes occurred after the concerted eruption started and before Fountain had finished erupting. On August 29, 6 intervals were recorded, ranging from a 71 minute interval (the shortest recorded UNNG-FTN-2 interval during the summer of 1991) during the Fountain portion of the concerted eruption, to a maximum of 116 minutes. Even though the energy was balanced between Morning and Fountain, UNNG-FTN-2 appeared to be back on Fountain function. Intervals of 123 minutes on August 30, and 107 minutes on August 31 were consistent with Fountain function.

CONCLUSION

Observations of UNNG-FTN-2's activity during 1991 raised just as many questions as they provided answers. UNNG-FTN-2 responded to the exchange of function with longer intervals and durations. UNNG-FTN-2 retained most of its control over Jet. However, data collection was not complete enough to determine UNNG-FTN-2's complete cycle of activity when Fountain was active nor to determine the relationship between UNNG-FTN-2's intervals and durations. Also, the relationship shown between durations and preceding intervals during Morning function was positive, rather than the negative association that Old Faithful exhibits and that some geyser observers suspect may exist with other geysers. There are several avenues open for future research to determine whether the 1991 patterns were peculiar to the type of activity that Fountain and Morning exhibited in 1991 and what UNNG-FTN-2's behavior patterns are like under different conditions or types of activity by Fountain and Morning.

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TWIG GEYSER, ACTIVITY DURING 1991
FOUNTAIN COMPLEX, LOWER GEYSER BASIN
YELLOWSTONE NATIONAL PARK

by Lynn Stephens

ABSTRACT: During 1991, Twig Geyser erupted at irregular intervals ranging from 7 to 40 hours. Twig's durations ranged from 50 minutes to over 5 hours. Some of the irregularity in both intervals and durations was associated with exchanges of function between Fountain and Morning. This paper describes Twig's activity during 1991 and discusses the changes in Twig's behavior that took place when the Fountain Complex switched from Fountain function to Morning function.

INTRODUCTION

Twig Geyser is located about 5.5 meters east of Fountain. Published references to Twig's activity patterns are scanty. Marler [1973] did not include any information about Twig in his *Inventory*, even though he occasionally mentioned it in his annual *Thermal Reports*.

Whittlesey [1988, p. 1893] states "In recent years, it [Twig] has erupted 5-6 feet high at frequent intervals for durations of up to an hour." Bryan [1991, p. 143] notes that "The only time when Twig shows clearly that it is a part of the Fountain Complex comes at the end of eruptions by Fountain Geyser. Then it sometimes (definitely not always) begins to enter a steam phase sort of play, in which steamy spray is played several feet high. Otherwise, its eruption is a bursting action up to 10 feet high. Overall, Twig seems to be in eruption about half the time." In his table summarizing behavior patterns of geysers in the Fountain Group, Bryan [1991, p. 147] lists Twig's intervals as frequent, duration 5 minutes to hours, and height 5-10 feet. In 1990, Bower [1992] recorded 5 intervals with a mean of 2 hours 29 minutes and 9 durations with a mean of 1 hour 24 minutes.

Observations of Twig's activity from July 21 to August 31, 1991, showed that Twig's activity in 1991 did not vary from Bryan's listed height of 5-10 feet. Few complete durations in 1991 were observed because durations were very long, consistent with Bryan's "hours" rather than Whittlesey's "up to an hour." No observed durations lasted less than 60 minutes. Intervals generally were 13-20 hours, although intervals outside this range occurred.

Twig's relationship with Fountain during 1991 also varied from previously published reports. Twig would have a steam phase at the end of its eruption. However, since most of Twig's eruptions while the Fountain Complex was operating on Fountain function **started** near the end of a Fountain eruption, this steam phase did not correspond with the end of eruptions by Fountain. Twig **stops** did coincide with Morning eruptions, so Twig's steam phase did occur concurrently with Morning.

Observations of activity by Twig's Satellite Vents, discussed in a separate report, did not show any evidence of correlation with Twig.

Discussion of Twig's activity in 1991 is organized into six sections: (1) May 4 and 5, complete exchange of function from Morning back to Fountain, (2) July 4-6, partial exchange of function between Fountain and Morning, (3) July 21-August 9, Fountain Complex on Fountain function, (4) August 10-28, Fountain Complex on Morning function, (5) August 28-September 1, partial exchange of function from Morning back to Fountain and recovery to Fountain function, and (6) speculation about a model explaining Twig's behavior.

MAY 4-5--COMPLETE EXCHANGE OF FUNCTION FROM MORNING BACK TO FOUNTAIN

The Fountain Complex was operating on Morning function from at least 09:38 on May 4 to 00:25 on May 5. Then the energy shifted back to Fountain, with Fountain erupting at 1723 on May 5.

Twig was in eruption at 10:40 on May 4, stopped sometime between 11:30 and 14:00, and did not erupt again until 04:19 on May 5, a quiet spell of more than 14 hours. The 04:19 eruption had a duration of 2 hours 36 minutes. Twig next erupted at 07:34, an interval of 3 hours 15 minutes. This eruption lasted 1 hour 17 minutes. Twig then had a series of short intervals--1 hour 54 minutes, 1 hour 31 minutes, 1 hour 41 minutes, 2 hours 38 minutes, and 1 hour 27 minutes. The durations of the first two eruptions in this series were each 50 minutes. Durations for the other eruptions were not noted.

Twig was active during the first observed eruption of Morning, quiet during the remainder of Morning's activity, seemed to show a period of recovery with a relatively long duration for the 04:19 eruption, and then had a series of short intervals. During this series of short intervals, Twig's behavior did match Bryan's description of "being in eruption about half the time." However, the frequency with which Twig erupted on May 5 was not noted again during the 1991 season, and neither was it in eruption about half the time.

JULY 4-6--PARTIAL EXCHANGE OF FUNCTION BETWEEN MORNING AND FOUNTAIN

Morning and Fountain had concerted eruptions on July 4 and 5. The Fountain Complex was operating on Fountain function prior to this attempted shift of energy to Morning, and returned to Fountain function (at least for about 4 weeks) after the attempted energy shift to Morning failed.

Dunns and Benders reported that "The [solo] eruption [of Fountain] of July 6th was different from those [concerted eruptions of Fountain and Morning] of July 4th and 5th in that it was preceded by repeated eruptive play from Twig." This is the only mention of Twig in their letter about the events they witnessed at the Fountain Complex for July 4-6. They were at the Fountain Complex at 09:15, 10:30, 12:30, and from 13:30 until 22:26 on July 4. It is possible that Twig may have had an eruption lasting about an hour between their visits at 09:15, 10:30, 12:30, and their return at 13:30. However, the only Twig durations observed during 1991 that were about an hour occurred on May 5 and on August 29. In both cases, the energy was shifting from Morning back to Fountain, whereas on July 4 the energy was shifting from Fountain toward Morning. Thus, it seems more likely that Twig did not have any short durations during that time. In any case, Twig was quiet for at least 6 hours--from 17:30 until 23:30.

The Complex was not under observation between 23:30 on July 4 and 06:20 on July 5 and Twig was not marked, so it is possible that Twig may have erupted during that time. Again, however, there is evidence to support an argument that it did not erupt. From July 21 through September 1, Twig eruptions were preceded first by periods of boiling noises from Twig without any visible water, and then periods of splashing inside Twig's tube, with water visible from the Fountain overlook, but not reaching above ground level. In most cases, these periods of noise and splashing occurred for at least 2-3 hours before Twig's eruption, and in one case periodic splashing continued for over 5 hours before Twig erupted. There was no activity of this type between 17:30 and 23:30 on July 4, and at 06:20 on July 5 there was no water around Twig's crater.

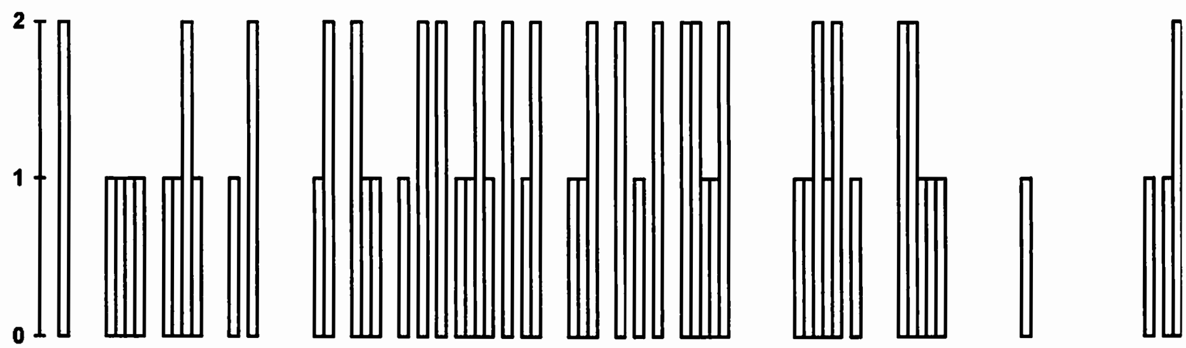
Twig was quiet from 06:20 on July 5 until Twig erupted at 09:18 on July 6, a known interval exceeding 27 hours, and possibly longer than 40 hours if Twig did not erupt between 23:30 on July 4 and 06:20 on July 5. A 40 hour interval is consistent with the 41.5 hour interval Twig had following the August 9 concerted eruption of Fountain and Morning.

The 09:18 July 6 eruption had a duration of 3 hours 32 minutes. This duration is comparable to the first Twig eruption following the cessation of Morning's activity in early May. The following interval of Twig was not determined, but was in excess of 5 hours, unlike early May, when the succeeding interval was 3 hours 15 minutes.

JULY 21-AUGUST 9--FOUNTAIN COMPLEX ON FOUNTAIN FUNCTION

From July 21 through August 5, 18 eruptions of Twig were recorded. Some eruptions of Twig were missed so this is not the total

FIGURE 1. Twig's Eruptive Status July 21 - August 9



Legend: 0 -- Twig's Status Unknown 1--Twig Inactive 2--Twig Erupting

number of eruptions that occurred in this time frame.

Twig's Eruptive Status: No complete durations of Twig's eruptions were obtained for July 21 - August 9. Figure 1 shows Twig's known periods of eruption and quiet, with each day stratified into 4 hour blocks. Examination of times when Twig was known to be quiet and times when Twig was known to be active indicated that Twig eruptions generally lasted at least 1.5 hours but less than 4 hours, although an eruption on August 5 exceeded 7 hours. The exact proportion of time Twig was in eruption is not known, but it appears that it was in eruption much less than "half the time" from July 21 to August 9.

Twig's Relationship With Fountain: Twig's eruptive cycle was synchronized with Fountain's eruptive cycle, with Twig starts occurring in conjunction with the end of Fountain's eruptions. Table 1 shows observations of the relationship between Twig and Fountain. Actual start times of Twig were recorded for 15 (83%) of the 18 Twig eruptions that were observed. Thirteen (87%) of the 15 actual starts are closely associated with the end of a Fountain eruption.

Two actual starts of Twig were not associated with Fountain eruptions. Two eruptions recorded "ie" were probably also closely associated with a Fountain eruption, and the other probably was an independent eruption. The three independent eruptions coincided with long Fountain intervals, and two of these occurred on August 4 and 5 when the energy was starting to shift from Fountain to Morning.

The probability of observing this many Twig starts associated with Fountain eruptions if the two events were really independent is quite small. Using, for the moment, only the 13 positively Yes and 2 positively No cases, the probability of seeing 2 or fewer stops is only .0037. In other words, there is only a 3.7% probability of being wrong in stating that the two events were related. Even if all three unknown cases were positively No, the probability of seeing 5 or fewer stops in a sample of 18 is only .0481. The relationship between Twig starts and Fountain eruptions is statistically significant.

Lag times between the start of a Twig eruption and the stop of a Fountain eruption for the 13 cases where actual Twig start times are available range from Twig starting 11 minutes before Fountain ended to 6 minutes after Fountain ended, have a median of 4 minutes, a mean of 3.6 minutes, and a standard deviation of 4.1 minutes.

The two Twig eruptions observed "ie" that were probably also associated with Fountain stops occurred on July 26 and 31. On July 26, Twig was in eruption at 14:38. Fountain had probably started an eruption between 12:30 and 13:30, so it is reasonable to assume Twig started near the end of that eruption.

Table 1. Twig Starts and Fountain's Eruptions

Twig Eruption Date	Twig Eruption Time	Fountain Stop	Lag Time	Association with Fountain: Yes	Unknown	Not Associated
7/21	**0947**	**0951**	**4 min.**	**X**		
7/23	**1415**	**1420**	**5**	**X**		
7/24	**1704**	**1708**	**4**	**X**		
7/25	**2335**					**X**
7/26	**1438ie**				**X**	
7/27	**1817**	**1828**	**11**	**X**		
7/28	**0152**	**0200**	**8**	**X**		
7/28	**1744**	**1750**	**6**	**X**		
7/29	**0711**	**0718**	**7**	**X**		
7/29	**2057**	**2100**	**3**	**X**		
7/30	**1737**	**1737**	**0**	**X**		
7/31	**0750ie**	**0751**			**X**	
7/31	**2210**	**2212**	**2**	**X**		
8/1	**1055**	**1055**	**0**	**X**		
8/2	**0033**	**0036**	**3**	**X**		
8/3	**1708**	**1702**	**-6**	**X**		
8/4	**0052**					**X**
8/5	**0545ie**					**X**
Number of Cases				18	2	3

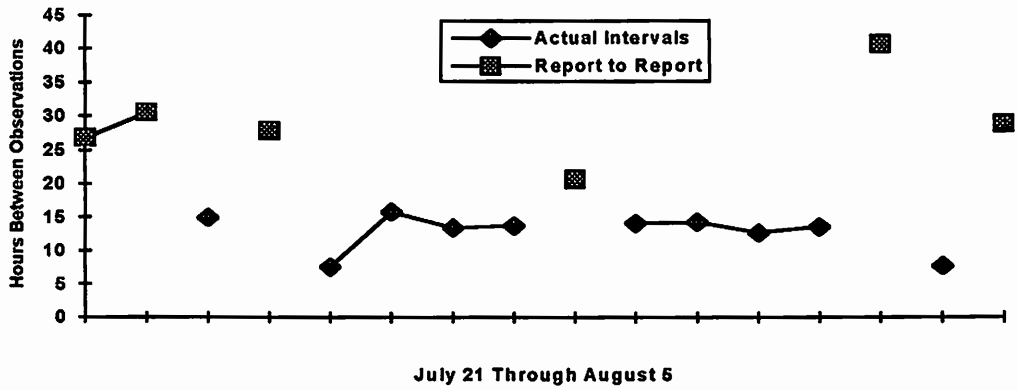
On July 31, Twig was "ie" at 07:50, and Fountain stopped at 07:51, so this eruption probably also started just a few minutes before Fountain ended.

On July 25 at 23:35, there was an independent Twig eruption. This is also the night that Fountain had an interval exceeding 16 hours. On August 4, Twig erupted at 00:52. I left the Complex shortly thereafter, when it had been 8 hours 37 minutes since the last Fountain eruption. Fountain's next observed eruption occurred at 1104, a double interval of 18 hours 41 minutes, or 9 hour 20 minute average.

On August 5, Twig was in eruption at 05:45 and was still in eruption at 12:55, but stopped before 15:50. Fountain eruptions occurred at 11:04 and 20:19 on August 4, overnight August 4-5, and 09:41 and 19:42 on August 5. It was overnight August 3-4 that Fountain started having the long intervals that presaged the shift of energy to Morning on August 9-10. It is possible that the same factor that triggered the shift of energy affected Twig, resulting in an independent Twig eruption and the very long duration on August 5. There were no observed eruptions of Twig on August 6, 7, and 8. This doesn't mean that there weren't any eruptions, just that no one saw or reported any eruptions. But it does mean that Twig wasn't starting near the end of Fountain's eruptions anymore either, adding further support to the speculation that whatever affected Fountain between August 4 and 9 also affected Twig.

Twig's Intervals: Closed intervals for Twig between July 21 and August 9 where actual start times were recorded for consecutive Twig eruptions range from 7 hours 35 minutes to 15 hours 52 minutes. Elapsed times between observations of Twig eruptions were computed by taking the difference between known consecutive start times, differences between actual and "ie" consecutive start

FIGURE 2. Elapsed Time Between Observed Eruptions of Twig



times, and differences between observed eruptions where consecutive observations did not represent closed intervals (report to report). Figure 2 shows these times.

The elapsed times fall into three groups. One group contains two closed intervals--one of 7 hours 35 minutes on July 27-28 and one of 7 hours 44 minutes on August 3-4. Nothing unusual happened in the Fountain Complex on the evening of July 27. But on the evening of August 3-4, Fountain had a long interval, so this Twig interval may be associated with the beginning of the energy shift from Fountain to Morning.

The second group of elapsed times between observations is eight cases in the 13 to 16 hour range. There is a possibility that some of these could represent double intervals since two 7 1/2 hour intervals would equal 15 hours. However, examination of my notes for the observation period surrounding the Fountain eruption that would have occurred between the two Twig observations showed no notations that Twig was making boiling noises nor that Twig was splashing inside the tube during the observation period. Since there were several occasions when such activity from Twig was observed for hours prior to the start of a Twig eruption, I am reasonably confident that most of these cases represent closed intervals, even though only two cases could be verified as closed intervals through the use of markers.

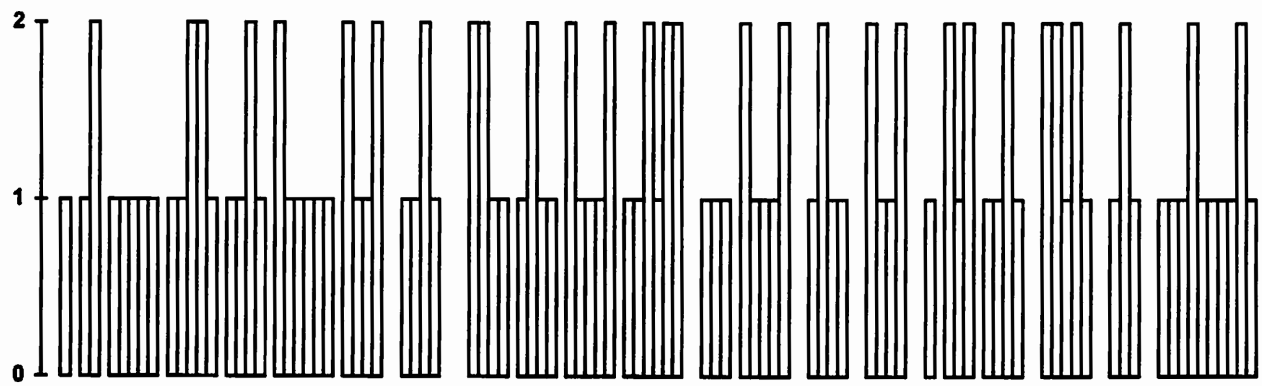
The third group of elapsed times contains four cases, one of 24 hours 53 minutes (involving an "ie" observation), one of 26 hours 49 minutes, one of 27 hours 50 minutes (involving an "ie" eruption), and one of 30 hours 31 minutes. Three of these involve a washed marker placed at a time that would indicate these are double intervals of 13-15 hours.

There are two isolated cases. One case, elapsed time of 20 hours 40 minutes, occurred between Twig eruptions at 20:57 on July 29 and 17:37 on July 30. Twig is known to have been quiet from 07:55 to 10:40 on July 30 and from 15:35 until the next observed eruption started at 17:37. It is possible that Twig started an eruption near the end of the Fountain eruption that occurred between 3 and 4 am. So this could be a combination of one 7 hour and one 13 hour interval for Twig.

The other isolated case, 40.5 hours, occurred between Twig starts observed at 00:33 on August 2 and 17:08 on August 3. The Fountain Complex was not observed for most of this time, so this case represents missing data.

An overall average interval for Twig from July 21 to August 9 cannot be computed because the number of eruptions that occurred is not known. However, the observations support a general statement that Twig erupted at 13-16 hour intervals, with an occasional 7.5 hour interval.

Figure 3. Twig's Eruptive Status August 9 - August 29



Legend: 0 -- Twig's Status Unknown 1--Twig Inactive 2--Twig Erupting

AUGUST 10 - AUGUST 28--FOUNTAIN COMPLEX ON MORNING FUNCTION

By 5 am on August 10, the energy had completely shifted from Fountain to Morning, and remained with Morning until the afternoon of August 28. Because Morning was erupting at 3 hour 15 minute to 5 hour intervals, observation times at the Fountain Complex were more frequent between August 10 and 28 than they had been between July 21 and August 9.

Twig's Eruptive Status: Five exact durations of Twig were observed, ranging from a minimum of 2 hours 46 minutes on August 12 to a maximum of 5 hours 27 minutes on August 11, with a median of 4 hours 40 minutes, and average of 4 hours 20 minutes. Three additional durations were observed where an "ie" start time combined with a known end time resulted in durations exceeding 4 hours 36 minutes, 4 hours 41 minutes, and 4 hours 45 minutes. Figure 3 shows Twig's eruptive status, stratified in 4 hour time frames.

Figure 3 seems to show that Twig was in eruption about 25-30% of the time. Beginning with the start of the 12:39 eruption of Twig on August 11 and ending with the start of the 19:09ns eruption on August 28, 414.5 hours elapsed. No eruptions of Twig were missed during this time. Twenty-three (23) eruptions occurred. Assuming an average duration of 4 hours 20 minutes, Twig was in eruption about 100 hours, or about 25% of the time.

Twig's Relationship with Morning: Twig starts were not as synchronized with Morning starts as they had been with Fountain starts. Table 2 shows he relationship between Twig's starts and stops and Morning's status.

Twenty-one (21) eruptions of Twig were observed, in some stage, between August 11 and 27. For these 21 eruptions, exact start times were recorded for 8 eruptions (38%) and "ie" times were recorded for the other 13 eruptions (62%). For the 8 eruptions where exact start times were recorded, 5 of the eruptions (62.5%) started during a Morning eruption, 1 (12.5%) started 6 minutes before Morning started, and 2 (25%) occurred midway between Morning eruptions. Six (6) of the 13 "ie" times occurred when the preceding Morning eruption had not been witnessed, so could have possibly started during Morning's eruption. For the other 7 "ie" eruptions, it is known that Twig's start did not coincide with a Morning start because Twig started sometime after one Morning eruption ended and the next one started. Thus, for the 21 eruptions, Twig's start did happen in conjunction with a Morning start for 6 eruptions (29%), did not coincide with Morning for 9 (43%) eruptions, and the status of Morning with regard to 6 (29%) of Twig's eruptions is not known.

Table 2. Twig's Association With Morning

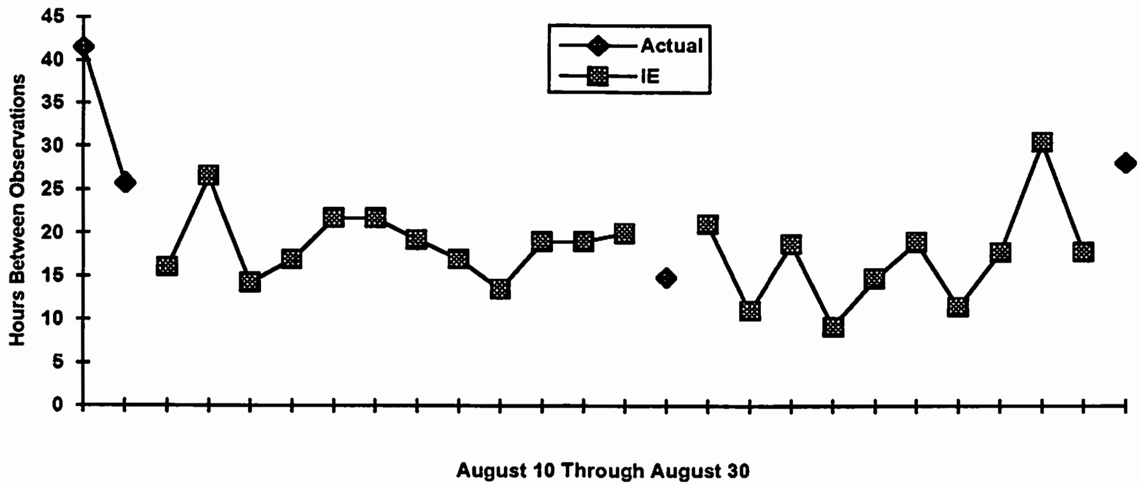
Twig Eruption			Twig's Association with Morning			
Date	Start	Stop	Start	Twig's Stop	Unknown	No
8/11	1239	1806	Yes			X
8/12	1429	1716	No	20 min after Morning start		
8/13	0320ie	0444	Unk.	1 min after Morning ended		
8/14	0545ie	0705	Unk.	14 min after Morning start		
8/14	1957		Yes		X	
8/15	1250	1730	No	12 min after Morning start		
8/16	1037ie	1513	No	4 min after Morning ended		
8/17	0824ie	1309	No	16 min after Morning start		
8/18	0345ie	0440	Unk.	15 min after Morning start		
8/18	2008		Yes		X	
8/19	0936ie	1118	No	5 min after Morning ended		
8/19	overnight		Unk.			X
8/20	overnight		Unk.			X
8/21	1901		Yes		X	
8/22	0953	1320	Yes	9 min after Morning started		
8/23	0700ie	0752	Unk.	15 min after Morning started		
8/23	1752ie		No		X	
8/24	1240ie		Unk.			X
8/24	2200ie	2252	No	15 min after Morning started		
8/25	1215	1700	Yes	6 min before Morning started		
8/26	0716ie	1015	Unk.			X
8/26	1844ie	2000	No	15 min after Morning started		
8/27	1235ie	1716	No	15 min after Morning started		
8/28	1909ns		Yes	Twig started near beginning of concerted eruption of Morning and Fountain		

On the other hand, Twig stops were associated with Morning eruptions. For the 23 eruptions, 14 (61%) Twig stops were associated with a Morning eruption, 3 (13%) were not associated with a Morning eruption, and for 6 cases, Morning's status could not be determined.

Stop times were observed for 16 (76%) of the 21 eruptions. Fourteen (88%) of the known Twig's stops were associated with Morning eruptions. In 10 cases, Twig stopped during Morning's eruption. In one case, Twig stopped 6 minutes before Morning started, and in three cases Twig stopped within 5 minutes after Morning ended. Most of Twig's stops occurred about 15 minutes after Morning started.

One stop time not associated with a Morning eruption occurred on August 11, midway between two Morning eruptions. This was the first eruption of Twig since the August 9 eruption that occurred in conjunction with the concerted eruption of Fountain and Morning. The eruption occurred after an interval of approximately 40.5 hours. This exceedingly long interval is consistent with the exceedingly long interval observed July 4-6 that also happened in conjunction with a concerted eruption of Fountain and Morning. The start of this Twig eruption was concurrent with a Morning eruption. This, plus the long interval preceding the eruption, indicates that Twig had not yet adjusted to the exchange of energy from Fountain to Morning and that Twig's cycles had not yet become synchronized with Morning's cycles. The other Twig stops not associated with Morning eruptions occurred on August 24 and 26, and were probably random occurrences.

FIGURE 4. Twig's Approximate Intervals August 10-30



It is unlikely that Twig stops coinciding with Morning eruptions were unrelated. If Twig stops were completely unrelated to Morning eruptions, the proportion of stops would be 50%. Ignoring, for the moment, the 6 unknown cases, 3 of 17 stops were not associated with Morning eruptions. There is only a .0064 probability of observing 3 or fewer stops not associated with Morning in a sample size of 17 if the true proportion of stops with (or without) Morning is 50%. In other words, there is a .64% probability of being wrong in rejecting the hypothesis that the stops associated with Morning eruptions were coincidental. Including the unknown cases increases the sample size to 23.

If half of the unknown cases were not associated with Morning eruptions, the probability of being wrong is less than 2%. If 4 of the 6 unknown cases were not associated with Morning eruptions, the probability of being wrong increases to 4.6%. If 5 of the unknown cases were not associated with Morning eruptions, the probability of being wrong increases to 10.5%. Finally, if all 6 of the unknown cases were not associated with Morning eruptions (a worst case scenario), the probability of being wrong increases to 20.2%. But the joint probability that 5 of the cases were not associated and the probability of seeing 8 or fewer cases is only .009850, and the joint probability that 6 of the cases were not associated and the probability of seeing 9 or fewer cases is only .003157. The relationship between Twig stops and Morning eruptions is statistically significant.

Twig's Intervals: Figure 4 shows elapsed time between observed eruptions of Twig. Elapsed times were computed by taking the difference between times when Twig was noted in eruption for both actual and "ie" times. Elapsed times range from a minimum of 9 hours 20 minutes (both eruptions observed "ie") to a maximum of 26 hours 25 minutes (both eruptions observed "ie"). There were only two cases where exact closed intervals were observed--one of 16 hours 53 minutes, and one of 14 hours 52 minutes. Examination of Figure 4 shows that the elapsed times do not group as cleanly as did the elapsed times between eruptions when the Fountain Complex was on Fountain function. Twig starts were not synchronized with Morning starts. Therefore, most of Twig's eruptions for August 10-28 were recorded "ie" rather than actual start time. Given the long durations that were observed, the elapsed time computations may be significantly different from what the actual closed intervals would have been. Elapsed time computations for Twig from July 21-August 9 did not have this difference because actual Twig starts were observed. This may account for the fact that the Morning function intervals do not group as neatly as do the Fountain function intervals.

Because the number of Twig eruptions beginning with the August 9 20:01 eruption and ending with the August 28 19:09ns eruption was determined, it is possible to compute an average interval for Twig. Starting with the 12:39 August 11 eruption, after which it appeared Twig had stabilized following the exchange of function between Morning and Fountain, 23 intervals occurred in the 414.5 hours, for an average of 18 hours.

Twig's adjustment to the exchange of energy included longer durations and longer intervals, and a switch from synchronization of Twig starts with Fountain eruptions to Twig stops with Morning eruptions.

AUGUST 28-SEPTEMBER 1--PARTIAL EXCHANGE OF FUNCTION FROM MORNING BACK TO FOUNTAIN AND RECOVERY TO FOUNTAIN FUNCTION

On August 28, the energy started to switch from Morning back to Fountain. Morning erupted solo at 11:38. Fountain and Morning erupted in concert at 18:53. Twig was not in eruption from 6 am to 8 am, from 11 am to noon, and 14:15 to 17:45. This time, Twig started soon after the start of the concerted eruption, rather than waiting until 40 minutes into the eruption at what would have been a normal lag time between the starts of Fountain and Twig the way Twig had on the August 9 concerted eruption. The eruption ended sometime between 21:30 and 21:50, a duration exceeding 2 hours 30 minutes.

Twig's next eruption occurred at 12:59 on August 29, an interval of approximately 18 hours. The duration of this eruption was 64 minutes, a very short duration compared to the greater than 4 hour durations observed in late July and in August. However, this duration is comparable with durations of Twig observed on May 5 when energy in the Complex was switching from Morning back to Fountain.

At 5 am on August 30, it appeared that Twig had recently finished--there was water in the runoff channel. Twig erupted at 17:09 on August 30, 29 minutes after the start of a Fountain eruption, or 10 minutes before the end of that Fountain eruption. At 8 am on August 31, Twig had recently finished an eruption, and Twig was in eruption at 17:45 that afternoon. And, on September 1, Twig started an eruption at 0:910 and stopped at 14:39, a duration of 5 hours 29 minutes. This duration is consistent with the durations observed while the Fountain Complex was operating on Morning function. From the few available observations, it appears that Twig had recovered from the energy exchange, and was erupting at 12 to 14 hour intervals instead of 18 hour average intervals as it had been when the Complex was on Morning function.

SPECULATION

In 1990 when Fountain was generally erupting at 10-12 hour intervals with durations of 50 minutes, Twig was in eruption about 50% of the time with intervals of approximately 2 hours 30 minutes [Bower, 1992]. Neither Twig starts nor Twig stops were associated with Fountain eruptions in 1990. In 1991 when Fountain was generally erupting at 7.5 hour intervals with durations of 40 minutes, Twig erupted at irregular intervals, but these were generally 13-16 hours, with an occasional 7.5 hour interval, Twig was in eruption much less than 50% of the time, and Twig **starts** were associated with the end of Fountain eruptions. Then, when the Fountain Complex switched to Morning function, with Morning erupting every 3 hours 45 minutes, Twig's intervals lengthened, and Twig **stops** were associated with eruptions of Morning.

One model that could explain these facts is two water supplies for Twig, T90 and T91. Normally T90 supports Twig's eruptions. When Twig does use T91, T91 takes much longer to recharge than does T90. Morning and Fountain share a water supply (M/F). Fountain normally uses the F portion of that supply and is generally blocked from using the M portion. Similarly, Morning uses the M portion is and usually blocked from the F portion

In 1990 Fountain was using F, there was not enough energy in M or combined M/F for Morning to erupt, Twig was using T90, and the energy in Fountain was such that Fountain's use of F did not affect T90 so there was no apparent relationship between Twig and Fountain.

Assume that the energy in F increased in 1991. This increased energy not only supported shorter Fountain intervals, but also blocked Twig from using T90 until Fountain's eruption(s) released enough energy to allow T90 to initiate a Twig eruption at the end of Fountain's eruption, similar to Grotto and Rocket. But while Fountain was active, there was enough energy in T90 that Twig did not tap T91.

Then the energy shifted to Morning. Assume that Morning was using both M and F. In most other active periods, Morning only used M but in 1991 Morning used both, which explains Morning's 3 hour 45 minute intervals. Each eruption of Morning released a small amount of the force F was exerting on T90, but not enough to allow Twig to erupt. Over several of these cycles, T91 gradually built enough energy by itself to initiate a Twig eruption. Eventually the energy in T91 reached the level necessary for Twig to erupt. After awhile, Morning's cumulative effect on F was sufficient to allow Morning to access T90 and drain the energy from it completely, forcing Twig to stop until T91 generated enough energy to initiate another Twig eruption.

Although T91 would be enough to explain the fact that some of Twig's starts also coincided with Morning starts, it is possible that T90 initiated some of Twig's starts. Perhaps there were times when Morning's cumulative effect on F reached just the right point, sufficient to allow T90 to initiate a Twig eruption but not enough for Morning to drain T90. This concept may seem unlikely, but then so did the possibility of non-earthquake induced concerted eruptions of Fountain and Morning before they happened in 1991.

CONCLUSION

Because no complete durations of Twig were observed when the Fountain Complex was operating on Fountain function, it is not possible to determine whether the shift of energy to Morning affected Twig's durations. Twig's intervals lengthened while the Complex was on Morning function. The type of synchronization between Twig's cycles and the cycle of the actibe major geyser changed. While the Complex was on Fountain function, Twig **starts** were associated with the end of Fountain eruptions. When the Complex was on Morning function, Twig **stops** were associated with eruptions of Morning.

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ACTIVITY OF "BEARCLAW" ("TWIG'S SATELLITE VENTS) IN 1991
FOUNTAIN COMPLEX, LOWER GEYSER BASIN
YELLOWSTONE NATIONAL PARK

Lynn Stephens

ABSTRACT: This paper describes the behavior patterns exhibited by Twig's Satellite Vents during the summer of 1991. Twig's Satellite Vents showed three adjustments to the exchange of function in the Fountain Complex that occurred on August 9. No evidence of connections with Twig was seen in 1991.

INTRODUCTION

The feature known as "Twig's Satellite Vents" and referred to as "Bearclaw" by Bower [1992] consists of three visible vents, arranged in a triangle, about 6 meters south of Twig. Rocco Paperiello has indicated that there is a fourth vent buried in the gravel. In 1991 the northwest and central vent usually erupted, with the central vent being more vigorous, erupting about 25 centimeters high. The eastern vent usually just received overflow from the central vent, but would occasionally erupt a few centimeters high.

Eruptions started from the central vent, and then the northwest vent joined in. Visitors enjoy "Bearclaw" because of its proximity to the boardwalk and the gurgling and sputtering noises that the vents make prior to and during an eruption. "Bearclaw" was in eruption about 40% of the time during the summer of 1991. Since many intervals were in the range of 10-15 minutes, most visitors saw "Bearclaw" active at some stage in its eruption. Indeed, some visitors would ignore Fountain's eruption while spending several minutes watching "Bearclaw".

Bower [1992] noted that in 1990 there was a "clear relationship" between Twig and "Bearclaw". He divided intervals into three types: (1) Fountain, which occurred during and immediately after Fountain eruptions, that were 10-13 minutes with durations of 3.5-5 minutes; (2) Twig, which occurred while Twig was in eruption, and were 48-54 minutes with durations of 1.5-3 minutes; and (3) Non-Twig, which occurred when neither Fountain nor Twig was active, and were 24-32 minutes. Although there were some similarities between "Bearclaw's" activity in 1990 and 1991, there were also differences. Discussion of "Bearclaw's" activity in 1991 is organized into three sections: wild phase activity, intervals, and durations.

WILD PHASE ACTIVITY

Table 1 shows the observations of "Bearclaw's" wild phase activity. From July 22 to August 9, when the Fountain Complex was on Fountain function, 8 episodes of wild phase activity were observed. Wild phase activity was also observed on August 9 during the Fountain portion of the concerted eruption of Morning and Fountain (after Morning had stopped), providing a total of 9 cases. All 9 cases occurred during a Fountain eruption. But not all Fountain eruptions resulted in wild phase activity by "Bearclaw". My notes contain observations of 13 Fountain eruptions where Bearclaw was erupting at 10-15 minute intervals, similar to Bower's Fountain type intervals.

Wild phase activity between July 22 and August 9 also did not serve as an indicator for Twig. Eruptions of Twig accompanied wild phase activity in 4 of 9 cases.

There do not appear to be any regular intervals at which wild phase activity occurred, other than multiples of 7 hours. Fountain's average interval was close to 7 hours. However, many consecutive eruptions of Fountain were observed without wild phase activity from "Bearclaw". The multiples of 7 range from a short of 7 hours on July 24 to a long of 56 hours on July 31.

Wild phase activity was observed 14 times between August 10 and 28 when the Fountain Complex was on Morning function. One case occurred on August 16, and another on

Table 1. Wild Phase Activity by "Bearclaw"

Date	Time	Duration (in min.)
7/21	0941	> 19
7/23	0719	55
7/24	1003	> 42
7/24	1703	> 18
7/26	0609ie	> 40
7/28	1000	> 25
7/29	0005	> 32
7/31	0745ie	> 33
8/9	1958	> 51
8/16	1208ie	> 47
8/19	0936ie	> 57
8/20	0819ie	> 24
	0901	101
	1434ie	>108
	1727ie	>173
8/21	0600ie	> 70
	0918ie	> 96
	1226	> 94
8/22	0525ie	> 60
	0825ie	> 70
	1538ie	> 56
	1945ie	> 49
8/25	0530ie	>185

August 25. A 2-hour quiet period followed the August 16 episode of wild phase activity, but this was the only long quiet period observed following wild phase activity. In all other cases, the quiet period following wild phase activity was brief. The interval preceding wild phase activity was also a normal interval, except when consecutive wild phase eruptions occurred August 20, 21, and 22.

The other 12 cases occurred August 19-22. This clumping of the observations may indicate some long term cycle in "Bearclaw's" activity when the Complex is on Morning function. That could only be verified if the Complex stayed on Morning function for several weeks, something it hasn't done in recent history.

Table 2. Association of "Bearclaw's" Wild Phase Activity with Morning and Twig

Morning in Eruption	Twig in Eruption: Yes	No	Total
Yes	1	6	7
No	2	5	7
Total	3	11	14

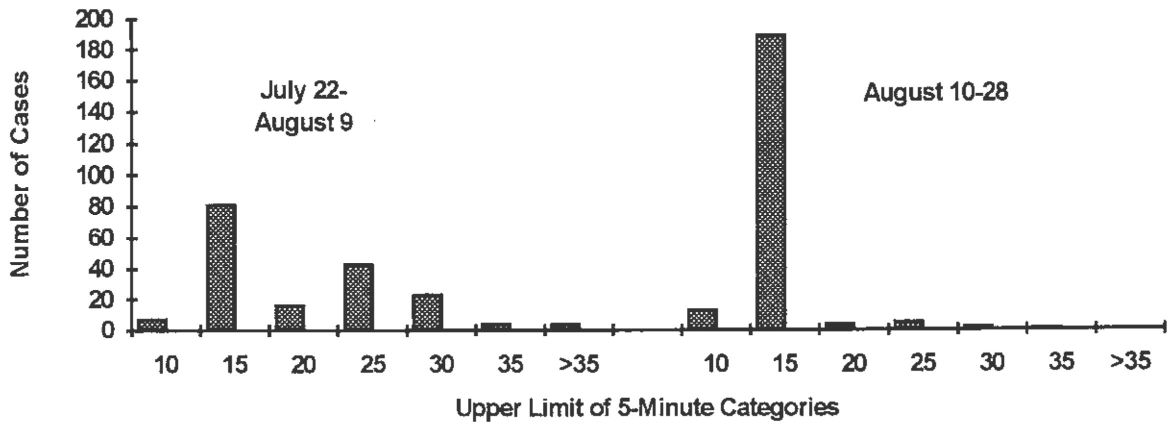
As shown in Table 2, wild phase activity was not correlated with activity by either Morning or Twig. Only three of the cases occurred in conjunction with, or close proximity to, an eruption of Twig. Half the cases occurred in conjunction with an eruption by Morning. But, even though Morning's durations were less than 30 minutes and all but one of the wild phase eruptions exceeded 24 minutes, in only half the cases was a Morning eruption observed during the wild phase activity. An eruption of Morning did overlap the wild phase activity case recorded as ">24 minutes", but did not overlap the one recorded as ">185 minutes". So, one of the adjustments "Bearclaw" made to the energy shift from Fountain to Morning was that wild phase activity started happening without an accompanying eruption by the active major geyser.

INTERVALS

Figure 1 shows the interval distributions for "Bearclaw's" intervals, excluding intervals that contained wild phase durations, for July 22-August 9 and for August 10-28. Unless otherwise stated, all references to intervals in this section refer only to non-wild-phase intervals.

Between July 22 and August 9 while the Fountain Complex was on Fountain function, 178 intervals for "Bearclaw" were recorded. These intervals range from a minimum of 8 1/2 minutes to a maximum of 56 1/2 minutes and have an average of 18 1/3 minutes with a standard deviation of 7 1/2 minutes.

FIGURE 1. "Bearclaw's" Intervals (Excluding Intervals that Included Wild-Phase Durations) July 22-August 9 and August 10-28



The Fountain function distribution is somewhat bimodal. One group of intervals, 10-15 minutes, contains 46% of the observations. A second group, 25-35 minutes, contains 37% of the observations.

In 1990 Bower [1992] observed 10-15 minute intervals only during and immediately after Fountain's eruptions. In 1991, 10-15 minute intervals occurred at other points in Fountains cycle in addition to during and immediately after Fountain's eruptions. Bower observed 24-32 minute intervals when neither Twig nor Fountain was active and noted that these were the most common variety of intervals. In 1991 these intervals again occurred only when neither Twig nor Fountain was active except sometimes the first "Bearclaw" interval after Fountain started an eruption would also be in this range. Because the proportion of 10-15 minute intervals increased in 1991, 25-35 minute intervals were not the most common type of intervals in 1991.

The two types of intervals did not intermix. "Bearclaw" would be erupting at 25-35 minute intervals, and then would abruptly switch to 10-15 minute intervals. Switches sometimes, but not always, occurred at the time of a Fountain or Twig eruption. Since switches didn't always happen in conjunction with a Fountain or Twig eruption, switches could not be used to predict an eruption of either of these geysers.

The type of interval also could not be used to predict wild phase activity. Wild phase activity was just as likely to be preceded by 10-15 minute intervals as it was by 25-35 minute intervals. Also, the intervals, excluding wild phase intervals, showed no correlation with durations (r^2 = .13 for 115 cases where duration and interval could be paired).

After the Fountain Complex switched to Morning function, almost all (88%) "Bearclaw's" intervals were in the 10-15 minute range, with only 3.3% in the 25-35 minute categories. The intervals for Morning function range from a minimum of 5.2 minutes to a maximum of 33 1/2 minutes, and have an average of 11.9 minutes and a standard deviation of 3 minutes. Durations during Morning function also were not correlated with intervals (r^2=.01).

The differences between the Fountain function and Morning function intervals are statistically significant for both variability (F=2.52, df 177/213, p<.005) and mean interval (t=22.93, df 89, p<.0005). The second adjustment "Bearclaw" made to the exchange of function was elimination of the 25-35 minute intervals.

DURATIONS

Figure 2 shows durations, excluding wild phase activity, for July 22-August 9 and August 10-28 in 1-minute categories. The 148 observed durations for July 22-August 9 range from a minimum of 2 minutes to a maximum of 8.25 minutes. The average is 5.2 minutes with a standard deviation of 1.3. The 209 durations for August 10-28 range from a minimum of 1.25 minutes to a maximum of 15 minutes. The average is 5.5 minutes with a standard deviation of 1.3 minutes.

Durations appeared to be shorter when the Complex was on Fountain function than when the Complex was on Morning function. The variability of the two distributions is not statistically significant ($F=1.03$, df 147/298, $p>.25$). The difference between means for the two groups is statistically significant ($t=2.42$, df 355, $p<.01$). "Bearclaw's" durations were significantly longer when the Complex was on Morning function than they were when the Complex was on Fountain function.

The proportion of time "Bearclaw" was in eruption was estimated using pairs of observations where both duration and the preceding interval were known. Total durations were divided by total intervals. For July 22-August 9, 115 pairs were available and for August 10-28, 163 pairs were determined. When the Complex was on Fountain function, "Bearclaw" was in eruption 30% of the time, and on Morning function 46% of the time, with an overall percentage for the summer of 1991 of close to 40%. The greater proportion for Morning function is due to the fact that the "Bearclaw" showed none of the 25-35 minute intervals exhibited when the Complex was on Fountain function.

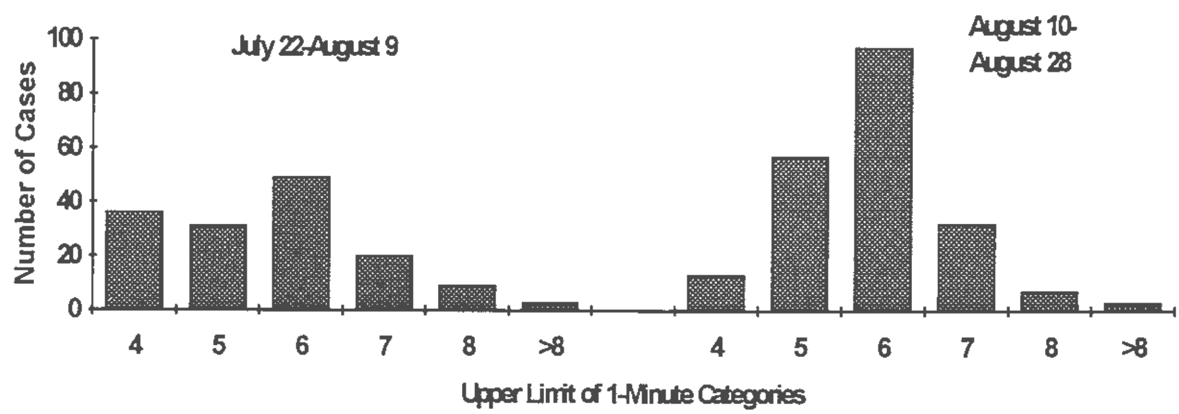
CONCLUSION

"Bearclaw" made three adjustments to the shift in energy from Fountain to Morning--(1) wild phase activity not occurring in conjunction with an eruption of the active major geyser, (2) elimination of the 25-35 minute intervals shown on Fountain function, and (3) longer durations on Morning function. Because Bower's 1990 observations showed a connection between "Bearclaw" and Twig, but observations collected during the summer of 1991 showed no evidence of connections between Twig and "Bearclaw", a fourth adjustment was demonstration of independence from Twig.

REFERENCES

Bower, Gordon R. "Activity of the Fountain Geyser Complex [1990], Yellowstone National Park, Wyoming," *GOSA Transactions III*, pp. 53-66.

FIGURE 2. "Bearclaw's" Durations July 22-August 9 and August 10-28



SPASM GEYSER, ACTIVITY DURING 1991 FOUNTAIN COMPLEX, LOWER GEYSER BASIN YELLOWSTONE NATIONAL PARK

by Lynn Stephens

ABSTRACT: During 1991 Spasm's eruptions consisted of boiling and bursting activity a maximum of 1 meter above ground, with most bursts being 30 to 50 cm above ground level. All observed eruptions of Spasm started with muddy water, which turned clear 5-15 minutes into the eruption. Spasm's intervals and durations changed when the Fountain complex switched from Fountain function to Morning function. Regardless of which major geyser in the Fountain Complex was active, Spasm's intervals closely corresponded with the intervals of that major geyser. This paper describes Spasm's behavior during the summer of 1991, and contains some speculations about causes for that behavior and underground connections among Spasm, Fountain, and Morning.

INTRODUCTION

Spasm Geyser, located in the Lower Geyser Basin, is part of the Fountain Complex. Spasm was given the name "Jet Geyser" in 1872, and was called "Impulsive Geyser" in 1873. Whittlesey [1988] notes that it was probably the 1927 park place names committee that placed the name Spasm on the present feature.

In 1878, Peale studied this geyser and did not believe that it was connected with Fountain Geyser. However, Hague stated in 1911 that "...in an impulsive way it seems to be affected by the overflow from the central [Fountain] geyser" [Whittlesey, 1988, p. 1673]. Marler [1973] does not comment on any relationship between Fountain and Spasm. Bryan [1991, p. 145] states that "[B]ecause of its connections with other geysers in the Fountain Complex, Spasm is very irregular in its performances. The nearly constant action of Clepsydra Geyser during recent years has rendered Spasm nearly dormant."

Marler [1973] notes that today's activity is in marked contrast to what is known about its pre-1959 behavior, due to an explosion that formed a new crater in Spasm in early 1963. Marler described Spasm as "...consists of two craters, an east and a west one....Water no longer stands at the outside rim of the old crater. Periodically water will rise in both craters, with boiling occurring from two vents in the east crater. Due to the flow of Clepsydra's water into the west crater, the original geyser, boiling does not occur. Following the boiling in the east crater, which lasts 28 to 32 minutes, water ebbs about 18 inches in both craters. During the eruptive period about 50 gallons per minute are discharged [p. 351]." Whittlesey [1988, p. 1674] states that "[I]n recent years, Spasm Geyser has erupted to heights of 3-25 feet for durations of 10-40 minutes at very irregular intervals." Bryan [1991] lists Spasm's intervals as irregular, durations as 5-20 minutes, and height as 1-3 feet. None of these descriptions fits Spasm's behavior in 1991, with the exception of the height listed by Bryan, proving that Spasm is indeed irregular across years, although it showed regularity for the summer of 1991.

The first section of this paper describes Spasm's activity on May 4-5, July 4-6, and August 9, 28, and 29. The second section contains a discussion of Spasm's behavior for July 21-August 9 when the Fountain Complex was operating on Fountain function. The third section presents an analysis of Spasm's behavior when the Fountain Complex was operating on Morning function. The final section contains some speculation about connections among geysers in the Fountain Complex and possible explanations for Spasm's observed behavior in 1991.

ACTIVITY ON MAY 4-5, JULY 4-6, AND AUGUST 9, 28, AND 29

Spasm's activity at these times is presented separately because May 5 represents Fountain's recovery from Morning's activity in early May, and concerted eruptions of Fountain and

Morning occurred on July 4 and 5, and August 9, 28, and 29.

May 4-5: Spasm was under observation from 14:00 on May 4 through 11:30 on May 5. While Morning was active, Spasm was quiet before Morning's eruptions. During Morning's eruption, Spasm's water level would rise and Spasm would start erupting. The eruption started with muddy water and would gradually clear. Following Morning's eruption, Spasm's water level would again drop, with Spasm resuming eruption during the next eruption of Morning. Spasm's intervals were about the same as Morning's intervals, and the cycles of the two geysers synchronized with respect to eruption start times.

Spasm started an eruption sometime during the eruption of Morning that started at 00:25 on May 5. Spasm was in constant eruption between 00:47 and 11:30. The stop time of this eruption is not known, but the duration was much longer than any Spasm eruption observed during the times when the Fountain Complex was operating on either Fountain or Morning function.

July 4-6: After the concerted eruption of Fountain and Morning at 14:40 on July 4, Spasm was under observation from 18:00 to 23:25, and was not in eruption during this time. The Complex was not under observation from 23:25 on July 4 to 06:00 on July 5. Spasm erupted at 09:42ns on July 5, stop time undetermined, and again at 12:52, stop after 13:43 when Fountain and Morning again started a concerted eruption. This interval of approximately 3 hours 10 minutes was similar to intervals observed when the Complex was operating on Morning function. Spasm was next observed in eruption at 19:25, stop time undetermined. On July 6, Spasm was off from 03:38 until an eruption started at 07:02. The stop time was not noted, but Spasm was still in eruption at 09:50, almost 2 hours later--a long eruption for 1991.

August 9: On August 9 Spasm started an eruption at 09:02, which ended about 10 minutes after Fountain started a solo eruption at 10:04. Spasm was next observed at 16:24, and was in eruption at that time. The interval of approximately 6 hours 30 minutes is consistent with Spasm's intervals when the Complex was on Fountain function. Spasm was not in eruption when Fountain started the dual eruption with Morning at 19:23. Spasm's activity between 21:25 and 05:00 on August 10, when the Complex had shifted to Morning function, is not known.

August 28 and 29: Spasm was in eruption at 11:03, 35 minutes before the start of Morning's final solo eruption of 1991. Spasm was still erupting after Morning finished. Spasm erupted again at 16:23, duration of 57 minutes, interval of approximately 5 hours. Spasm was not in eruption when Fountain and Morning started the dual eruption at 18:53.

Spasm remained off from 17:20 until sometime between 06:00 and 06:43 on August 29. This eruption ended at 07:15. This interval of approximately 13 hours is the longest known quiet period for Spasm during 1991. Spasm erupted again at 10:05, duration of 69 minutes. The interval of approximately 4 hours was consistent with Morning function, even though the Complex was in a partial energy shift. Spasm was not in eruption when Fountain started its concerted eruption with Morning at 12:14. Spasm still had not erupted at 19:30, an interval exceeding 9 hours 25 minutes.

Note that on May 5, when the energy shifted from Morning to Fountain without a concerted eruption, Spasm went into an unusually long eruption--over 10 hours. If it can be assumed that Spasm did not erupt between 16:30 and 18:00 on July 4 (which is unlikely since Spasm had received runoff from Fountain from 14:40-16:15), Spasm had an unusually long quiet spell on July 4 between the two concerted eruptions. In this case the direction of the energy shift was an attempted shift from Fountain to Morning. Between the concerted eruptions of Fountain and Morning on August 28 and 29, when the energy was shifting from Morning to Fountain, Spasm had an unusually long quiet spell following the first concerted eruption. So, when there were partial energy shifts between Fountain and Morning, Spasm had an unusually long quiet spell, the exact opposite of what happened on May 5 when there was no partial energy shift.

ACTIVITY WHEN FOUNTAIN COMPLEX WAS ON FOUNTAIN FUNCTION (July 21-August 9)

For most of its interval, Spasm was empty. Then, the east crater had periodic boiling spells where water appeared in the bottom of the crater, boiled below ground level, then drained, before filling and boiling again. Once the bursting reached above ground level (the point at which start time was recorded), Spasm was in full eruption. The pool filled, and Spasm generally remained in eruption for over an hour, or until about 10 minutes after the start of Fountain, whichever came first.

Durations: Most of Spasm's eruptions ended 5-10 minutes after Fountain started. It is believed this was due to overflow from Fountain entering Spasm's pool. However, as discussed in the section "Speculation", there may be other explanations for this. Four eruptions of Spasm were recorded where Spasm completed an eruption before Fountain started. The durations of these eruptions range from 45 to 128 minutes, and average 81 minutes.

In all four cases where Spasm completed an eruption before Fountain started, something unusual happened. In one case, the preceding Spasm eruption had a duration in excess of 5 hours. In the other three cases, Fountain had a longer than average interval. These three cases support the hypothesis that run-off from Fountain causes Spasm's eruptions to abort.

There were 15 observations where Spasm started before Fountain, Spasm's exact start time is known, and Spasm's eruption ended 10-15 minutes after Fountain started. Average duration for these eruptions is 55 minutes.

Intervals: Between July 21 and August 9, 7 exact intervals for Spasm were determined. The intervals range from 6 hours 20 minutes to 8 hours 13 minutes, with a median of 6 hours 52 minutes, an average of 7 hours 3 minutes, and a standard deviation of 39.6 minutes. Fountain's overall average for 1991 excluding intervals around the times of concerted eruptions with Morning was about 7 hours 30 minutes. For most of July 21-August 9, Spasm's cycles synchronized with Fountain's cycles.

Spasm and Fountain: Spasm's eruptive status at the time Fountain started an eruption was determined for 31 eruptions of Fountain (Table 1). Spasm was in eruption for 21 (68%) of the eruptions. Spasm's exact lead time on Fountain was determined for 15 (71%) of the "on" cases. Spasm's lead time ranged from 8 to 75 minutes, with a median of 32 minutes, a mean of 40 minutes and a standard deviation of 20.7 minutes. For the other six cases, Spasm's lead time was noted as ">0", ">9m", ">29m", ">40m", ">40m", and ">3h47m" prior to the start of Fountain's eruption.

Spasm was not in eruption for 10 (32%) of the 31 eruptions. The end of the preceding Spasm eruption is known for 5 (50%) of the "off" cases. These stops were 59, 107, 107, 109, and 151 minutes before Fountain started, an average of 107 minutes.

Six of the 10 "off" cases occurred between July 22 and August 3 when Fountain was erupting at an average of 7 hours. For some reason, Spasm's and Fountain's cycles lost their synchronization for these six cases. Four of the 10 "off" cases occurred between August 4-9 when Fountain was erupting at an 8 hour average, but all four cases were associated with 9-10 hour intervals of Fountain.

Summary: While the Fountain Complex was on Fountain function during 1991, Spasm erupted about every 7 hours. Since Spasm's cycles generally synchronized with Fountain's cycles, Spasm's independent durations were generally not determinable.

TABLE 1. Spasm and Fountain

Spasm's Eruptive Status When Fountain Erupted	Lead Time Known	Lead Time Not Known	Total
On	15	6	21
Off	5	5	10
Total	20	11	31

ACTIVITY WHEN FOUNTAIN COMPLEX WAS ON MORNING FUNCTION (August 10-28)

Spasm reacted to the energy shift from Fountain to Morning with shorter intervals and less variable durations.

Durations: From August 10-28, 13 exact durations (Figure 1) of Spasm were determined. Durations range from a minimum of 49 minutes to a maximum of 96 minutes, have a median of 59 minutes, a mean of 66 minutes, and a standard deviation of 13.7 minutes. The difference between this mean of 66 minutes and the mean of 55 minutes for Spasm's eruptions aborted by Fountain is not statistically significant. Because Spasm had no 3-5 hour durations when Morning was active, variability of Spasm's durations was much less when the Complex was on Morning function.

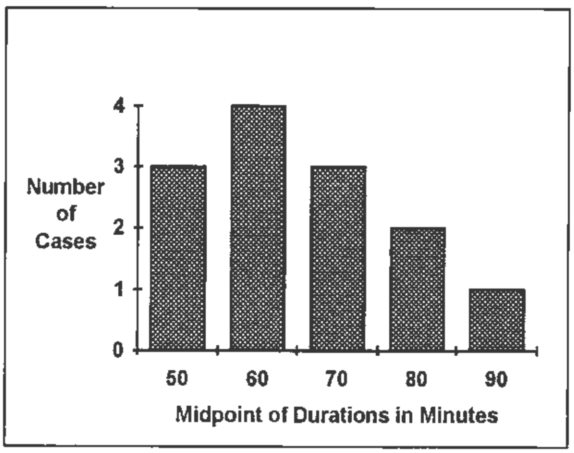


Figure 1. Spasm's Durations August 10-28

Intervals: Thirty-four (34) closed intervals (Figure 2) for Spasm were determined from August 10-28. The intervals range from a minimum of 134 minutes (2h14m) to a maximum of 271 minutes (4h11m), have a median of 220 minutes (3h40m), an average of 219 minutes (3h39m), and a standard deviation of 27.8 minutes. Sixty-two percent (62%) of the intervals are between 200 and 240 minutes, and 88% are between 180 and 260 minutes.

Spasm's intervals were significantly less variable when Morning was active ($F=2.026$, df 7/34, $p<.10$) than when Fountain was active. Spasm's intervals were also significantly shorter ($t=12.986$, df 7, $p<.0005$) when Morning was active.

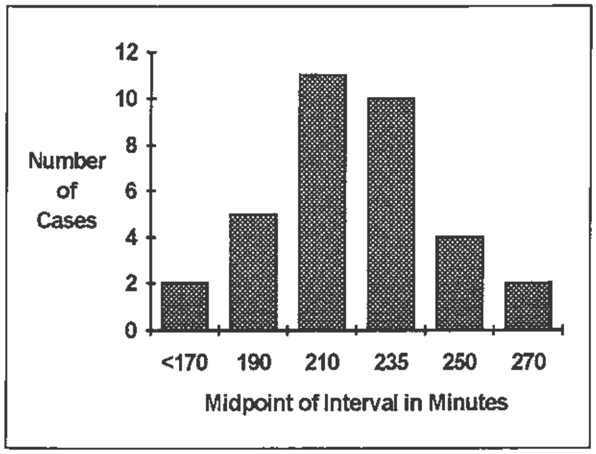


Figure 2. Spasm's Intervals August 10-28

Spasm and Morning: Table 2 shows Spasm's eruptive status at the time Morning started an eruption for 83 Spasm eruptions. Spasm was on when Morning started for 60 of the cases (72%). The proportion of time that Morning started while Spasm was already in eruption is only 4% greater than the proportion of time Spasm was erupting when Fountain started.

Spasm's exact lead time on Morning was determined for 47 (78%) of the 60 "on" cases. Spasm's lead time on Morning ranges from a minimum of 1 minute to a maximum of 59 minutes, with a median of 22 minutes, a mean of 24.3 minutes, and a standard deviation of 15.89 minutes. Figure 3 shows the distributions of Spasm's lead times on Morning and Fountain.

TABLE 2. Spasm and Morning

Spasm's Eruptive Status When Morning Erupted	Lead Time Known	Lead Time Not Known	Total
On	47	13	60
Off	13	10	19
Total	60	23	31

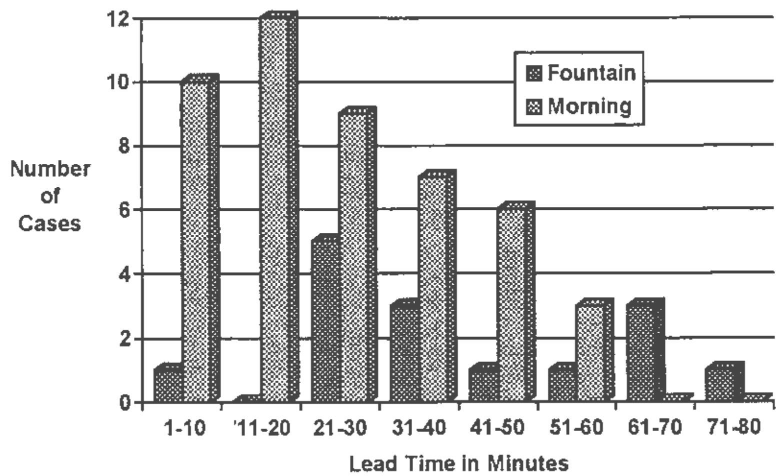


FIGURE 3. Spasm's Lead Times on Fountain and Morning

For the 13 cases where Spasm was in eruption when Morning started but Spasm's start time is unknown, the difference between the time Spasm was noted in eruption and Morning's start time of Morning was computed. These differences range from a minimum of 5 minutes to a maximum of 76 minutes, with a median of 28 minutes, a mean of 32.5 minutes, and standard deviation of 22.07 minutes.

The primary purpose of my observations in the Fountain Complex during the summer of 1991 was to collect data on Fountain and Morning. Once I had a general idea of what behavior patterns the other geysers in the Complex were exhibiting, monitoring of the Complex became less continuous. I would leave the area, then return 3 hours after the start of the preceding eruption of Morning. So, for example, when Morning had a shorter than average interval, data collection on other features was not as extensive as when Morning had an average or longer than average interval. Thus, an observer bias could have been introduced into the data because short intervals or long durations of Spasm where Spasm started before the time of arrival to collect data on Morning were more likely to be missed than were short durations or long intervals of Spasm. To test whether observer bias was introduced into Spasm's lead times on Morning, the hypothesis of no difference between the actual lead times for the 47 cases where Spasm's exact lead time was known and the 13 cases where the difference between Spasm's "ie" time and Morning's start was known was tested. Although the groups did not have equal variability (F=1.927, df 13/47, p<.10), the lead times of the two groups were equal (t=1.26, df 16, p>.10), alleviating some of the concern about bias in the data collection procedures.

Spasm's lead time on Morning was significantly less variable than was Spasm's lead time on Fountain ((F=1.69, df 15,47, p<.10). Spasm's lead time on Morning was significantly shorter than Spasm's lead time on Fountain (t=2.68, df 19, p<.005). This finding is consistent with the fact that Fountain's intervals were twice as long as Morning's intervals, and Spasm's intervals were almost twice as long when Fountain was erupting.

Spasm was not in eruption for 19 (23%) of the 83 eruptions for which a determination of Spasm's eruptive status at the start of Morning was made. The end of the preceding Spasm eruption is known for 9 (47%) of the 19 cases. The stops ranged from 1/2 minute to 102 minutes before Morning started, with an average of 27 minutes. This average is much shorter than the 107 minute average between Spasm stops and Fountain starts when Spasm was not erupting at the start of Fountain. Knowing that Spasm's lead times on Morning were significantly shorter than were Spasm's lead times on Fountain may not in itself be important, but it does lend additional support to the overall hypothesis that the energy switch from Fountain to Morning affected Spasm.

Analysis of the 19 "off" cases showed that they tended to come in clumps, indicating that Spasm's and Morning's cycles would temporarily become incongruent. On August 10, the first day Morning was active, four consecutive starts of Morning occurred where Spasm was not in eruption at the time of Morning's start. This may indicate that Spasm had not yet adjusted to the change from Fountain function to Morning function. Three consecutive "off" cases were recorded on August 20 and August 24. There were two consecutive "off" cases on August 14 and August 25. Only two of the "off" cases were preceded and succeeded by "on" cases. (Spasm's status with regard to the preceding or succeeding eruption of Morning is unknown for 3 cases.)

There were four cases where Spasm started during Morning's eruption. These starts were 1, 3, 11, and 22 minutes after Morning's start. There were no cases where Spasm started during Fountain's eruption. Even if Spasm had been quiet long enough to expect an eruption to start during Fountain's eruption, Spasm might have been prevented from doing so by water from Fountain's runoff that was entering Spasm's crater, or because Fountain was using the water supply that Spasm had been using.

The fact that Spasm was able to start an eruption during Morning's eruption, especially as long as 22 minutes into a Morning eruption, indicates that Spasm had at least some degree of independence from Morning. There were 56 cases where Spasm was in eruption when Morning started and Spasm continued after Morning's eruption, but only 4 cases where Spasm stopped during Morning's eruption. This indicates Morning's eruptions did not cause Spasm's stops. This idea will be pursued further in the section "Speculation".

Summary: Once the energy in the Fountain Complex shifted from Fountain to Morning, Spasm's behavior changed. Durations were much less variable when Morning was active than when Fountain was active. Spasm's intervals were significantly shorter when Morning was erupting than they were when Fountain was erupting. Spasm's lead time on Morning was significantly shorter than Spasm's lead time on Fountain. And, Spasm showed some degree of independence from Morning that it had not shown from Fountain.

SPECULATION

When I first started observing the Fountain Complex in 1991 and watched eruption after eruption of Spasm stop 10-15 minutes after Fountain started erupting, I believed the cause of those stops was the fact that Fountain's overflow entered Spasm's crater, presumably lowering Spasm's water temperature sufficiently to cause Spasm's eruptions to abort. I thought perhaps this was Hague's "impulsive way" Spasm was affected by Fountain's overflow. But as I watched Spasm while Morning was active, I began to wonder whether there might be another factor causing Spasm's eruptions to end during Fountain's eruptions.

When Fountain was active, water from Fountain's eruptions flowed into Spasm's crater. Water from Morning's eruption did not flow into Spasm. Spasm's eruptions started with muddy water both when Fountain was active and when Morning was active. While Fountain was active, it was believed that the cause of the muddy water was the fact that each eruption of Fountain sent water and accompanying debris into Spasm. But during the three weeks Morning was active, no debris was washed into Spasm from the surface. So why did Spasm's eruptions continue to start with muddy water?

One suggestion made was that accumulated silt and debris on the sides of Spasm's crater caused the dirty water at the start of Spasm's eruption. But if so, why did the water clear after 5-15 minutes? Spasm's overflow did not appear vigorous enough to wash the dirt out, neither when it was erupting on 7 hour intervals nor when it was erupting on 3 hour 40 minute intervals. And where did enough dirt come from every 3-4 hours to cause muddy water for the next Spasm eruption when Morning was active?

Morning's eruptions washed large quantities of debris into Fountain's crater. Another possible explanation for muddy water at the start of Spasm's eruptions when Fountain was not active is that the debris washed by Morning into Fountain was moving directly into Spasm's upper level water source and being circulated quickly into Spasm's eruptions without allowing the water to percolate through layers of rock, which would allow the particles to be removed. But if so, why did the time it took the water to clear stay the same as it had been when Fountain was erupting?

A third possibility is that the Fountain Complex was experiencing an underground disturbance similar to those experienced in the Norris Geyser Basin that cause muddy water to appear in selected features. The only water supply that turned muddy in the Fountain Complex during the summer of 1991 was Spasm's. Clepsydra, UNNG-FTN-2, Jet, Twig, Twig's Satellite Vents, and Morning were never observed erupting muddy water. Even on August 9 during the concerted eruption of Fountain and Morning when Morning reactivated after being quiet for over 4 weeks, Morning's eruption started with clear water. Morning did throw out rocks, but not muddy water. Fountain erupted muddy water on May 5 and August 28, but this was probably due to the massive amounts of debris that washed into Fountain's crater during Morning's eruptions.

Now consider the fact that Spasm was able to continue eruptions during and after Morning's eruptions. This indicates that Spasm and Morning were tapping different water sources for their eruptions during 1991. If they had been directly tapping the same water source, it would seem that Morning's eruption would have exhausted the water supply, causing Spasm's eruption to end.

Perhaps then, Fountain's eruptions caused Spasm to stop not just because of water from Fountain's overflow flowing into Spasm's crater but also because Fountain was tapping some of the same water supply that Spasm was tapping, and Fountain's ability to tap that water supply was stronger than Spasm's ability to tap the water supply.

Maybe Spasm was tapping two water supplies--one small reservoir with muddy water that was tapped by Spasm's eruption first, and being tapped by no other geyser in the Complex since none of the other geysers erupted muddy water, and then another source of clear water that was tapped after the reservoir with muddy water had been emptied. If Fountain was also tapping this supply of clear water, but Morning was not, this would explain why Spasm's eruptions during August started with muddy water. And, if Fountain's ability to tap the clear water source was stronger than Spasm's ability to tap that supply, would explain why Spasm's eruptions ended once Fountain started.

In order to explain why Fountain was still able to erupt after Spasm had completed an eruption (the "off" cases), a third water supply that was being tapped by Fountain, but not by Spasm, must be added into the model. Assume it is this water supply that is also being tapped by Morning. And, assume this water supply is usually capable only of being tapped by either Fountain or Morning, but not both. This would explain why normally when Fountain is erupting Morning is not, and vice versa.

However, something happened on July 4 and 5, and August 9, 28, and 29, 1991, that allowed Fountain and Morning to simultaneously tap this common Fountain/Morning water supply. Whatever happened also unblocked something else underground temporarily, supplying Fountain with enough water to support durations up to 2 hours long. If these very long eruptions of Fountain exhausted the common Fountain/Spasm clear water supply, this would explain Spasm's unusually long quiet spells between the July 4 and 5 concerted eruptions, and again between the August 28 and 29 concerted eruptions of Morning and Fountain.

One last "abnormal" eruption of Spasm needs to be placed in this speculative model--the eruption on May 5 that exceeded 10 hours. A possible explanation for the lack of a long quiet spell by Spasm presents itself. Exchanges of energy between Fountain and Morning that took place on July 4, 5, August 9, 28, and 29, were "partial" exchanges where the energy appeared to be temporarily balanced between these two major geysers, with both able to tap the common Fountain/Morning water supply, and Fountain tapping the common Fountain/Spasm source to support its continued eruption after Morning ended. However, the exchange of energy that took place on May 5 involved a complete shift from Morning back to Fountain. There was no concerted eruption where Fountain exhausted the common Fountain/Spasm supply, which is why Spasm did not have an unusually long quiet spell on May 5.

Explanation of Spasm's long eruption requires another assumption--that Fountain's ability to tap **any** water source was completely suppressed during the time the energy shift was taking place, allowing Spasm to continue tapping the Fountain/Spasm supply until Fountain had gathered enough energy to offset Spasm's pull on that water.

Ralph Taylor [1992] offered another explanation: "Perhaps the large Fountain/Morning water supply also contains more energy and is necessary to initiate eruptions of either Fountain or Morning. Fountain's use of the Spasm/Fountain clear water supply might be a secondary effect--maybe Fountain can use the Spasm/Fountain water to continue or augment an eruption, but that supply does not carry sufficient energy to initiate a Fountain eruption."

I will leave it to someone else to speculate about what happens underground that causes the ability to tap that clear water supply to shift from Spasm to Fountain, or that causes the energy shift, or exchange of function, between Fountain and Morning to occasionally occur, rearranging activity patterns of other geysers in the Fountain Complex as well.

CONCLUSION

During the summer of 1991, Spasm's behavior, regardless of whether the Fountain Complex was operating on Fountain function or on Morning function, was apparently much different from what it had been in prior years. The majority of the intervals during 1991 were regular, either at an average of 7 hours on Fountain function or 3 hours 40 minutes on Morning function. Durations during 1991 were much longer than ranges indicated by Bryan and Whittlesey, regardless of which average duration is considered--the 55 minute "aborted" durations of Spasm or the 81 minute average for completed durations of Spasm when the Fountain Complex was on Fountain function, or the 66 minute average when the Fountain Complex was on Morning function. In fact, during 1991, Spasm's durations seemed to show more irregularity than did Spasm's intervals. It is this change in geyser behavior that makes observing geysers a fascinating endeavor.

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CLEPSYDRA GEYSER, ACTIVITY DURING 1991
FOUNTAIN COMPLEX, LOWER GEYSER BASIN
YELLOWSTONE NATIONAL PARK

by Lynn Stephens

ABSTRACT: During the summer of 1991, Clepsydra Geyser was in almost constant eruption, with the exceptions of pauses after Fountain's eruptions and occasional pauses between eruptions of Morning. This paper describes observations of Clepsydra's activity during the summer of 1991.

INTRODUCTION

Clepsydra Geyser is part of the Fountain Complex in the Lower Geyser Basin. Whittlesey [1988, p. 297] notes that "...over its history Clepsydra Geyser has had many periods of little or no activity interspersed with periods of fairly regular activity." Changes in Clepsydra's activity have been at least partially related to activity by Fountain and Morning Geysers, the other major geysers in the Fountain Complex. The summer of 1991 offered a unique opportunity to observe Clepsydra's relationships with Fountain and Morning since Fountain was inactive for three weeks in August while Morning was active.

The first section of this paper compares Clepsydra's 1991 activity with reports of activity in prior years. The second section discusses Clepsydra's activity on May 4-5 during Morning's first 1991 period of activity, and activity following the concerted eruptions of Fountain and Morning on July 4 and 5, and August 9, 28, and 29. The third section analyzes Clepsydra's activity from July 21-August 9 when Fountain was active. The fourth section describes Clepsydra's activity when Morning was active from August 10-28.

COMPARISON OF CLEPSYDRA'S ACTIVITY PRIOR TO 1991 WITH 1991 ACTIVITY

Marler [1973] stated that Clepsydra erupted at about three minute intervals until the 1959 earthquake, with occasional periods of power displays that Marler termed "wild-phase eruptions". Marler reported that during 1946 a special effort was made to determine the nature of Clepsydra's activity. Most of the intervals were either three or four minutes, although they varied between one and five minutes.

Since the 1959 earthquake, Clepsydra has been in almost constant "wild-phase" eruption. During 1960, 1961, and 1962 the only variation in Clepsydra's eruptions observed by Marler was the proportion of steam in relation to water.

Beginning in 1963, Clepsydra began to have brief pauses in its activity. The pauses only occurred after an eruption of Fountain. In 1964 the pauses usually lasted from 8-10 minutes, although some lasted as long as 45 minutes. Fountain was dormant from the end of 1964 to early 1968, and Clepsydra was not known to have any pauses during that time. In 1968 Clepsydra's pauses after Fountain's eruptions lasted from 30 minutes to an hour.

Bryan [1991, p. 146] stated that "...Clepsydra will normally quit about 10 minutes after Fountain quits. This pause lasts about 30 minutes." Bower [1992, p. 55] reported that during 1990 Clepsydra paused "[S]hortly after some of Fountain's eruptions...". He stated the pauses lasted two to five minutes, but did not report what proportion of the time Clepsydra paused after Fountain's eruptions, and did not report data on the length of time between the end of Fountain's eruption and the start of Clepsydra's pause.

During 1991 Clepsydra paused after 48% of Fountain's eruptions, stopped after all Fountain's eruptions that had a duration of at least 50 minutes, and stopped after all 5 concerted eruptions of Fountain and Morning. Most of the pauses occurred about 10 minutes after Fountain stopped, and lasted 2 minutes 30 seconds to 5 minutes. Table 1 summarizes Clepsydra's pauses observed during 1991.

TABLE 1: Clepsydra and Fountain

Date	Fountain Start Time	Fountain's Duration	Clepsydra	Time after Fountain stopped	Length of Pause
Concerted Eruptions of Fountain and Morning:					
7/4	1440	95m		app. 10-15m	11m
7/5	1343	81m		9m	7m
8/9	1923	122m		8m	3m30s
8/28	1853	140m		7m	4m45s
8/29	1214	98m		6m	5m
"Recovery" Eruptions of Fountain:					
5/5	1723	62m	Stop during Fountain		
7/4	2226	50m		2m	6m
7/6	1322	40m		11m	4m
8/29	2101		Clepsydra "dead" during Fountain		
Fountain Complex on Fountain function:					
7/21	0856	55m	stop	5m15s	3m15s
7/22	1117	40m	continue		
7/22	1816	40m	continue (roar noted at 1824)		
7/23	0713	38m	stop	11m	4m
7/23	1341	39m	continue (roar noted at 1357)		
7/23	2012	39m	stop	11m	4m
7/24	0952	38m	stop	11m	2m40s
7/24	1629	39m	stop	10m30s	3m
7/26	0609ie	>40m	stop	9m	4m
7/26	2103	38m	continue (no roar)		
7/27	1017	39m	stop	9m	3m40s
7/27	1750	38m	continue (roar noted at 1811)		
7/28	0102	58m	stop (roar noted at 0114)	4m	4m40s
7/28	0946	39m	stop	10m40s	3m
7/28	1712	38m	continue		
7/28	2348	39m	continue (no roar)		
7/29	0640	38m	continue		
7/29	1334	36m	stop (roar noted at 1407ie)	10m	3m45s
7/29	2023	37m	stop (Clepsydra did roar)	10m	5m
7/30	0945.30	38m	stop	9.m30s	2m45s
7/30	1659	38m	continue (no roar)		
7/31	0745ie	unk	continue		
7/31	2136	36m	continue (roaring from 2143-2223)		
8/1	1018	37m	continue (roar noted at 1053)		
8/8	1930ie	unk.	continue		

ACTIVITY ON MAY 5, JULY 4-6, AND AUGUST 9, 28, AND 29

Clepsydra's activity on these dates is presented separately because May 5 represents Fountain's recovery from Morning's activity in early May; and concerted eruptions of Fountain and Morning occurred on July 4 and 5, and August 9, 28, and 29.

May 5: Clepsydra was in constant eruption from 14:00 on May 4 until 17:26 on May 5. Clepsydra did not pause after Morning's eruptions. Clepsydra paused three minutes after Fountain's eruption (d=62m) started at 17:23 (the first Fountain eruption since Morning was first realized to be active at 09:38ie on May 4). Clepsydra restarted at 17:40 for a few minutes, then stopped, and restarted at 18:38, seven minutes after Fountain's eruption ended.

July 4-6: Following the July 4 concerted eruption of Fountain (d=95m) and Morning Dunns and Benders reported that approximately 10-15 minutes after the end of Fountain, Clepsydra shut off for 11 minutes. Fountain had a solo eruption at 22:26 on July 4 (d=50m). Two minutes after Fountain's eruption ended, Clepsydra stopped for 6 minutes. Fountain (d=81m) and Morning had a concerted eruption starting at 13:43 on July 5. Clepsydra stopped from 15:13 to 15:20, a pause that started 9 minutes after Fountain ended and lasted 7 minutes.

The partial energy shift to Morning ended sometime after the concerted eruption on July 5 and before 13:22 on July 6, when Fountain had a solo eruption (d=40m). Clepsydra stopped 11 minutes after Fountain's eruption ended. Clepsydra's pause lasted 4 minutes.

August 9: Fountain (d=122m) started a concerted eruption with Morning at 19:23. Clepsydra's roaring from steam phase activity was noted at 19:44, 21 minutes after Fountain started. At 20:24, Clepsydra was still roaring. Clepsydra stopped 8 minutes after Fountain ended. The pause lasted approximately 3 minutes 30 seconds.

August 28-29: Fountain (d=140m) started a concerted eruption with Morning at 18:53 on August 28. Clepsydra was already in steam phase at 19:08, less than 15 minutes after Fountain started. Clepsydra stopped 7 minutes after Fountain's eruption ended. The pause lasted 4 minutes 45 seconds. At 12:14 on August 29 Fountain (d=98m) started a concerted eruption with Morning. Clepsydra stopped 6 minutes after Fountain's eruption ended. This concerted eruption was Morning's final 1991 activity.

Fountain erupted at 21:01 on August 29. Tim Goodrich reported that Clepsydra was "dead" during Fountain's eruption.

Conclusions: Clepsydra was inactive **during** Fountain's first solo eruptions on May 5 after Morning had been erupting, and was also inactive **during** Fountain's first solo eruption on August 29 after Morning had been active in August. However, Clepsydra was **not** inactive during Fountain's solo eruption on July 4 between the July 4 and 5 concerted eruptions of Fountain and Morning, and was also **not** inactive during Fountain's solo eruption on July 6. On May 5 and August 29 the energy shifted from Morning to Fountain; on July 4-5 it attempted to shift from Fountain to Morning, but did not completely succeed.

Clepsydra's inactivity/activity status during the concerted eruptions and Fountain's solo eruptions on these dates may be related to the nature of the energy shift that occurred between Fountain and Morning, and/or the direction of the energy shift (Fountain to Morning--FM--or Morning to Fountain--MF).

Two types of energy shifts between Fountain and Morning occurred in 1991. The concerted eruptions represented partial energy shifts where the energy attempted to shift from one major geyser to the other but stopped between the two, allowing them to erupt in concert. Accomplished energy shifts occurred when the energy completely shifted from one major geyser to the other. Accomplished energy shifts do not necessarily have to be preceded by partial energy shifts. Three combinations of energy shifts occurred in 1991--partial/accomplished (P/A), partial/failed (P/F), and no partial/accomplished (N/A).

The partial energy shifts do not appear to be a factor affecting Clepsydra's behavior. Clepsydra's behavior (stop during Fountain's solo eruption) was the same on May 5 (N/A/MF) and August 29 (P/A/MF), despite the difference in partial energy shift.

Assuming that the partial energy shifts did not affect Clepsydra's behavior, two variables remain--direction of energy shift and accomplishment of the energy shift. Accomplishment failed on July 4-6 (F/FM), and succeeded on May 5 (A/MF), August 9 (A/FM), and August 29 (A/MF). Conclusions about the impact of these variables on Clepsydra's behavior are not possible because there were no solo Fountain eruptions between the August 9 (A/FM) and August 29 (A/MF) and there was no (F/MF).

Clepsydra's pauses after the 5 concerted eruptions of Fountain and Morning are attributed to Fountain's eruption rather than to Morning's eruption because (1) Clepsydra did not pause shortly after Morning's solo eruptions in May and August, and (2) Clepsydra paused regardless of whether the energy was attempting to shift from Fountain to Morning (July 4-5 and August 9), or attempting to shift from Morning to Fountain (August 28-29).

ACTIVITY WHEN FOUNTAIN COMPLEX WAS ON FOUNTAIN FUNCTION

Between July 21 and August 8, whether or not Clepsydra paused was determined for 25 eruptions of Fountain. Clepsydra stopped after 12 of these eruptions, or 48% of the time. Most of the pauses started 9-11 minutes after Fountain ended. The pauses lasted an average of 3 minutes 40 seconds.

The pauses that happened on July 21 after a Fountain duration of 55 minutes and on July 28 after a Fountain duration of 58 minutes started 5 minutes 15 seconds and 4 minutes, respectively, after the end of Fountain's eruption. The durations of the pauses (3m15s and 4m40s) were not unusual. One other difference distinguished the pauses on July 21 and 28. Generally, if Clepsydra paused after Fountain's eruptions, Clepsydra's bursting activity would gradually slow down before the pause, exhibiting what I termed "coughing". But for these two pauses, the start of the pause was quite abrupt--one second Clepsydra was on, the next second it was off.

When Clepsydra paused, the last vent to cease activity was the east vent, or the vent closest to the boardwalk, in front of Clepsydra's mound. Bursting at Clepsydra's restart also started from this vent first.

Clepsydra would enter steam phase during Fountain's eruption even if Clepsydra did not pause after Fountain stopped. Whether or not Clepsydra exhibited steam phase activity was noted for 11 of the 25 Fountain eruptions. Steam phase activity was noted for 8 of the eruptions. For the three eruptions when Clepsydra did not enter into steam phase, Clepsydra did not pause after Fountain's eruption. For the 8 eruptions where steam phase activity was noted, Clepsydra paused after 3 (37.5%) of the eruptions and continued after 5 (62.5%) of the eruptions. Thus, lack of steam phase activity seemed to indicate that Clepsydra would continue, but presence of steam phase activity occurred in about the same proportions as did Clepsydra's pause/continue for the overall Fountain function observations.

When Clepsydra paused, steam phase also ended. But when Clepsydra continued after Fountain ended, steam phase activity continued. The duration of Clepsydra's steam phase activity was timed on only one occasion--July 31 for the 21:36 eruption of Fountain. Steam phase started 7 minutes after Fountain started, and stopped after a total duration for steam phase of 40 minutes.

ACTIVITY WHEN FOUNTAIN COMPLEX WAS ON MORNING FUNCTION

Eruptions of Morning were not followed by Clepsydra pauses, but were generally associated with steam phase activity from Clepsydra. During the first 10 days of Morning's activity, start of Clepsydra's steam phase activity was noted for 17 eruptions of Morning. Beginning on August 18, eruptions of Morning occurred without Clepsydra entering into steam phase activity. Clepsydra did have periods of slowdown ("coughing") between eruptions of Morning, and there were two verified pauses plus two visitor reports of pauses between eruptions of Morning. Table 2 summarizes Clepsydra's steam phase activity during Morning function.

Table 2. Clepsydra and Morning

			Clepsydra's Steam Phase Activity		
		Morning's		Relationship to Morning's Start	
Date	Time	Duration	Start	Beginning	Other
8/10	1807	23m50s	1819	12m	
8/12	1302	13m50s	1316	14m	
8/12	1654	26m10s	1714	20m	
8/13	1518	22m0s	1507	-11m	Before Morning
		"Coughing" at 1627, 27 minutes after Morning end			
8/13	1937	23m0s	1958	21m	
8/13	2318	25m32s	2333	15m	
8/14	1527	27m24s	1548	21m	
8/15	1348	22m	1405	17m	
		VR: Clepsydra stop sometime between 1440 and 1600			
8/15	1718	23m0s	1745		After Morning, 4m
8/16	1855	25m30s	1918	22m	
8/17	0533	19m25s	0553		After Morning, 1m
8/17	1253	20m40s	1310	16m30s	
8/17	1654	21m15s	1705	11m	
8/17	2044	27m0s	2104	19m	
8/18	0425	26m20s	0451	26m	
8/18	0819	15m45s	0830	11m	
8/18	1200	18m0s	1211	11m	
8/18	1551	17m 0s	No roaring		
8/18	1953	29m2s	2029		After Morning, 7m
8/19	0334	24m40s	0359ie		
8/19	0725	31m57s	No roaring		
8/19	1058	14m50s	No roaring		
8/19	1413	16m8s	1427	14m	
8/19	2159	20m30s	2219	20m30s	
8/20		Clepsydra started coughing at 0950			
		Clepsydra stopped from 1032-1040			
8/20	1225	19m20s	No roaring		
8/20	1622	20m8s	1633	11m	
8/20	2003	24m0s	2021	18m	
8/21	0658	23m37s	0722	23m30s	
8/21	1053	29m15s	1120	27m	
		1215: Clepsydra coughing but did not stop			
8/21	1448	13m45s	1506		After Morning, 4m
		1800:19-1802:45 Clepsydra pause			
8/21	1850	24m12s	1911	20m	Duration 40m
8/22	0611	14m0s	No roaring		
8/22	0937	16m45s	Very weak (at best) steam phase		
8/22	1311	19m30s	No roaring		
8/22	2053	18m35s	No roaring		
8/23	0737	20m25s	No roaring		
8/23	1912	30m0s	1929	17m	
8/24	1503	17m50s	1425	-38m	Before Morning
8/24	1907	28m20s	1930	23m	

Table 2. Clepsydra and Morning (continued)

Date	Time	Morning's Duration	Clepsydra's Steam Phase Activity Start	Relationship to Morning's Start: Beginning	Relationship to Morning's Start: Other
8/25	0844	15m0s	No roaring		
8/25	1222	22m20s	1238	16m	
8/25		Coughing at 1657			
8/25	1706	26m0s	1721	15m	
8/25	2112	14m10s	2018	-54	Before Morning
8/26	1055	22m40s	1113	18m	
8/26	1528	26m40s	1500	-28m	Before Morning
8/26		1840-1940			Before Morning
8/26	1945	24m45s	No roar during Morning		
8/26	2303	13m0s	No roaring		
8/27	1326	24m48s	1336	10m	
		VR: Clepsydra off sometime between 1400 and 1630			
8/27	1701	23m30s	1713	12m	
8/27	2015	23m40s	No roaring		
8/28		Clepsydra coughing from 0602ie to 0745			
8/28	0745	18m5s	0800	15m	
		Clepsydra coughing at 1134			
8/28	1138	11m30s	No roar		

Between August 10 and the 12:00 eruption of Morning on August 18, the start of Clepsydra's steam phase activity was noted for 17 eruptions. In one case Clepsydra's steam phase activity started 11 minutes before Morning's eruption, and Clepsydra's coughing was noted 27 minutes after that eruption ended. In two cases Clepsydra's steam phase activity started after Morning ended (1 and 4 minutes after). There were no eruptions between August 10-18 for which a note was made that Clepsydra did not enter steam phase activity.

Starting with the 15:51 eruption of Morning on August 18 and ending with Morning's last solo eruption at 11:38 on August 28, Clepsydra's steam phase activity was noted for 35 eruptions. Four times steam phase started before Morning--28, 38, 54, and 65 minutes before Morning erupted. When the steam phase started 65 minutes before Morning, the steam phase activity lasted 60 minutes and ended 5 minutes before Morning started. Clepsydra remained in water phase throughout the ensuing eruption of Morning. Twice Clepsydra started steam phase after Morning ended (4 and 7 minutes after). Clepsydra's steam phase activity was noted for 15 additional eruptions of Morning. Thus, steam phase activity was associated with a total of 21 of the 35 eruptions (60%). For one (3%) eruption, "very weak (at best) steam phase activity" was noted. For 13 (37%) of the eruptions, Clepsydra had no steam phase activity. Only one duration of Clepsydra's steam phase activity that started during an eruption of Morning was times. That activity lasted 40 minutes.

Between August 10 and noon on August 18, Clepsydra's coughing was noted once, and there was one visitor report of a complete pause.

From 15:50 on August 18 through noon on August 28, Clepsydra's coughing was noted five times--on August 20 from 09:50 until Clepsydra paused at 10:32, on August 21, on August 25, and twice on August 28 from 0:602ie to 07:45 before the 07:45 eruption of Morning, and just prior to the 11:38 eruption of Morning. There was a visitor report that

Clepsydra paused on August 27. Clepsydra is known to have stopped on August 20 from 10:32 to 10:40, a pause of 8 minutes that happened 2 hours 2 minutes after the 08:30 eruption of Morning and 1 hour 53 minutes before the 12:25 eruption of Morning; and again on August 21 from 18:00:19 to 18:02:45, a pause of 2 minutes 26 seconds that occurred 50 minutes before the 18:50 eruption of Morning.

When Clepsydra's steam phase activity started during an eruption of Morning, the start varied from 10 to 27 minutes after the start of Morning, with an average of 17 minutes. The length of time between Morning's start and start of Clepsydra's steam phase was related to Morning's duration. Regression analysis was performed with Morning's duration as the independent variable and the start of Clepsydra's steam phase as the dependent variable for the 29 cases where Clepsydra's steam phase started during Morning's eruption. The relationship was statistically significant ($F=12.54$, df 1/27, $p<.005$). The r^2 value of .31718 indicates that 32% of the variation in the length of time between Morning's start and the start of Clepsydra's steam phase (Y) could be explained by Morning's duration (X). The regression formula was

$$Y = 1.923028 + .657989X,$$

with a standard error of the intercept of 3.979896, and a standard error of the X coefficient of 0.185796.

CONCLUSIONS

Morning's 1991 rejuvenation affected Clepsydra's activity. It appears that it took 10 days for Clepsydra to react to the exchange of function from Fountain to Morning in August. Perhaps the short durations of Morning's eruptions, compared to Fountain's durations, did not exhaust the water supply available to Clepsydra sufficiently to allow Clepsydra to pause after Morning's eruptions. Or, perhaps Clepsydra's main water supply is connected to Fountain's portion of the shared Fountain/Morning supply but not connected to the Morning portion. This would also help explain why Clepsydra reacted immediately to an energy shift from Morning to Fountain with pauses during Fountain's first solo eruption. And, without Fountain acting on Clepsydra's main water supply, Clepsydra would pause only when the cumulative effect of Clepsydra's eruptions released enough energy to inhibit Clepsydra's eruptions, thus explaining Clepsydra pauses not associated with Morning's eruptions.

The length of time between the end of Fountain's eruption and the start of Clepsydra's pause appears to be related to Fountain's duration. When Fountain erupted solo with durations of at least 50 minutes, Clepsydra's pauses occurred 2, 4, and 5 minutes after Fountain ended, compared with 9 to 11 minutes when Fountain durations were 35-40 minutes. But Clepsydra did not pause until at least 6 minutes after Fountain stopped when Fountain erupted in concert with Morning. Fountain durations for the concerted eruptions ranged from 81 to 140 minutes If Fountain's duration represents the amount of water expelled during a Fountain eruption and the amount of water expelled is inversely related to the length of time between the end of Fountain's eruption and the start of Clepsydra's pause, it would seem that Clepsydra pauses should have started sooner than they did following the concerted Fountain/Morning eruptions.

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The Kaleidoscope Group
Lower Geyser Basin, Yellowstone National Park: Activity From 1989 Through 1991

Mike Keller

Abstract

Next to the Porcelain Basin portion of the Norris Geyser Basin, the Kaleidoscope Group might be Yellowstone's most volatile thermal group. Numerous hydrothermal explosion craters can be found in the area. When the group is undergoing one of its "energy surges", any hole is capable of displaying major eruptions. During the spring of 1988 and the early summer of 1991, the complex experienced such surges. This paper discusses the activity of the group during and after each surge.

Introduction

The Kaleidoscope Group is located in the area called Fountain Flats, about one half mile northwest of the Fountain Paint Pots (the location of the "Fountain Overlook" referred to in this article). About 200 feet to the east is the Sprinkler Group. These two groups combined contain no fewer than 80 erupting vents. Although most of these are within the Sprinkler Group, there are at least 23 geysers in the Kaleidoscope Group. Of significance is that eleven of these geysers erupt to heights of 25 feet or more. Because most of these springs are members of a single subsurface plumbing complex, the term "Kaleidoscope Complex" is nearly synonymous with Kaleidoscope Group[1]. (See Table I and Map.)

The area is named after Kaleidoscope Geyser. There is still some question as to which vent is the original Kaleidoscope, but it might well be one of the other eruptive craters in the area. The only other feature of the group that had a name prior to the 1950s was Old Surprise Spring. Even with the Fountain Hotel nearby, the Kaleidoscope Group received practically no attention until the time of the 1959 earthquake.

When there was any historic mention of this area, it was usually due to a new geyser or explosion in the area. Several vents still display evidence of explosive origins. Between Drain and Blowout Geysers there are numerous boulders from an explosion in the late 1880s. Deep Blue Geyser's vent, when closely examined, has upturned shelves at at least three different levels. In the first two weeks of June, 1990, the 2- by 3-foot crater of spring #5b ("Collapse" Geyser) evolved into a 14- by 31-foot geyser vent with cyclic eruptions up to 40 feet high.

Another curiosity of the group is the almost complete absence of overflow away from the complex. Almost every geyser or spring drains into another. The only vents with steady discharge away from the area are spring #3, "Firehose", and Deep Blue.

Just to the west of the Kaleidoscope Complex is an area of old craters. No water can be seen in any of them, but water was heard in at least two, in June of 1990. Most of these craters are very deep, and all the geyserite in this area has been extremely weathered.

Spring Descriptions

1a. Kaleidoscope Geyser

From 1989 through June of 1991, Kaleidoscope was one of the largest geysers in all of Yellowstone. Eruptions 60 to 120 feet high were among the largest ever recorded from it.

At first glance, Kaleidoscope's vent does not appear capable of such large displays. There are two basins: the outer measures 16 by 25 feet, and the inner 3 by 4 feet. Within the outer basin are remnants of geyserite 'biscuits', which would indicate a prehistoric history of high water levels.

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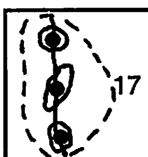
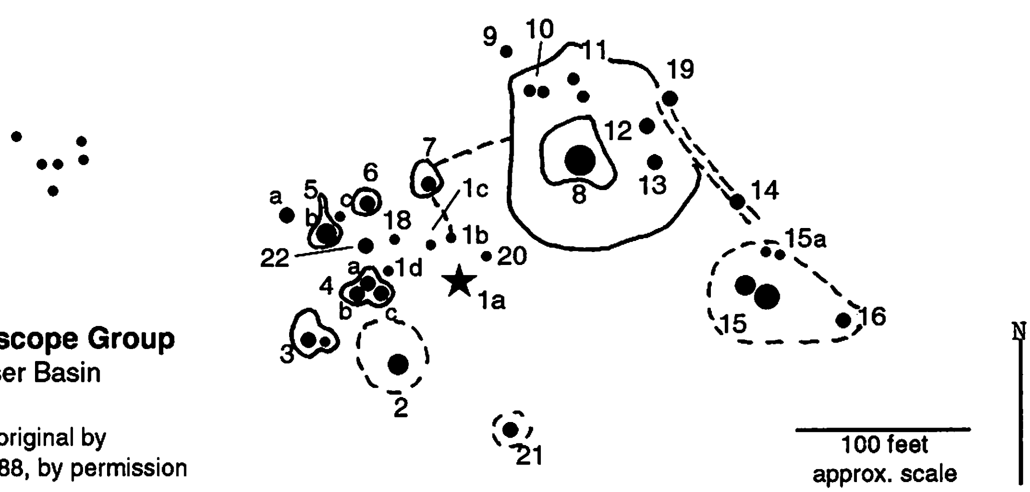
1. Per the most commonly used terminology, a hot spring *group* simply encompasses some number of features within a relatively small portion of a geyser basin, but these springs are not necessarily physically related to one another. In a *complex*, there are direct subsurface connections between the individual spring plumbing systems.

Table I
Thermal Features and Map of the Kaleidoscope Group

Number	Name	Function*	Notes
1a	Kaleidoscope Geyser	G	erupts to 120 feet
1b	unnamed	G	acts as indicator
1c	unnamed	G	rare, to 2 feet
1d	unnamed	G/S	pressure pool
2	unnamed	G/S	dormant since 1971
3	unnamed	G	to 1 foot before dormancy of 6/18/91
4a	"Three Vent Geyser"	G	cyclic, to 60 feet
4b	unnamed	G	rare, to 10 feet
4c	unnamed	G	rare, to 5 feet
5a	unnamed	PS	subterranean
5b	"CollapseGeyser"	G	cyclic, to 40 feet
5c	unnamed	G	subterranean indicator
6	Blowout Geyser	G	rare; cyclic, to 60 feet
7	Drain Geyser	G	cyclic, to 75 feet
8	Deep Blue Geyser	G	cyclic, to 40 feet
9	unnamed	PS	to 2 feet
10	unnamed	PS/G	left, spouter to 2 feet; right geyser to 1 foot
11	unnamed	G	frequent, to 2 feet
12	unnamed	G	rare, to 130 feet
13	unnamed	G	cyclic, to 70 feet
14	"Firehose Spouter"	PS (?)	cyclic, to 50 feet
15	Honeycomb Geyser	G	minors to 30 feet; majors to 70 feet
15a	unnamed	G	3 vents, to 2 feet
16	Honey's Vent Geyser	G	frequent, to 12 feet
17	Old Surprise Spring	S	former major geyser
18	unnamed	G	subterranean
19	unnamed	G	angled, to 50 feet
20	unnamed	PS	subterranean, to 1 foot
21	unnamed	S	shallow depression
22	unnamed	G/S	low water levels



* function abbreviations:
G = geyser
S = spring
PS = perpetual spouter



Map of Kaleidoscope Group
Lower Geyser Basin

based on an original by
Rocco Paperiello, 1988, by permission

The inner basin contains two vents. The eruptive vent is that on the northern side.

In 1989 and 1990, the activity prior to an eruption was as follows:

Following the "final" burst of an eruption series, the water level would drop until it was about 2 feet below overflow. Apart from minor boiling spells, the water level remained unchanged for 2 to 5 hours.

At some point during this 2 to 5 hour time span, spring #1b would start to erupt. With this, the water would slowly cycle up and down in Kaleidoscope and nearby spring #1d. These cycles came at near 14 minute intervals. Except on July 16, 1990, when Blowout Geyser was active, there had to be at least three of these cycles (about 40 minutes) before Kaleidoscope could erupt.

Eventually, the water in Kaleidoscope and spring #1d rose to within 4 inches of overflow. At this point there would be increased boiling over the main vent. Suddenly, Kaleidoscope and #1d would surge up, overflow, and palpitate, flooding the outer basin. After 10 to 20 seconds of heavy overflow, the water in Kaleidoscope domed and exploded, sending rockets of water to between 80 and 120 feet in height. This was the initial burst of an active series. The duration was from 30 seconds to 2 minutes. Following this eruption, the water level in both Kaleidoscope and #1d would drop about 2 feet. Then one of two things would happen:

1. Kaleidoscope would have a second eruption within 2 minutes; *or*

2. Kaleidoscope would have a second eruption after an interval of 8 to 12 minutes.

Between 1989 and June of 1991, I observed 289 eruptions of Kaleidoscope. Of these, 194 (67%) had the second eruption within 2 minutes of the first. Like the initial burst, there would be a rapid water level rise in both Kaleidoscope and #1d, culminating in the eruption. However, the ensuing bursts lasted only 30 seconds to 1 minute. These eruptions were also smaller than the initial bursts, generally being 70 to 90 feet high.

Following the second burst, the water level would again drop about 2 feet. After another 2 minute pause, there would be a third burst. The start of this was similar to the first and second bursts, but this eruption lasted only 15 to 45 seconds and reached 40 to 70 feet high. Most eruptive series of Kaleidoscope had three to five of these "middle" bursts, but there could be as few as one (on July 16, 1990) or as many as 13 (on September 3, 1990) (see Table II).

On the other 95 occasions, when the pause was greater than 2 minutes, Kaleidoscope would not have the second burst until an additional 6 to 10 minutes had passed. During this time, the water in Kaleidoscope and #1d remained 2 feet below overflow. Finally, the water level would rise and the second burst followed; it was exactly like those without the long delay. Kaleidoscope normally would then return to two minute pauses between eruptions. On seven different occasions, however, Kaleidoscope had long pauses between the second and third bursts, and on May 31, 1990 it had long pauses between the first, second, third, fourth, and fifth bursts!

The cause of these long pauses between bursts seems clear. Of the 95 eruptions with long initial pauses, 61 (64%) had an eruption of Deep Blue Geyser take place during the pause. The remaining 34 were all closely followed by strong eruptions (greater than 10 feet high) of Deep Blue. On these occasions, too, the intervals of Deep Blue were strongly bimodal, 78% of the intervals falling at either less than 20 or greater than 38 minutes.

In any event, following the "middle" bursts, there was the "final" burst. This burst was the longest in duration, shortest in height, and last in the eruptive series of Kaleidoscope. After the last of the "middle" bursts, there was little or no drop in the water levels in Kaleidoscope and #1d. The pause leading to the final burst lasted only 30 to 45 seconds. At first, Kaleidoscope reached 15 to 25 feet high, but this rapidly dropped until the play was only 1 to 10 feet high. These final bursts had average durations of 50 minutes but varied between 12 and 105 minutes. Toward the end of this burst, spring #1b would quit erupting, at which time Kaleidoscope had some stronger surges reaching up to 20 feet high.

Table II — Statistical Analysis, Burst Activity of Kaleidoscope Geyser, 1989–1991

	1989	1990	1991	TOTAL
Eruptions with:	31	114	268	420
2 bursts	0	1	0	1
3 bursts	4	13	0	17
4 bursts	6	16	36	58
5 bursts	18	28	43	89
6 bursts	1	33	66	100
7 bursts	0	5	55	60
8 bursts	1	4	39	44
9 bursts	1	8	15	24
10 or more bursts	0	6	14	20
Average per year:	4.8	5.7	6.4	5.6
Minumum Number Observed:	3	2	4	2
Maximum Number Observed:	9	14	11	14
Standard Deviations:	1.7	2.6	1.3	1.4

Burst Durations: Average per year (minutes:seconds), excluding final burst:

	1989	1990	1991	TOTAL
First	1:36	1:07	1:39	1:27
Second	0:48	0:58	0:51	0:50
Third	0:41	0:45	0:44	0:42
Fourth	0:37	0:33	0:37	0:34
Fifth	0:28	0:27	0:34	0:30
Sixth	0:27	0:39	0:30	0:31
Seventh	0:22	0:31	0:23	0:25
Eighth	0:20	0:28	0:24	0:22
Ninth	0:17	0:29	0:29	0:25
Tenth	none	0:25	0:26	0:26
Eleventh	none	0:22	0:20	0:21
Twelfth	none	0:18	none	0:18
Thirteenth	none	0:13	none	0:13

Burst Durations: Average for Final Burst (minutes:seconds)

	1989	1990	1991	TOTAL
Final Burst Duration:	44:28	53:29	51:30	50:42
Minumum Duration:	18:42	12:00	13:19	12:00
Maximum Duration:	93:30	105:45	153:00	153:00
Standard Deviation:	24:21	33:23	17:01	29:57

At the end of the "final" burst, the water level again dropped about 2 feet. Kaleidoscope then began another 2 to 5 hour quiet interval.

During the 2½ years of this study, Kaleidoscope's intervals were remarkably short. Despite a standard deviation of 2 hours, the average interval was only 5h 07m. The only features in the area which seemed to influence the intervals of Kaleidoscope were springs #4a, 5b, and 6— if they were active prior to the start of #1b, then Kaleidoscope would have intervals longer than 6 hours.

All of this changed on June 18, 1991. Sometime in the early morning hours, there was an energy shift or surge which affected the entire Kaleidoscope Complex and resulted in the resurrection of Drain Geyser. I first visited the area on the afternoon of June 19. When I arrived it was readily apparent that Kaleidoscope had recently erupted. Figuring that I had a couple of hours to wait, I started moving to Deep Blue Geyser to take data. Almost immediately, Drain Geyser erupted. This was the first time I had ever seen Drain. The eruption lasted only a few seconds, but it reached 20 feet in height. When I left the area nine hours later, Drain was still active.

Throughout the activity by Drain, Kaleidoscope remained essentially unchanged, the pool lying 2 feet below overflow. I placed markers[2] on Kaleidoscope. The markers were still in place the following morning, even though Drain was no longer active. The water level in Kaleidoscope was only 2 inches below overflow, however, and the levels in spring #s 1b, 1c, 1d, 2, 4a, 4b, 4c, 5a, 5b, 6, 7, 18, 20, and 22 were all between 1 and 3 feet higher than they had been at any observed time during the previous 2½ years. Several small sizzling vents were forming between spring #s 3 and 4b, and several small but noisily hissing steam vents had opened along the same buried fissure which includes spring #s 2 and 18.

Due to the time of day, I had to leave the area. When I returned 12 hours later, the markers on Kaleidoscope were gone, and the surrounding springs had dropped to their former water levels. Drain Geyser was again active, but it was overflowing into Blowout Geyser, which it was not doing the day before. Over the next two weeks, the area was spot checked at least once a day.

It was not until the evening of June 25 that I was able to see an eruption of Kaleidoscope up close. None of the past indicators were evident before the eruption. When I arrived at 20:45, both Kaleidoscope and #1d were in light overflow. Drain was inactive, but its pool level was up and connected with that of Blowout. All the nearby vents were once again at higher than normal levels.Since #1b was not erupting, I assumed that Kaleidoscope was at least an hour from erupting. At 21:55, both Kaleidoscope and #1d were boiling up as much as a foot, but #1b was still inactive. Finally, at 22:18, Kaleidoscope erupted; at no time did #1b become active. The eruption had a total of six bursts, with the final burst lasting 49 minutes. Once finally started, it was a normal eruption in all respects. During the middle bursts, Deep Blue had an eruption which sent water over its *outermost* berm and into Honeycomb Geyser, yet this massive eruption did not influence the pauses between the middle bursts.

By July 1, the complex had settled into a cycle in which the Drain was active for 6 to 14 hours, followed by a pause of 4 to 7 hours, then an eruptive series by Kaleidoscope, another pause of 3 to 5 hours, and finally a new active period by Drain. (There were two occasions when Kaleidoscope managed to have a second eruptive series when the Drain seemed ready to begin). These cycles had total periods of 14 to 27 hours.

These activity cycles by Drain continued, with slowly but steadily decreasing durations, until August 10, 1991, when another energy shift/surge hit the complex. Kaleidoscope's activity returned to that seen between 1989 and June, 1991, but on an accelerated scale. The average interval was only 3h 28m! What made this even more remarkable was spring #4a, which was having eruptions every 2 to 5 minutes. There was no change in the nature of the eruptions of Kaleidoscope. Even spring #1b had reactivated, although

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2. Markers are indicators, such as small gravel or pine needle piles, which are placed in the runoff channels of a geyser. If properly placed, they will be washed away by the runoff of an eruption.

Table III — Statistical Analysis, Activity of Kaleidoscope Geyser, 1989-1991

	1989	1990	1991	TOTAL
Number of Data Points	17	84	126	227
Average Interval (hours:minutes)	5:02	5:16	4:49	5:07
Minimum Interval	2:50	3:19	2:39	2:39
Maximum Interval	10:37	11:40	7:04	11:40
Standard Deviation	1:25	2:01	2:24	2:09
Data From June 18, 1991 to October 28, 1991 only:				
Number of Data Points			79	
Average Interval (hours:minutes)			3:28	
Minimum Interval			0:27	
Maximum Interval			5:08	
Standard Deviation			0:21	
Duration of Spring #1b Prior to Kaleidoscope Eruption:				
Number of Data Points	8	27	16	51
Average Duration (minutes)	169	154	149	155
Minimum Duration	92	73	77	73
Maximum Duration	263	264	243	264
Standard Deviation	26	38	51	44

its play had become perpetual. This new activity was short lived, lasting only until August 18.

From August 18 through September 13, the Kaleidoscope Complex was back into the Drain-pause-Kaleidoscope-pause-Drain mode. The cycles during this time were 15 to 20 hours in total duration. It was during this span when the only known dual eruptions of Drain and Kaleidoscope took place.

Starting on September 13 and lasting through late October, Kaleidoscope entered yet another type of activity, the short mode. The only witnessed dates of this activity were September 13, and October 2, 11, 17, 20, and 22. When Kaleidoscope was in the short mode, the activity was essentially the same as when in the normal mode, but it was greatly accelerated. Over a seven hour span on September 13, for example, Kaleidoscope had eight eruptive series with series intervals of only 37 to 88 minutes. The only major difference was in the height of the eruptions: instead of the usual 80 to 120 feet, these initials reached only 40 to 70 feet high. It is worth noting that during the other dates between September 13 and October 28, the complex was always in the alternating Kaleidoscope-Drain mode.

1b. unnamed

The vent of spring #1b lies on the sinter platform between Kaleidoscope and Drain Geysers. When this feature is not erupting, it is merely a long fissure in the geyserite. In 1988, the eruptions came from the southern side of the fissure; by 1989 and continuing through 1991, they had moved to the northern side of the fracture.

Prior to June 17, 1991, #1b was a true geyser which acted an an indicator for Kaleidoscope (Table III), with total durations of 1 to 7 hours.

In early May, 1990, there was a slight energy shift from spring #4a to #5b. Around this time, #1b enlarged its vent. The fissure expanded to the northwest, and by July had grown some six feet longer. All eruptive activity along the southern side had quit. In August, the ground north, northwest, and west of the fissure visibly palpitated during the eruptions of #1b.

When Drain activated on June 17, 1991, the eruptive activity by #1b changed. The palpitating area partially collapsed and formed a true vent, from which most of the eruption came. Instead of acting as an indicator for Kaleidoscope, #1b instead became a "barometer" for the entire complex. If #1b was active, then either Kaleidoscope or Drain was about to start. Apart from August 10-18, 1991, when Kaleidoscope was the dominant geyser, #1b remained in this barometric mode of activity for the remainder of 1991.

1c. unnamed

Between 1989 and June 17, 1991, the only known eruption of this feature was seen on July 16, 1990. Blowout was active at the time. That eruption lasted about 30 seconds and was 2 feet high. Since that eruption caused its pool to become murky, it was assumed that eruptive activity was rare in this vent.

Starting on June 17, 1991 and continuing until June 26, 1991, #1c was in an active cycle. It would erupt only when Drain was active. Intervals were erratic, ranging from 7 to 33 minutes in length. The durations were 28 to 41 seconds, and the height was 2 feet. These eruptions again caused the water to become murky, a condition which lasted until August. No eruptions by #1c are known since June 26, 1991.

1d. unnamed

This vent is the closest to Kaleidoscope, lying 14 feet to the west. From 1989 through June 17, 1991, there were no known eruptions of this feature. However, during the same nine day span when spring #1c was active, #1d was also having small eruptions. Although they were not much more than heavy boiling reaching not more than a foot high, they had durations of 16 to 52 minutes. Like #1c, #1d quit playing on June 26.

2. unnamed

This was unquestionably a major geyser in the past. The remains of a large berm of broken sinter gravel still remains some 15 feet from the crater. The last known eruptions of this geyser were in 1971. It is definitely connected with the spring #4a-c and the Kaleidoscope-Drain systems. When the complex was in the Drain mode after June 17, 1991, the water level in #2 would rise as much as 3 feet, and its temperature would increase from 126°F to 139°F.

3. unnamed

This geyser erupted from a vent located in the center of a rust colored, pear shaped, shallow basin. Prior to the eruptions, the pool level would rise and overflow. The first bursts were small, but they rapidly increased in size until reaching up to 3 feet high. During 1989 and 1990, the intervals were of 1 to 3 minutes. When Drain reactivated on June 17, 1991, #3 fell dormant, and no eruptions were known for the remainder of the year.

4a. "Three Vent Geyser"

To the west of Kaleidoscope is a large three-vented pool. All three of these vents are known to be separately active as geysers. Three Vent (#4a) is the northernmost. It is also the largest of the three geysers.

In June, July, and August of 1989, there was little to no activity from this vent. In September, major eruptive activity took place. Marie Wolf and Rocco Paperiello witnessed a major eruption by Three Vent on September 12, 1989, and reported:

> "This geyser sent a wide consolidated column of water up to 35 to 40 feet and was at first mistaken for Kaleidoscope. Maximum height was attained for about 30 seconds, when it abruptly subsided and the pool drained."

On October 2, 1989, I witnessed an eruption of a geyser from the Fountain Geyser Overlook. It reached about 50 feet high and rose from a vent to the west of Kaleidoscope. Marie and Rocco saw another eruption on October 8. Following all three of these eruptions, Three Vent entered a cycle of activity in which it would erupt at 2 to 5 minute intervals from 15 to 25 feet high. Unlike the initial eruptions, these follow-up bursts lacked a definite column. They continued for several hours, gradually becoming weaker as the cycle progressed.

By the spring of 1990, the activity had changed. When I was in the area on May 29, 30, and 31, this vent was always active. Eruptions came at near 3 minute intervals, lasted about 30 seconds, and were 10 to 15 feet in height. The only known pauses came immediately after an eruption of Kaleidoscope. When spring #5b began enlarging its vent on June 5, 1990, the eruptions of Three Vent started becoming more erratic. By the time #5b was finished enlarging itself and having its own series of eruptions (on June 15), Three Vent was dormant. Apart from a single day of activity on August 12, 1990, it remained dormant until June 17, 1991 (a fact confirmed by markers).

When Three Vent was first seen on June 18, the eruptions were similar to those in May of 1990. However, they were cyclic in nature, as there were several hours without activity. Over the eight day span when only Kaleidoscope was active, Three Vent became the dominant geyser of the complex. Again, the only time Three Vent would pause was when Kaleidoscope had just finished erupting. These pauses lasted 53 to 98 minutes. When the energy shifted back to Drain, Three Vent continued as the dominant geyser, and excepting October 6, 1991, when spring #4b was briefly active, it remained so through the end of this study.

4b. unnamed

In the summer of 1989, this was the dominant geyser of the group. The vent of #4b is the southwestern most of the three openings in the #4 crater. The activity consisted of four distinct types, which varied from minor boiling just 12 to 18 inches in height to bursting play reaching up to 8 feet high.

When #5b began playing in June of 1990, #4b began having small eruptions. Also, at the conclusion of an eruption by Kaleidoscope, #4b would have small, 2- to 3-foot eruptions. This was essentially all that #4b did until June, 1991.

With the reactivation of Three Vent, #4b's water level dropped about 18 inches and began to act as a drain for the water from Three Vent. From June 17 through October 5, 1991, there were no known eruptions by #4b. On October 6, Rocco Paperiello and Marie Wolf witnessed five eruptions of #4b during the post-Kaleidoscope pause in Three Vent. They were from 3 to 10 feet in height and lasted 2 to 22 seconds. No further activity is known.

4c. unnamed

The funnel shaped vent of #4c is the largest of the three in this crater, but it was the least active member of the group during the three years I spent in the area. No eruptions were known in either 1989 or 1990. On May 26, 1991, I witnessed two eruptions while at Honeycomb. The play was 5 to 6 feet in height and lasted only a couple of seconds. The eruptions were separated by an interval of 6 minutes. Following the eruptions there was a lot of silt suspended in the water.

5a. unnamed

The vent of spring #5a is surrounded by large thin sheets of sinter. When walking near it, one can hear the echo of their footsteps. Before June 5, 1990, this vent acted as a drain for the erupted water of Three Vent Geyser. No standing water was visible in the crater. When spring #5b began to enlarge itself, the water level in #5a rose until it was visible in the southwest side of the crater. By June 15, when #5b began having series of eruptions and Three Vent fell dormant, #5a began perpetually spouting. The play was subterranean, and reached only a foot or so above the pool level. This continued until #5b retuned to dormancy on June 20, 1991. While the pool level did not drop, the perpetual activity quit and did not resume until October.

5b. "Collapse Geyser"

During the first two weeks of June, 1990, this long buried geyser reappeared. The fact that this was a geyser in the past is made evident by the large masses of geyserite found along the shoulders of its vent. In 1989, this vent was described by Rocco Paperiello and Marie Wolf as:

> "...consisting of two parts. One part is a perpetual spouter to about 1 to 2 feet. A few feet southwest of this spouter, in the areas of thick sinter, extends an irregular break several feet long. Water spouts

perpetually out from under a ledge a couple of feet below its northwest margin; spray reaches ground level."

A few feet to the northeast there was a roughly oval shaped vent being 2 by 3 feet in dimensions. Its water level could vary from 1 to 6 feet below overflow.

When I visited the area on the morning of June 5, 1990, the spouter had enlarged its vent to 4 by 7 feet, and was sending a highly pressured spray as far as 5 feet from the vent. By June 8, the crater was 10 by 14 feet, and the play periodic. The intervals were 2 to 6 minutes; the eruptions consisted of one or two quick jets angled from under the ledge, reaching 6 to 8 feet in height. These eruptions started forming a runoff channel leading toward spring #s 5a and 4c.

My next visit was not until June 15. At some point over the preceding week, there was further enlargement of the crater. Upon arrival that evening, the crater was 14 by 31 feet! Large sheets of sinter had collapsed into the basin. About six feet below overflow was an opaque, sizzling pool of water. Externally, there was evidence of at least one massive eruption. The oval shaped vent to the northeast was completely filled with gravel. Several pounds of sinter was also washed into the vent of spring #4c. Extensive runoff channels were carved leading toward the east, south, and northwest. The water levels in springs #s4a-c were all 12 to 18 inches below overflow. Over the next 5 hours, the level of Collapse slowly rose until it was only 3 feet below overflow, but no eruption took place. Markers were placed. They were gone two days later. Although no eruptions were actually witnessed until August, that they were coming fairly frequently was clear since markers were always washed between visits.

I finally saw an eruption on August 8, 1990. When I arrived in the Kaleidoscope Group, the water surface in Collapse was only 2 feet below overflow and sizzling heavily. Just 10 minutes later, Collapse erupted. The play proved to be cyclic. The initial eruption was always the largest, reaching 25 to 40 feet high and 60 to 80 feet wide (!), lasting 20 seconds. Following the initial there would be from 6 to 23 additional eruptions at intervals of 1 to 3 minutes. These were normally 10 to 25 feet in height and 20 to 40 feet broad. When the series finally concluded the water level in Collapse dropped about 8 feet. The only closed interval, obtained the following year, on June 15, 1991, was 2h 53m[3]. When spring #4c reactivated on June 20, 1991, all eruptive activity in Collapse quit. Apart from a single eruption between August 10 and 12, 1991, Collapse remained dormant through the year.

5c. unnamed

About 20 feet to the north of Collapse's vent is a small crater on the shoulder of Blowout Geyser. In June of 1990, this vent acted as an indicator for both Three Vent and Collapse. As the water level rose in the area, small subterranean eruptions took place.

6. Blowout Geyser

Very little data on the activity of this geyser was obtained between 1989 and 1991. Only one eruption is known for 1989. It was witnessed by Rocco Paperiello and Marie Wolf, who reported:

"A single surprise eruption of Blowout was witnessed on July 4th at 10:10 am. The "indicator" [spring #1b] of Kaleidoscope had been playing vigorously indicating an energy build up in Kaleidoscope. Suddenly and unexpectedly Blowout exploded; about 12 to 15 separately spaced bursts occurred over about a 2 minute period. About half of these were over 40 feet, and a couple were over 50 feet."

The lack of activity continued into 1990 and 1991. Only two eruptions are known in 1990 and one for 1991. The 1990 eruptions took place on July 16 and September 4. Several hours before them, the entire Kaleidoscope system was "stalled". The eruption of July 16 lasted only 47 seconds, but had several bursts which reached over 30 feet[4]. The eruption of September 4 was

3. During August of 1990 and May of 1991, the intervals of Collapse were gradually decreasing. It is believed that the intervals during August, 1990 were around 12 to 16 hours.

4. When Kaleidoscope finally erupted on July 16, there never was a final burst. This was the only time this is known to have occurred until the reactivation of Drain in June of 1991.

very weak, lasting but 22 seconds and never reaching over 20 feet high. The 1991 eruption was witnessed from the Fountain Overlook on May 2. It appears that the increased activity in both Kaleidoscope and Drain had rendered Blowout nearly dormant. The only sure sign of an active Blowout was the color of the water— if clear, then the geyser is dormant; the only time the water is murky is during eruptive cycles.

7. (Kaleidoscope) Drain Geyser

Drain's basin consists of a funnel shaped vent opening into a large bowl measuring 60 by 63 feet. Also within this bowl is Blowout Geyser. When the Drain is active, the water level is high enough to fill the entire basin. When inactive, the water is from 2 to 8 feet below the rim. There is never any overflow except from occasional "super bursts".

With the increased activity of Kaleidoscope in early 1989, Drain entered dormancy. Brief active cycles were known for May and June, but it was definitely dormant by August. During the dormancy, the water level would rise and fall within the basin. It was always at its highest in the middle of the interval of Kaleidoscope and at its lowest just before and after eruptions by Kaleidoscope.

All of this changed on June 18, 1991. It is not known when Drain had its first eruption— the first seen were on June 19— but it is believed that they took place on the 18th. The first observed eruptions consisted of one or two bursts reaching from 5 to 20 feet in height. They came at 7 to 10 minute intervals and lasted from 7 to 16 seconds. this continued without change for the next 9 hours. At no time did the water level rise high enough for there to be overflow into Blowout Geyser.

The following evening, Drain was again found to be active. The intervals between eruptions had lengthened to 15 to 30 minutes. This time the water level of Drain rose enough to fill Blowout, creating a large thermal pond. From June 19 through August 1, Drain was active at least once each day (except on June 29, when it might have been active although no eruptions were seen). Over this span the intervals varied from 3 to 47 minutes. The largest bursts were estimated to be near 60 feet high.

Sometime between August 1 and 10, 1991, the eruptions of Drain started increasing in power. This was made evident in the number of second bursts observed in its eruptions. During June and July, only 43% of the eruptions were followed by a second burst. From August through October, the number followed by a second burst had increased to 77%. Meanwhile, the durations of Drain's active series declined— in June and July, the series lasted from 11 to 14 hours; from August through October, they lasted only 6 to 9 hours.

The only other significant difference during this period was between August 10 and 18, when Kaleidoscope again acted as the dominant geyser of the complex. Cycles of Drain are known to have occurred only on August 13 and 17.

Following this eight day period, Drain began having massive initial eruptions. About an hour before the first eruption in a cycle, the pool level of Drain would rise high enough to overflow into Blowout. When Drain was within 10 to 30 minutes of erupting, bubbles would begin to rise over the vent. Apart from this there was little to no change in Drain's appearance. The initial eruption began with a sudden doming of the pool. Almost immediately, the dome would explode, sending large rockets of water up to 80 feet in height and flooding the surrounding formations with large waves. The first three or four following eruptions could reach 75 feet high. This activity was continuing in late October, 1991[5].

8. Deep Blue Geyser

The crater of Deep Blue is the largest of any in the Kaleidoscope Group, and one of the most beautiful in all of Yellowstone. The geyserite is a light cream color. Add to this the rich azure blue of the deep water. Circling the geyser are

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5. Rocco Paperiello believes that Drain had an even larger eruption on October 9, 1991, which washed "several tons of gravel and sand as well as the boulders between Drain and Blowout." While I agree that the boulders were moved, I saw no evidence of the "tons of gravel and sand".

Table IV — Statistical Analysis, Activity of Deep Blue Geyser, 1989-1991

	1989	1990	1991	TOTAL
Before June 18, 1991:				
Number of Data Points	113	684	104	901
Average Interval (minutes)	32.7	31.0	32.3	31.6
Minimum Interval	14	8	11	8
Maximum Interval	43	71	64	71
Standard Deviation	8.3	8.9	7.6	7.8
After June 18, 1991:				
Number of Data Points			76	
Average Interval (minutes)			26.9	
Minimum Interval			6	
Maximum Interval			93	
Standard Deviation			14.9	
All Intervals:				
Number of Data Points	113	684	180	977
Average Interval (minutes)	32.7	31.0	29.3	30.8
Minimum Interval	14	8	6	6
Maximum Interval	43	71	93	93
Standard Deviation	8.3	8.9	11.2	9.7

numerous small geyserite terraces. Within the main basin are no less than seven separate geysers and spouters, and to the west and northwest forming a semicircle are not fewer than another fifty spouting springs which occasionally increase and decrease in activity.

The vent of Deep Blue is the large, seemingly bottomless crater on the western side of the bowl. From 10 to 15 minutes before an eruption, there was a slight upwelling of water over the main vent. About 5 minutes before the play, small bubbles began to form. Strong ground thumping started just a minute before the eruption; these thumps could be felt as far as 200 feet from the crater. Some of the eruptions consisted of "just thumps", but most managed to send at least one steam bubble to the surface. When this happened, the bubble "popped" and sent water from 3 to 15 feet in height. Frequently observed during 1989 but with declining frequency in 1990 and 1991 were "super" or "blue bubble" bursts. During these the entire surface area of the pool above the vent domed upward and burst from 20 to 40 feet high. When viewed up close, these were most impressive. It was only during these eruptions that any water was discharged from Deep Blue's basin.

Deep Blue is highly influenced by the activity of Drain and Kaleidoscope Geysers. The average interval of Deep Blue was 28 minutes when Kaleidoscope was active, and 41 minutes when Drain was active. Regardless of outside influences, the average of 977 timed intervals was 30.8 minutes. The observations are summarized in Table IV.

Like most features of the Kaleidoscope Complex, Deep Blue was affected by the energy surge of June 18, 1991. When I arrived on June 19, I found Deep Blue to be inactive! No eruptions were observed in 9 hours. The pool had risen about 8 inches, causing it to overflow from its northern margins. It soon became apparent where the energy had shifted: vents #12 and #13, located within the basin, were both seen to erupt for the first time[6]. From June 18 through August 25, the only time Deep Blue would erupt was during and shortly after eruptions of Kaleidoscope Geyser. These eruptions were usually very impressive since the higher water level of Deep Blue caused massive flooding of the surrounding areas.

9. unnamed

This spouter is the largest of the small vents lining the northwestern rim of Deep Blue Geyser. Its play reached 1 to 2 feet high.

10. unnamed

Within the northwestern portion of Deep Blue's crater are three vents lying along a linear fracture. All of them erupt through a few inches of water. The first two of these are #10. Of these, the west vent was never observed to stop its perpetual 2-foot eruption. The vent on the east was known to pause following the larger eruptions of Deep Blue; it reached only 1 foot high.

11. unnamed

The crater of #11 is the third vent along the fracture which includes springs #10. In 1989, it was observed to be periodic with intervals near 9 minutes. While the activity was perpetual in 1990, periodicity had returned by 1991. No data was obtained. The eruptions, through several inches of water, reached 2 to 3 feet high.

12. unnamed

During 1982, this vent was known to be a major geyser with eruptions reaching 50 to 75 feet high. No further activity was then known until July 16, 1990, the same day that Blowout was active. This eruption lasted only 15 seconds, but it shot water through Deep Blue's pool to a height of near 80 feet. This was the only known eruption during 1990.

When the "Firehose" (#14) stopped erupting on June 18, 1991, its energy shifted to spring #s 12 and 13. Of the two, #12 was the larger but least active. Its eruptions came in cycles— several would occur over the course of several hours, followed by hours to days of inactivity. Consisting of rocketing vertical bursts similar to those of Grand Geyser, the play was brief, usually no more than 25 to 30 seconds. Observed estimated heights varied from 70 to 130 feet, making #12 a truly major geyser. No eruptions are known to have occurred since August 25, 1991, when the "Firehose" restarted.

13. unnamed

Very little is known about the past history of this geyser. Marler mentions a small geyser located about 15 feet west of the fracture where "Firehose" and spring #19 lie. Those eruptions of 6 feet came from a crater measuring 3 by 6 feet. If this is the same geyser, then its activity has changed dramatically. It was definitely active in 1984, but no data was obtained at that time.

With the cessation of "Firehose" on June 18, 1991, this geyser became the beneficiary of a large amount of thermal energy. At first, the eruptions were erratic, but they gradually became more frequent during early July. Like nearby spring #12, the eruptions came in cycles— several would occur during a span of 10 to 25 minutes followed by 1 to 5 hours of inactivity. During the span of inactivity, there would be several smaller eruptions. During a series, which could contain from 4 to 9 eruptions separated by intervals of 1 to 9 minutes, the second and third eruptions were the largest. These bursts were angled to the southwest and would vary from 20 to 45 feet in height; the durations were 20 to 50 seconds. The initial and follow up eruptions were much smaller, seldom being angled and reaching just 5 to 15 feet in height. Like #12, this geyser returned to dormancy with the restart of "Firehose" on August 25, 1991.

14. unnamed/"Firehose"

Along the east and southeastern border of Deep Blue Geyser lies a long fracture. Following the 1959 earthquake, as many as 11 spouters formed with the largest reaching 6 feet in height.

6. Actually, #13 also had a single eruption on July 16, 1990, when Blowout was active.

one of the 11 spouters reported by Marler, but it beading evident. I believe the vent to be of *very* recent origin, perhaps forming in 1988!

During the early spring of 1988, all the energy along this fissure shifted to a vent on the southeastern end and created one of the most impressive spouters in all of Yellowstone. Although this feature is officially unnamed, many observers began calling it the "Firehose" because it resembles an upturned firehose jetting at an angle. The steady play of this feature normally remains between 20 and 30 feet high, but there are times, most commonly in May and June, when the water level will cycle up and down. At these times, the height can vary from 5 to over 45 feet.

Since Firehose began its activity in March of 1988, it has been known to completely pause eleven times. These known pauses ranged from just 9 minutes to over 53 days, as shown in Table V.

There has been much talk as to whether this feature is a true geyser or a cyclic spouter. It is my personal opinion that it is a spouter. I believe the pauses of May and June to have been seasonal, possibly related to the water table. With the spring thaw, Firehose acts as if its normal action is "drowned", so that occasional pauses take place. This is different from a true eruption interval. When it is actively erupting, there is no hint of periodicity to the play and the eruptions are fully perpetual.

Table V — Known Pauses Between "Firehose" Eruptions

Date(s)	Comment
7/24/88 to 8/31/88	Pause of ≈38 days
2/07/89 to 2/09/89	Pause of ≈2 days
5/89 and 6/89	Several brief pauses lasting minutes to hours known during both of these months
10/14/89	Pause of 23 minutes
5/90 and 6/90	Several brief pauses lasting minutes to hours known during both of these months
8/22/90	Pause of 14 minutes
9/04/90	Pause of 37 minutes
9/11/90	Pause of 87 minutes
6/02/91	Pause of 9 minutes
6/18/91 to 8/10/91	Pause of ≈53 days
8/18/91 to 8/25/91	Pause of ≈7 days

The Honeycomb Complex

The three geysers of the Honeycomb Complex are the easternmost of those in the Kaleidoscope Group. Although they did undergo definite changes in behavior at the same general time as did the geysers of the Kaleidoscope Complex, there is no evidence that the Honeycomb Complex is (directly) connected with the geysers in the vicinity of Kaleidoscope.

Among the objectives of my 1989-1991 study were to find:

1. proof of a definite connection between Honeycomb and Honey's Vent; and
2. a possible indicator for Honeycomb's eruptions.

During the many hours I spent watching this group, it often seemed that Honey's Vent became more erratic (with intervals of less than 16 *or* greater than 21 minutes) prior to an eruption of Honeycomb. When I mentioned this to Paperiello and Wolf, they said they had seen eruptions of Honeycomb with no changes observed in Honey's Vent as much as an hour before the eruption.

After looking more closely at the collected data, a "trend" emerged. About five hours prior to the eruption of Honeycomb, there would be a sudden change in Honey's Vent. This consisted of abruptly erratic activity. When this action would last from 4 to 5 hours, Honeycomb would erupt. The key here was the length of the erratic activity. Honey's Vent had been known to be erratic for an hour or two but then switch back to normal activity, without resulting in any eruptions of Honeycomb (see Table VI).

I managed to obtain 17 different complete cycles of Honey's Vent activity during the 5 hours immediately preceding an eruption of Honeycomb during 1990 and 1991. I then compared this to 17 complete 5 hour cycles of Honey's Vent without Honeycomb. The results are shown on the graph of Figure 1, where the plotted points represent

Table VI — Statistical Analysis, Activity of Honey's Vent Geyser, 1989-1991

	1989	1990	1991	TOTAL
When Honeycomb Not Within 5 Hours of Eruption:				
Number of Data Points	204	967	1082	2253
Average Interval (minutes)	17.7	17.5	18.1	17.8
Minimum Interval	11	12	7	7
Maximum Interval	29	26	38	38
Standard Deviation	2.5	3.2	3.0	2.8
When Honeycomb Was Within 5 Hours of Eruption::				
Number of Data Points	17	96	113	226
Average Interval (minutes)	26.6	23.2	24.7	24.8
Minimum Interval	10	11	13	10
Maximum Interval	34	36	42	42
Standard Deviation	5.8	7.2	5.9	6.3
Pause in Honey's Vent After Honeycomb:				
Number of Data Points	2	6	9	17
Average Duration (minutes)	220.0	216.9	219.5	218.8
Minimum Duration	203	209	194	194
Maximum Duration	237	252	248	252
Standard Deviation	17.0	13.4	15.4	16.2

average intervals for that point in a series. The total average interval (about 18.4 minutes) for all 2,479 timed intervals is also shown.

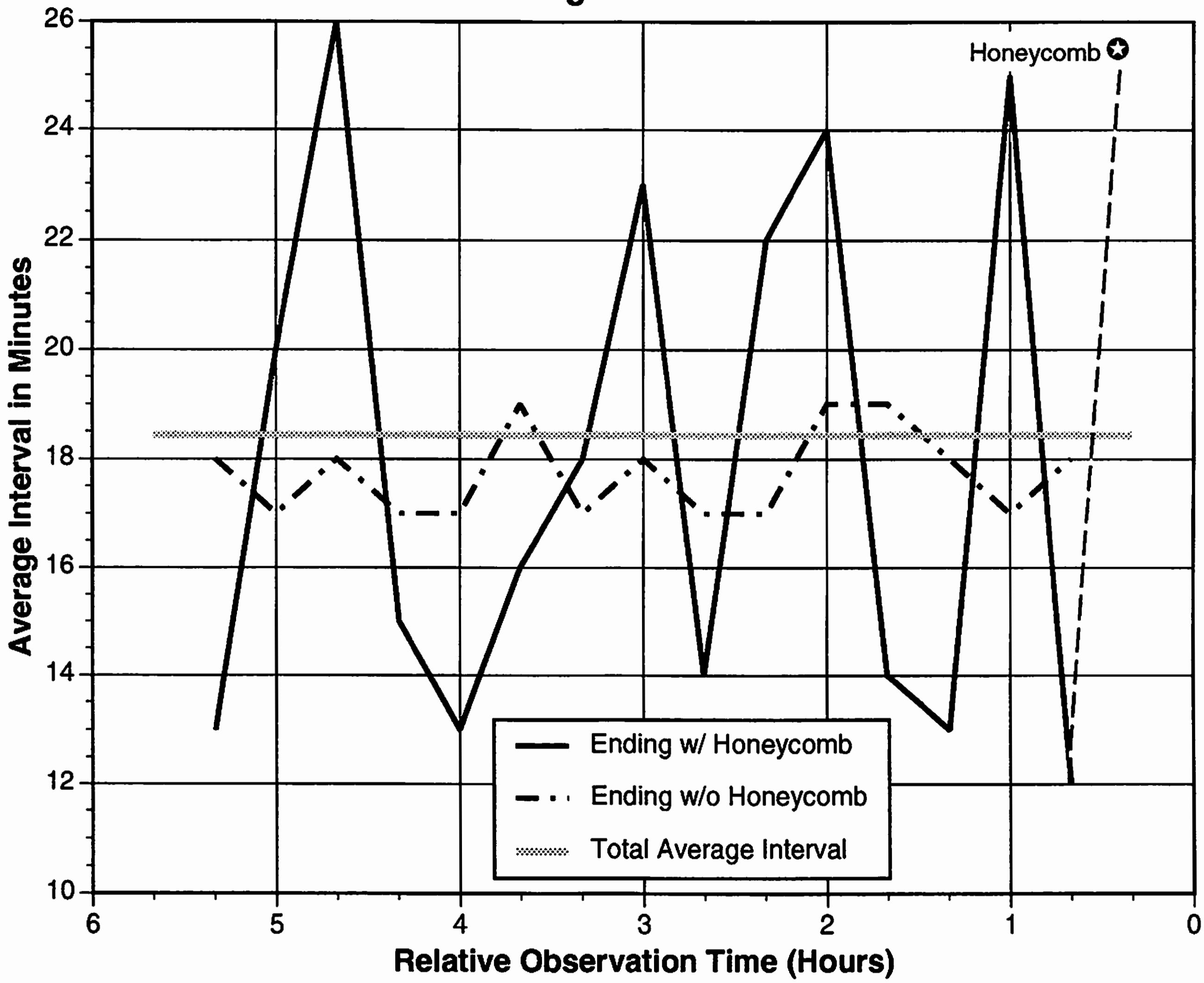
As the graph shows, there was a dramatic increase in the deviation from the total average interval as Honeycomb approached an eruption. Also, these deviations appeared to vary quite regularly on a 1–hour cycle. Unfortunately, this sort of action *could* take place for a time but then switch back to the more normal non-Honeycomb mode. Also, as noted above, the normal, "non-Honeycomb" mode could also lead to an eruption by Honeycomb; this corresponds to the activity seen by Paperiello and Wolf. Clearly, then, predicting Honeycomb is not as easy as watching the interval pattern of Honey's Vent. Increasing deviations from the average interval *may* indicate a possible eruption by Honeycomb, but not always. This pattern does at least indicate that the two geysers are related.

My attempt to find a true indicator for Honeycomb was less successful. In the summer of 1991, there was a slight trend developing between the activity of Honeycomb and spring #15a. The activity of #15a gradually became stronger as Honey's Vent became erratic. When the play of #15a became perpetual *and* if Honey's Vent had been erratic for at least 4 hours, then Honeycomb erupted on 8 of 13 occasions. This, however, is only 62% and could be due to chance, especially since such activity was definitely not observed during 1989 and 1990.

15. Honeycomb Geyser

The crater of this geyser measures roughly 70 by 90 feet and contains two vents in an east-west alignment. The western vent measures approximately 7 by 4 feet and overflows into the 12– by 8–foot crater of its eastern neighbor. The two vents are separated by a sinter ridge about 2

Figure 1



feet wide composed of "honeycomb-like" geyserite, hence the name.

Historically, little is known about Honeycomb. Marler states that it was active in 1959, and it is assumed to have been active in every year since then. Between 1988 and 1991, there was a major change in Honeycomb's intervals and eruptive activity.

As described by Marler and later witnessed by many observers are what I began calling "minor" eruptions during 1990. The term "minor" is purely arbitrary, but it applies well in light of more recent activity in Honeycomb. These eruptions consisted of "lazy" bursts which reached 10 to 30 (rarely 40) feet high. During such an eruption, the activity was intermittent, having pauses of 5 to 40 seconds followed by bursts over a 5 to 30 second period. All of this activity came from the eastern vent, but near the end of the eruption small bursting could occur from the western vent as well. The durations ranged from 6 to 22 minutes. Of 58 observed Honeycomb eruptions between 1988 and 1991, 49 (85%) were of this type.

First observed during 1987 and continuing into 1991 were "major" eruptions. Again, this term is arbitrary. These eruptions consisted of roiling from both vents and resembled Artemisia geyser in form. During these eruptions the water could surge as high as 100 feet, though 50 to 75 feet was more typical. Most of this activity still came from the eastern vent. Before the "Firehose" paused on June 18, 1991, the durations of the major eruptions averaged about 12 minutes; after the pause, they increased to 45 minutes.

Marler described intervals of 6 to 10

hours for Honeycomb. No interval in this range was recorded between 1988 and 1991. During 1988 and 1989, Honeycomb was thought to be having minor eruptions once or twice a day, with major eruptions believed to be a random occurrence. In August of 1990, though, I noticed a developing pattern in Honeycomb. Following a major eruption, there would be from 3 to 9 days in which markers would remain unmoved. Once minor eruptions began, they would continue for 6 to 15 days. These led into another major eruption. It is possible that Honeycomb was also doing this during 1988 and 1989, but there is not enough data to prove or disprove the idea. When Honeycomb was in the minor phase of its cycle, the intervals between the eruptions were from 12 to 36 hours.

15a. unnamed

Within the northern shoulder on Honeycomb's basin are three small cracks in the geyserite. These are spring #15a. They were definitely active in 1989, 1990, and 1991. As an eruption of Honeycomb approached, they could start erupting as much as 24 hours before Honeycomb. In 1989 and 1990, intervals of 6 to 30 minutes were followed by eruptions lasting 3 to 5 minutes and reaching about 2 feet in height.

When "Firehose" paused on June 18, 1991, there was a change in the nature of activity between this geyser, Honeycomb, and Honey's Vent. As Honey's Vent became erratic and Honeycomb was within 5 hours of an eruption, #15a would slowly become perpetual. This action ended when Firehose restarted on August 10.

16. Honey's Vent Geyser

Following the 1959 earthquake, a fracture developed to the east of Honeycomb. In early 1960, a steam explosion formed what is now called Honey's Vent Geyser.

In 1988, Phil Landis stated that the only time the activity would completely pause in Honey's Vent was immediately following an eruption of Honeycomb. However, between 1989 and 1991, Honey's Vent was a true geyser. Eruptions of Honey's Vent were frequent, but at any one time could also become irregular. Most intervals were between 15 and 20 minutes long, but they were observed to vary from 7 to 42 minutes. During the "quiet" phase, the water slowly rose within the crater. From 3 to 7 minutes before the eruption, a strong boiling developed in the northwest side of the crater. Honey's Vent's eruption began when the water reached a level about 6 inches below overflow. At this time, the boiling grew in strength, eventually sending bursts from 3 to 10 feet in height. The water level then almost immediately began to fall. After 2 or 3 minutes of play, the pool level had dropped as far as 1 to 3 feet. As the level dropped, the force of the bursts increased. Most of the water was jetted from the crater at this point, with some of the jets occasionally creating a thumping/popping sound as the water struck a ledge just above the erupting vent. The spray of these jets could reach 12 feet above the ground, thus 15 feet above the pool.

Despite its frequency, the durations of Honey's Vent tended to be very erratic. The average duration for 2,479 eruptions was 9m 22s, but the standard deviation was 3m 12s. Amazingly, active periods were longer than inactive periods nearly 70% of the time. No relationship between intervals and durations was seen. The only time Honey's Vent was observed to pause in its activity was from 2½ to 4 hours following an eruption of Honeycomb, longer pauses following major eruptions.

17. "Old" Surprise Spring

In the early days of Yellowstone, this was one of the largest geysers in the park. Eruptions were common and reached as much as 150 feet in height. The formation of a new geyser (location now unknown!) near Old Surprise Spring resulted in a dormancy which lasted until a brief resurrection at the the time of the 1959 earthquake.

Since 1911, there has been a gradual decrease in activity by this feature. When it was active as a geyser in the late 1880s, Peale reported:

> "...large pool...estimated to be 100 feet in diameter. It has a gray basin, in which there is a fissure over which the water has a greenish hue."

By 1959, the water level had receded into the fissure. Following the Hebgen Lake earthquake, Marler noted Old Surprise as a post-earthquake geyser. In 1964, the southern vent along the fissure was active as a small subterranean geyser. In 1989, a vent in the central crater was observed to be perpetually active, reaching about a foot above the pool. By August of 1991, this vent had cooled to just 134°F, and the southern vent was filled with gravel.

18. unnamed

Between Kaleidoscope and springs #4a-c is an old fissure. Spring #18 is the largest opening along this. Before 1990, there was little evidence of any activity from it. Beginning with the enlargement of #5b (Collapse), small subterranean eruptions were observed in #18. After Drain became active in mid June of 1991, these eruptions grew in force. The play at times reached above ground level and some 2 to 3 feet above the pool level. It should be noted that there was a general increase in activity along this entire fracture after Drain began erupting. Several hissing steam vents formed along the bowl of #4c. This fracture appears to terminate at its northern end with spring #2, and even that long-dormant feature increased its temperature and water level along with the new activity elsewhere on the fissure.

19. unnamed

The basin of this geyser lies along the same fracture as the "Firehose", but at the opposite end. Its crater measures 3 by 6 feet, the vent being at the southern end of the crater. It was seen by Bryan [1993] and others in 1981 or (probably) 1982, when the intervals were a few minutes, durations a few seconds, and heights about 20 feet, but no eruptive activity was observed in this geyser until Firehose quit playing on June 18, 1991.

Very little data was obtained on #19 when it was active. Several hours before it erupted there would be periodic minor boiling reaching 1 to 2 feet high. Sometimes this was the total activity. But on nine different observed occasions the boiling activity was concluded by one to three major eruptions. The first of these was always the largest. The play was sharply angled away from the basin of Deep Blue and could reach as much as 50 feet high. The durations were never more than 40 seconds. On eight of the nine observed series, there was a second eruption. When it took place, it followed the first eruption by about 15 minutes. These were smaller, generally about 25 feet in height, and lasted only 10 to 20 seconds. Four of the series had a third eruption similar to the second.

Following an eruption, the basin drained and acted as a receptacle for Deep Blue's overflow. It would take from 6 to 8 hours for the basin to refill. After the Firehose restarted on August 25, the water temperature in #19 dropped from 182°F to only 112°F.

20. unnamed

Between Deep Blue and spring #1b and within Kaleidoscope's outer crater is a small vent. Before the pause of Firehose, this feature was a small perpetual spouter reaching about a foot above its pool level. When Firehose stopped, this vent ended all activity. The restart of Firehose failed to revive #20.

21. unnamed

Some 40 feet beyond the outer edge of Kaleidoscope's outer basin and to the southeast lies a small depression which was lined with orange cyanobacteria. During the "final" burst of Kaleidoscope, this basin acted as a catchment for the overflow. Although no vent is visible, the water level in #21 was observed to rise in correspondence with that in spring #2.

22. unnamed

Between Kaleidoscope and spring #5b (Collapse) is the crater of #22. This spring had a much higher water level in the not too distant past than at present. The crater is lined with beautifully sintered pine needles, branches, and other wind-carried debris. In 1989 and 1990, the water level in the vent was from 4 to 6 feet below overflow, steadily boiling from 1 to 2 feet in height. No change was noted during the enlarging of spring #5b.

The fact that this spring is closely tied in with Drain was made evident after Drain's reactivation in June of 1991. Of all the springs that showed a marked rise and fall in water level, #22 was the most dramatic. At the peak of the rise in the system, #22 was overflow into spring #1d. At these times, a small vent within the same basin would start sputtering. After Drain finished its eruptive cycle, the water level in #22 receded back to a level some 4 to 6 feet from overflow. The only time this feature itself erupted was when its water level was low.

Acknowledgements

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Column Spouter As A True Geyser—
A Completely Quiet Interval and Bursting Eruption in July, 1992

T. Scott Bryan

Abstract
Column Spouter proved itself to be a true geyser during July, 1992, when it was observed to undergo an extended period of inactivity. This cycle is described.

Column Spouter (also known as Column Pool) lies next to the foot trail between Fountain Flats Drive and the Imperial Geyser-Fairy Falls area, in the eastern portion of the Fairy Meadows Group of the Lower Geyser Basin. Although sometimes listed as a geyser because of its spouting action, its has more typically been observed to act as a variable perpetual spouter, never quite ceasing to erupt. On July 3, 1992, I chanced to observe Column Spouter throughout an interval of completely quiet inactivity followed by true bursting.

I approached Column Spouter from the northwest, having been out in the open valley among the Fairy Meadows Springs. From a distance it appeared to be having its usual boiling eruption, doming the water as high as about 2 feet. The spring was being watched by two hikers ahead of me. Looking at other features nearby, my attention returned to Column Spouter when I heard one of the hikers exclaim, "Look, it quit!"

And indeed it had.There was neither subsurface bubbling nor surface boiling. The water level did pulsate slightly as it dropped at a rate of several inches per minute. In time, the level dropped to fully 24 inches below the low point on the crater rim.

Column Spouter then sat quietly for roughly five minutes before it started to visibly refill. The refilling was at first much slower than the drop had been. As it continued, the rate of filling accelerated and was progressively accompanied by renewed pulsations of the pool's surface. When the water level had risen to within about six inches of overflow, the pulsing suddenly became vigorous, pushing some water over the crater rim. Still, however, no vapor phase was visible.

Then, quite abruptly, the pulsing stopped. Large steam bubbles rose into the pool to produce true eruptive bursts as much as four feet high. The pool rapidly reached overflow, and the bursting declined as a surface boiling began. Within two minutes of the first bursts, Column Spouter was back to its usual self, its "eruption" powered entirely by the doming of superheated surface boiling.

The total time from the end of the prior eruption, through the drain-refill cycle, and back to overflow was approximately 30 minutes. Complete inactivity had previously been observed in this spring by Rocco Paperiello during 1983, when quiet intervals of 10 to 20 minutes were seen. At that time, however, all eruptive activity apparently consisted of the surface boiling and not the bursting of rising steam bubbles. This prompted Marie Wolf to respond: "Sorry, Rocco... the thing's a boiling spring in my book, not a geyser... it is very hot and vigorous, and obviously still evolving...[so] It may yet become a geyser." [Wolf and Paperiello, 1986].

The bursting seen in 1992, a first–time observation sufficient to classify Column Spouter as a true geyser, seems to have borne out Marie's prediction.

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VETERAN GEYSER

NORRIS GEYSER BASIN, YELLOWSTONE NATIONAL PARK 1991-1992

By: Ralph C. Taylor

ABSTRACT
This report describes Veteran Geyser, located in the Back Basin portion of Norris Geyser Basin. The report describes the geyser's formation, describes and classifies the types of activity, and describes the activity observed on six days of intensive observation in 1991 and 1992.

INTRODUCTION

Veteran Geyser is an intriguing medium sized geyser located in Norris Geyser Basin. It is often seen by gazers but is not often watched for extended periods. The eruptions are entertaining, and major eruptions are impressive. The description here includes the physical form of the geyser and detailed descriptions of the eruption patterns in Veteran's active and inactive phases. The eruption descriptions include definitions for several types of eruptions.

DESCRIPTION OF VETERAN GEYSER

Veteran Geyser is located in the Back Basin portion of Norris Geyser Basin on a shortcut trail that branches to the west at the foot of the stairway descending from the Steamboat Geyser observation platforms. This trail passes Cistern Spring, then emerges from a stand of pine trees and passes a few meters from Veteran Geyser's crater. It rejoins the Back Basin Loop at a point just north of Vixen Geyser.

Veteran Geyser erupts from three vents located in a complex formation on the south side of the trail. Figure 1 shows the formation from the trail to the west of the geyser. Nearest the trail is a large sinter lined basin, roughly elliptical in shape, located just above the sign in the photo. The long axis of the ellipse is parallel to the trail, extending east to west for about six meters. The minor axis of the basin extends south from the trail for about four meters, and the basin is about one meter deep. The back (south) wall of the basin, farthest from the trail, is roughly one meter thick. The center portion of the wall is hollow, containing the geyser's main vent.

The main vent of Veteran Geyser is a roughly circular hole, about 0.5 meter in diameter, centered on the top of the back wall of the crater. It is the steaming vent visible at the right of Figure 1. A second vent, the pool vent, is located in the back wall of the trailside basin. The pool vent is located in the shadow to the left of the main vent in Figure 1. These two vents both connect to a large hollow cavern in the back wall of the crater. The pool vent is pentagonal in shape, about 20 centimeters across. A third vent is located on the west end of the main basin separated from it by the thickness of the basin wall. The west vent, or "crack vent", is visible at the lower right corner of Figure 1. It emerges from a complex crack in the sinter, which looks

Figure 1: Veteran Geyser formation seen from the trail. The pool is at the center just above the sign. The main vent is the steaming vent at the right.

VETERAN GEYSER - 1991-92

like a miniature cave. The interior of the cave is nicely covered with gray beaded sinter. The water from Veteran's eruptions flows to Tantalus Creek to the south. There is a small dead pine tree in the runoff channel about 20 meters from the vent. This marks the approximate limit of the strongest of Veteran's major eruption bursts.

Another formation similar in form to Veteran Geyser is located a few meters to the east along the trail. It consists of a basin roughly the same size and shape as Veteran's basin. This basin is, like Veteran, located a few meters to the south of the trail. This basin is referred to as the "auxiliary pool" in [Paperiello 1984]. During the time I watched Veteran, the auxiliary basin steamed gently and occasionally thumped audibly from a vent at the south side of the pool, but did not fill with water or erupt. Sandy Snell, the Ranger Naturalist at Norris, said that she did not see any water in the auxiliary pool during the summer of 1992.

Another formation similar in form to Veteran Geyser is located a few meters to the east along the trail. It consists of a basin roughly the same size and shape as Veteran's basin. This basin is, like Veteran, located a few meters to the south of the trail. This basin is referred to as the "auxiliary pool" in [Paperiello 1984]. During the time I watched Veteran, the auxiliary basin steamed gently and occasionally thumped audibly from a vent at the south side of the basin, but did not fill with water or erupt. Sandy Snell, the Ranger Naturalist at Norris, said that she did not see any water in the auxiliary pool during the summer of 1992.

VETERAN GEYSER'S ACTIVITY

Veteran Geyser displays complicated patterns of behavior. It gives an initial impression of chaotic, unstructured surging, steaming, gurgling, and splashing. Only with time do the patterns of the play become evident. The full cycle of activity, when Veteran is in an active phase, extends over a period of one to two hours. An observer should plan for at least half a day of observation to discern the patterns of eruption and distinguish between the types of activity.

Veteran Geyser Modes

Veteran Geyser's pattern of eruptive behavior appears chaotic at first. There is almost constant boiling, rumbling, and splashing from the main vent and the vent in the main basin. Water continually spurts from the main and pool vents and there is constant evolution of steam. The activity ebbs and builds. The periods of increased activity last from 30 seconds to several minutes.

Veteran Geyser has major eruptions separated by periods of cyclic low intensity play and weak minor eruptions. Following a major eruption, Veteran stops all activity completely. Following the pause, activity gradually resumes, reaching a level of ***normal play***. Normal play continues, then after a time builds into an eruption, usually a weak minor eruption. The minor eruption ends in a pause. This cycle of normal play—minor eruption—pause continues, until a major eruption occurs. Further description of the Veteran Geyser eruption cycle follows a more precise definition of the types of play that make up Veteran's activity.

As I studied the patterns of activity, I classified the behavior into modes that are distinct and provide a convenient way to record the progression of Veteran's cycles. The definitions are somewhat arbitrary, but have been useful and are easy to apply. The categories are:

- ***normal play***
- ***minor eruptions***
- ***major eruptions***
- ***pauses***

Figure 19, Figure 20, Figure 21, and Figure 22 are graphical representations of the activity of Veteran Geyser on the days covered by this report. These graphs show the preponderance of normal play activity during the observation period. The much larger proportion of very weak minor eruptions in 1992 may be in part an artifact of my increasing care in classifying the activity, but probably represents a real shift in activity. During most intervals, the activity increases in strength as the time for the major eruption nears. Many intervals have one or two ***minor eruptions*** near the concluding major eruption. The major eruptions are generally evenly spaced for the

VETERAN GEYSER - 1991-92

four days shown here. The eruption interval patterns are discussed at greater length in the section titled **ANALYSIS OF VETERAN'S ERUPTIONS**.

Before examining the eruption patterns in greater detail, a more detailed description of the phases of activity is necessary. The following sections define and describe the modes of activity of Veteran Geyser.

Date	Normal Play	Eruption	Pause
9/17/91	61.85%	18.21%	19.94%
9/18/91	60.99%	18.04%	21.01%
9/21/92	57.21%	20.85%	21.93%
9/22/92	47.67%	24.65%	27.67%

Table 1: Veteran Geyser Activity by Date

Normal Play

In the absence of a better description, I call Veteran's most common activity ***normal play***. Normal play is characterized by nearly continuous activity from the pool vent and the main vent. Veteran bubbles, surges, and splashes in a random way, splashing water from the main vent every few seconds to heights from a few centimeters to a meter or slightly more. Since the main vent and the pool vent are both exits from a single chamber over the channel leading underground, these surges also force water into the pool. The surges are sufficiently short that the water runs back into the big cavity, and the water level stays below the middle of the pool vent.

Normal play is the most common mode of activity in terms of elapsed time. Table 1 shows the percentage of time that Veteran spent in each phase of activity on each of the days of observation. Veteran typically spent about 60% of the total time in normal play during my observations. In 1991, the normal play time was longer than in 1992, but the 1991 times are distorted by some gaps in the data when I was away from the geyser. Some additional observer bias toward lower normal play time may have been caused by a shift in classification, delaying the recorded start of normal play and recording minor eruption starts sooner.

Minor Eruptions

When Veteran is active, each period of normal play leads to an eruption, most of which are minor eruptions. After hours of watching, I categorized the minor eruptions into ***very weak minor***, ***weak minor***, and ***minor*** eruptions. This may seem to over-complicate the situation, but the activity of Veteran is almost continuous and some kind of differentiation helps one see the patterns of activity.

Veteran's minor eruptions vary in strength. During all of them, the activity is confined to the main and pool vents. The main basin fills until the water nearly covers the pool vent. As a minor eruption begins, the play from the main vent becomes more frequent, agitated, and stronger. The major jets emerge at a low angle to the southwest. The strength of the minor eruption can vary from very weak to almost the strength of a major eruption.

Very Weak Minor Eruptions

The ***very weak minor*** eruptions are differentiated from normal play in an almost arbitrary way, but the difference becomes clear with extended observation. Normal play is characterized by low water levels and low intensity activity. The bursts are mostly confined to the hollow inside the back wall of the pool, and occur every 5-6 seconds. The bursts are weak, surging noisily into the pool and splashing gently from the main vent.

The intensity of the normal play eventually builds. The jetting from the main vent reaches two or three meters horizontally and one to one and a half meters vertically, and the frequency of the bursts increases until the bursts are 2-3 seconds apart and significantly stronger. This increase in activity results in more water surging from the pool vent into the pool, and less water draining back into the vent.

If the eruption is a ***very weak minor***, the activity peaks here, having lasted between 25s and 4m (1m23s mean duration). Most very weak minor eruptions last between 30s and

2m. Even the longer very weak minors fail to build beyond a modest power level. The water level in the pool remains between the middle and the top of the pool vent, and the main vent bursts reach at most two meters in height. The main vent bursts are frequent but neither impressively strong nor continuous.

Weak Minor Eruptions

Weak minor eruptions usually occur near the end of a major eruption cycle, often on the last few cycles before the major eruption. A weak minor is similar to a very weak minor but has more intensity and power. Weak minor eruptions last from 30s to 5m, averaging 1m42s. Most durations are between 1m and 2m15s. The water level in the pool rises until it covers the pool vent. The surges from the pool vent are powerful, with steam bursting strongly through the water. The depth of the water in the crater increases the back pressure in the cavity, increasing the power of the main vent surges. The main vent splashes grow until they reach three or four meters in height, but the jetting is neither continuous nor heavy.

Minor Eruptions

A ***minor eruption*** is much more powerful than a weak minor eruption. In fact, a Veteran minor eruption is close in intensity to a full major eruption. The key factor that makes an eruption a minor is a complete lack of any activity from the west or crack vent.

As the minor eruption builds, the water level in the pool rises until the pool vent is covered completely. Meanwhile, the main vent jetting becomes stronger, reaching fully six meters horizontally and two to three meters vertically. During this phase, the main vent play becomes nearly continuous, with heavy jets of water thrown to the southwest at a 45° angle. A heavy volume of water is discharged during the peak of the eruption.

If the eruption is a minor eruption, it ends abruptly just as the main vent jetting reaches the continuous, strong level. During my observations, minor eruptions lasted from 1m to 7m21s, averaging 2m43s, with most durations in the range 1m20s to 3m20s. The largest of the minor eruptions can be very impressive, especially if one has not yet seen a major eruption.

Major Eruptions

A Veteran major eruption starts the same way as a minor eruption. The activity in the main vent increases, and simultaneously the activity in the pool vent increases in vigor and the volume of water emitted. The strong play from the pool vent prevents the pool from draining between surges. The pool level rises until the vent is submerged, eventually reaching 40 or 50 cm in depth. When the water reaches this depth, it shows a pronounced blue tint, apparently from colloidally suspended minerals. The depth of the water traps the steam in the hollow of the main vent, allowing much more power for the main vent bursts.

Driven by increased steam pressure, the activity in the main vent builds until the jetting becomes almost continuous. The water jets reach three meters vertically and four to five meters horizontally. The water is forced from the vent in strong sheets, emerging at about a 45° angle, directed generally southwest from the vent. Up to this point the eruption is the same as a minor eruption. A minor eruption would fade at this point, but a major eruption continues to build in power, growing to eight meters vertically and fully 20 meters horizontally. The water jets are propelled by strong steam pressure, which breaks the water jet into a fine spray before it hits the ground 25 meters or so from the trail. The strongest bursts reach the dead tree in the runoff channel down the slope to Tantalus Creek.

As the pool level rises, steam bursts through the water with enough force to splash water strongly all the way across the basin and occasionally onto the trail.

As the end of the major eruption nears, the strength of the eruption shifts toward the northwest. The small crack vent in the depression to the west of the main basin, which has been quiet until now, begins to gurgle and steam, and then emits a small amount of water. This play builds in strength as the end of the major eruption nears. Figure 2 shows a pool vent burst near the end of a major eruption. The main vent is in full eruption and the crack vent is just beginning to steam. Figure 3 shows a major eruption just as the crack vent starts. The main vent burst at the left center is just over the vent; the jet of the previous burst is in the air at the center. As the eruption nears its climax, the side basin fills and a jet of water with two streams shoots to the west with pulses of increasing power. These jets emerge at a low angle, perhaps 30°, parallel to the trail. The crack vent jets reach about five meters from the vent. A smaller, weaker jet splashes warm water across the trail.

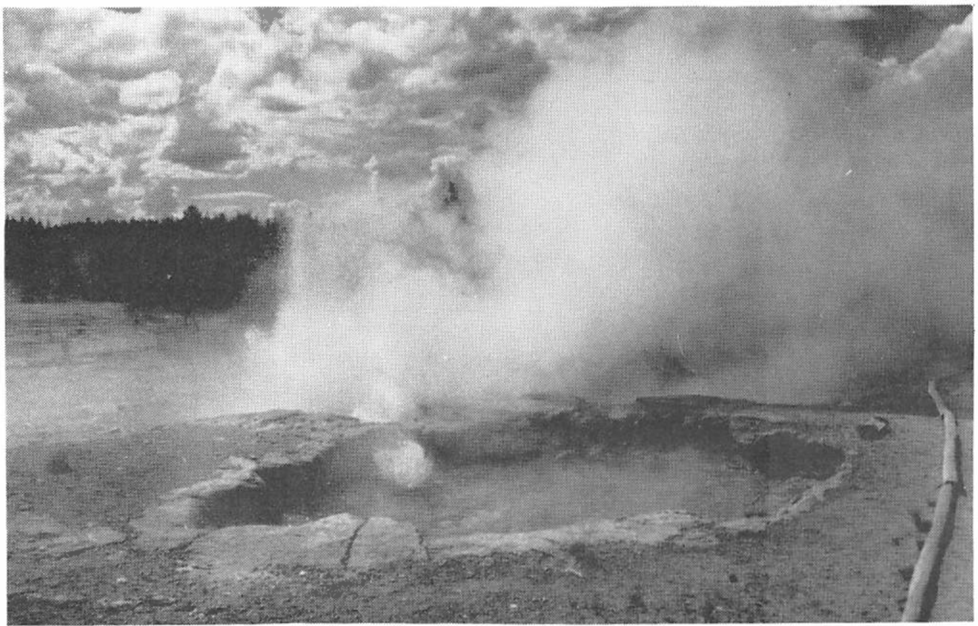

Figure 2: Veteran Geyser Major Eruption
The pool is full, and bursts from both the pool and main vent are visible. The crack vent is in eruption to the far right.

The end of a major eruption is jarringly abrupt. The eruption has been building for three to seven minutes, growing more violent and massive all the time. Suddenly, within a few seconds, the pool vent and the main vent surges diminish in vigor, then stop. The west vent stops a few seconds later. In a few seconds more, the entire complex is quiet; there is no activity at all. The contrast between the furious activity and the complete quiet is startling. Even the rumbling and boiling that characterized the periods between very weak minor eruptions stop. The pool, which reached a depth of half a meter at the height of the eruption, drains noisily into the pool vent. Then, for the first time in perhaps an hour, Veteran is completely quiet. Only the sound of water dripping from the pool and the walls of the main vent into the plumbing is heard.

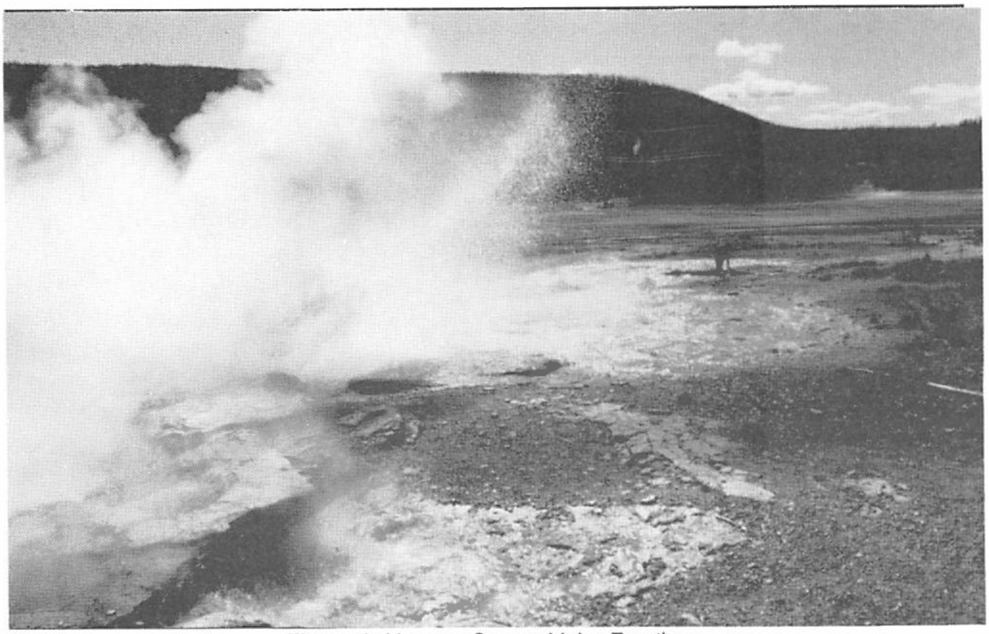

Figure 3: Veteran Geyser Major Eruption
The main vent bursts are visible at the center, and the beginning of the crack vent activity is visible at bottom center.

Pauses

All of Veteran's major and minor eruptions are followed by a ***pause***. The pause following a very weak minor eruption is not really complete, but the activity slows almost to a stop. The water drains from the pool and no splashes are visible in the main vent. The grumbling and splashing inside the hollow back wall continue at a low level. The pauses following more vigorous eruptions are longer and more complete. After a period of quiet (the length and "quietness" of which depend on the type of preceding eruption), activity restarts. I chose the first visible splash out of the main vent as the end of the pause.

ANALYSIS OF VETERAN'S ERUPTIONS

The patterns of activity in Veteran Geyser have changed since the early 1980s. During four separate periods of observation, I saw one period of inactivity, one day of decreasing intervals ending in a series of closely spaced major eruptions, and two 2-day periods of relatively constant activity, with major eruptions occurring every 60 to 90 minutes.

Previous Observations

Paperiello reports that in 1984 Veteran Geyser had both short term and long term cyclic behavior [Paperiello 1984]. He describes progressions of eruptions with *increasing* intervals, culminating in a "full pool mode" eruption in which both Veteran Geyser's basin and the auxiliary pool fill with water. The 1984 activity progressed from strong 12 meter (40 ft) eruptions to weaker eruptions as the series progressed. On each eruption, the "auxiliary pool" filled to greater depth. Only in the first eruptions of a progression was the "crack vent" or west vent, active. Paperiello notes that this cyclic activity was first reported by Tomáš Vachuda in the early 1980s.

Activity in 1991 and 1992

My 1991 and 1992 observations did not show any trace of the cyclic behavior reported in 1984. My 1991 and 1992 observations were limited in scope, covering one day in August and two consecutive days in September in both years. On each of the five days of observation when Veteran was active, my observations extended for at least seven consecutive hours, and on the two days in September 1992 covered 10 consecutive hours.

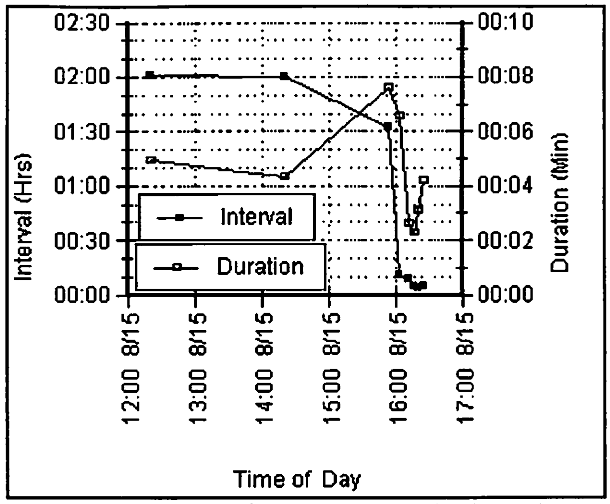

Figure 4: Veteran Geyser Major Eruption Intervals vs Time, 15 August 1991

On 15 August 1991, my first day of serious observation of Veteran Geyser, I witnessed a decreasing interval series that built to a spectacular series of six major eruptions in a single half hour period. The data for this series is not complete, as I had not yet worked out the complexities of Veteran's activity. Figure 4 shows the major eruption intervals for this series. This single day was the only occasion on which I saw any activity at all from the auxiliary pool, and the activity was limited to gentle steaming during Veteran's minor and major eruptions.

During the September 1991 and September 1992 observations, major eruptions occurred at approximately constant intervals on each day, and no trend in interval was evident. Table 2 shows the daily maximum, minimum, and average intervals between major eruptions.

Figure 5 shows the major eruption intervals and durations for 17-18 September 1991. The mean interval for the two days is 63m10s. Although there is a gap between the two sets of data, there is no indication that the interval changed from one day to the next. The slope of a straight line fitted to the data (the horizontal line at the 1h3m interval) is almost zero.

On 6 August 1992, Veteran was inactive. It had a continuous series of weak minors with no real pauses and no significant eruptions.

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Date	Number	Max	Min	Mean
9/17/91	6	90.58	26.75	63.55
9/18/91	8	80.67	54.43	62.89
9/21/92	6	105.78	62.13	91.09
9/22/92	7	108.18	68.27	88.22

Table 2: Veteran Geyser Major Eruption Intervals

On 21-22 September 1992 I observed Veteran for about 10h30m each day. The intervals varied somewhat, but were close to the two day mean of 89m33s. Figure 6 shows the major eruption intervals and durations for these two days. As with the 1991 data there is a gap between the two sets of data, but the eruption interval does not appear to change significantly. The least squares straight line fitted to the data (near the 1h30m grid on the graph) has a slope that is essentially flat, indicating no significant change of interval over time.

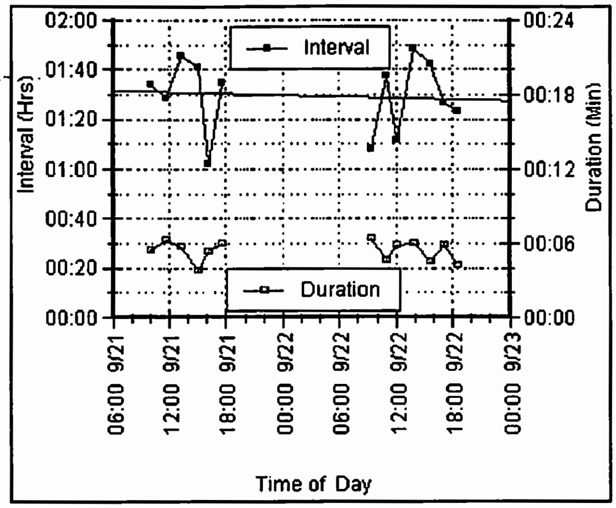

Figure 6: Veteran Geyser Major Eruption Intervals and Durations vs Time, 21-22 September 1992

Veteran's Inactive Phase

On Thursday, 6 August 1992, I found Veteran Geyser in an inactive phase. "Inactive" is a relative term; there was actually continuous activity of the normal play variety, occasionally building to an anemic very weak minor. The periods of activity ranged from 1m30s to 8m in length, separated by pauses of 15s to 1m30s. The pauses were not complete; splashing and surging of water into the pool did not stop, and the pool did not drain. Even during the strongest of the very weak minor play, the pool level did not reach the top of the pool vent. Most of the cycles of increased activity lasted between 5 and 8 minutes. During a rather boring three hour period of observation, no jets from the main vent, even at the peak of activity, exceeded 3 meters. The side vent was completely dry, including all of the catch basins in the geyserite. This suggests that the duration of the inactive phase was many hours or possibly several days.

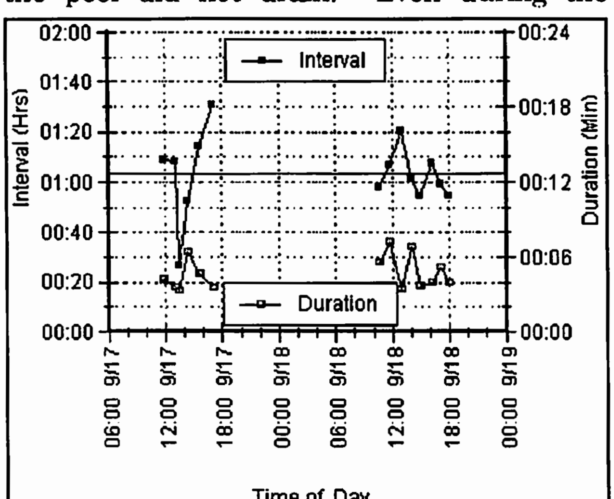

Figure 5: Veteran Geyser Major Eruption Intervals and Durations vs Time, 17-18 September 1991

I found no other observers who could help determine the length of Veteran's quiet phase. The naturalists at Norris had not seen any activity for several days, but had not spent any amount of time watching either. Since Veteran has such a complicated cycle, it is necessary to watch for a considerable time to be certain that it is not active. However, given the "dead" appearance of the play and the dryness of the side vent, it is likely that the inactive period had lasted for at least a few days.

Eruption Intervals and Durations

Veteran's eruption durations generally are longer for stronger eruptions. The intervals between major eruptions show interesting variations, which have been noted briefly earlier in this paper. The intervals between minor eruptions are interesting in that they suggest the variations in the energy supply during the major eruption cycle. The following sections discuss the interval and duration distributions in more depth.

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Major Eruptions

The six days for which major eruption data is available show varying intervals and patterns of intervals. On 15 August 1991, the intervals started at about two hours, then rapidly dropped, ending with five major eruptions with intervals of 10m38s, 8m40s, 4m23s, 3m52s, and 4m25s (see Figure 4). The next interval was much longer, but I was not able to stay to determine what happened to the intervals after this set of close-spaced eruptions.

On 17-18 September 1991, the eruptions occurred at approximately constant intervals averaging 1h03m10s, as shown in Figure 5. The one short interval during this period occurred during a 90 minute time with an unusual concentration of minor and major eruptions. Following the 26 minute interval, the intervals climb steadily for the rest of the series of observed data. It is interesting to note that the expected major eruption did not occur at 17:00, although the observations were not continued long enough to determine whether the interval continued the trend to longer intervals. When observations resumed just over 16 hours later, the intervals had steadied at about one hour. No extreme interval changes were observed during 8h30m of observation.

On 6 August 1992, there were no major eruptions in a four hour observation period. On 21-22 September 1992, the intervals were uniformly longer than those seen in September 1991, averaging 1h29m32s. The trend line shows a small decrease in intervals over the two days, about two minutes per day.

Overall, the major eruptions that I noted during my September observations varied from 3m15s to 7m10s in length, averaging 4m12s in duration. Most eruptions had durations of 3m30s to 6m25s. During the decreasing interval series on 15 August 1991, some durations as short as 2m19s were seen, but at this time, the corresponding intervals were as short as 4m20s.

The period of inactivity on 6 August 1992, the different intervals seen in September 1991 and September 1992, and the decreasing interval series of 15 August 1991 suggest that Veteran has a long term cycle that was not evident in the relatively short periods of observation covered by this report.

Minor Eruptions

Figure 7 and Figure 8 illustrate the intervals and durations for the minor eruptions that occurred during the period of observation. These intervals are those between successive minor eruptions. Since minor eruptions are relatively rare (one or two per major eruption interval), these intervals are of limited significance. The interval distribution is distinctly bimodal. This is because some major intervals had two minor intervals before the major and others had only one. In the latter case the interval is essentially the major interval, while in the former case the interval is one or two of the short cycles in length. This

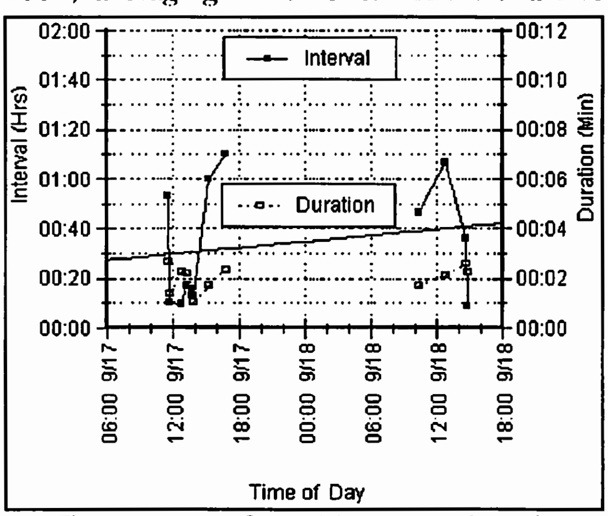

Figure 7: Veteran Geyser Minor Eruption Intervals and Durations vs Time, 17-18 September 1991

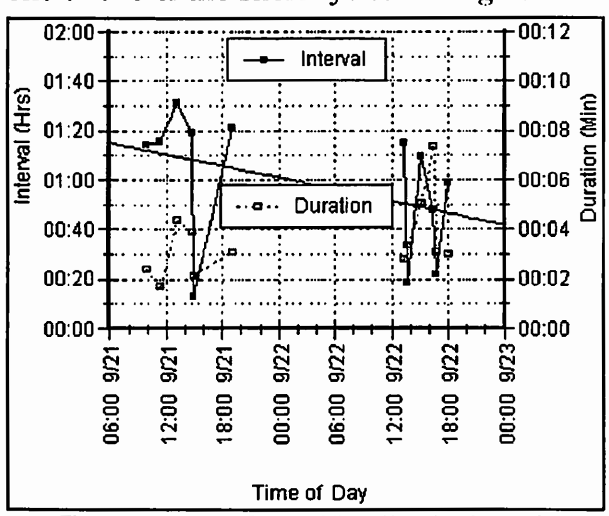

Figure 8: Veteran Geyser Minor Eruption Intervals and Durations vs Time, 21-22 September 1992

VETERAN GEYSER - 1991-92

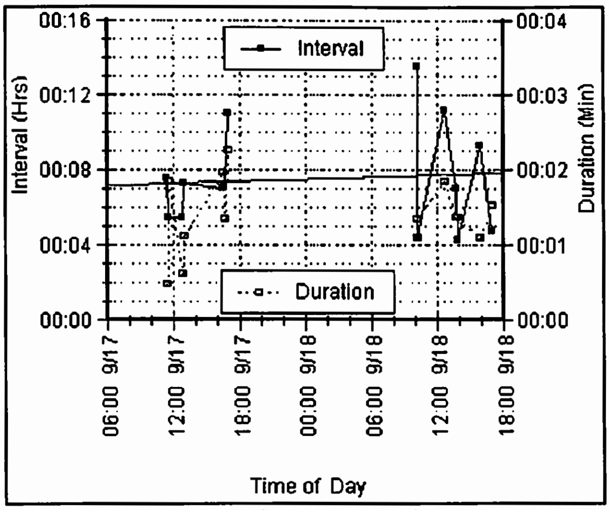

Figure 9: Veteran Geyser Weak Minor Intervals and Durations vs Time, 17-18 September 1991

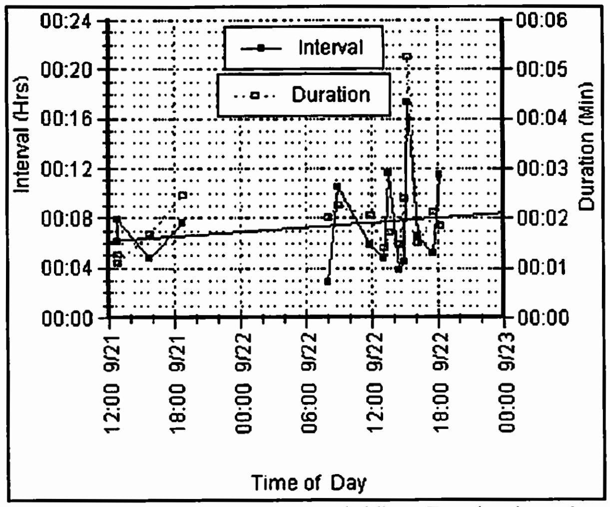

Figure 10: Veteran Geyser Weak Minor Eruption Interals and Durations vs Time, 21-22 September 1992

effect can be seen in Figure 19, Figure 20, Figure 21, and Figure 22 which show all of the observed eruptions. In 1991, there were more cases of two minor eruptions in a cycle, but the total number of observed minors is too small to draw any conclusions.

The minor eruption durations lie between one and seven minutes. The 1991 durations were all less than three minutes; the 1992 eruptions were longer, especially on 22 September. This may be related to a general increase in intensity of Veteran's play on 22 September 1992.

Weak and Very Weak Minors

Figure 9 and Figure 10 illustrate the intervals between and durations of the weak minor eruptions. These intervals are between any preceding minor, weak minor, or very weak minor eruption and a weak minor eruption. The intervals increased slightly over the observation period in both graphs, but the increase is probably not significant given the small amount of data. There tends to be an alternation between short (4-6 minute) and long (10-15 minute) intervals on both years. There is no obvious explanation for this phenomenon; it may simply be a coincidence.

Figure 11 and Figure 12 are plots of the very weak minor eruption intervals. Figure 13 and Figure 14 illustrate the very weak minor durations. The intervals were computed as for the weak minor eruptions; i.e., from the preceding minor eruption of any type. The weak minor and very weak minor eruption intervals were generally similar in range, but

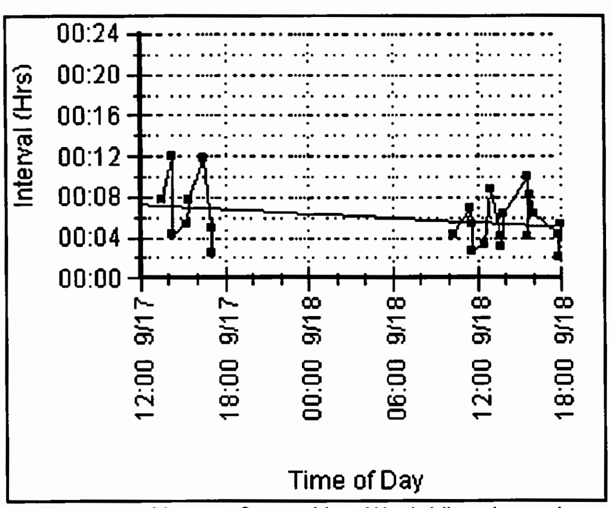

Figure 11: Veteran Geyser Very Weak Minor Intervals vs Time, 17-18 September 1991

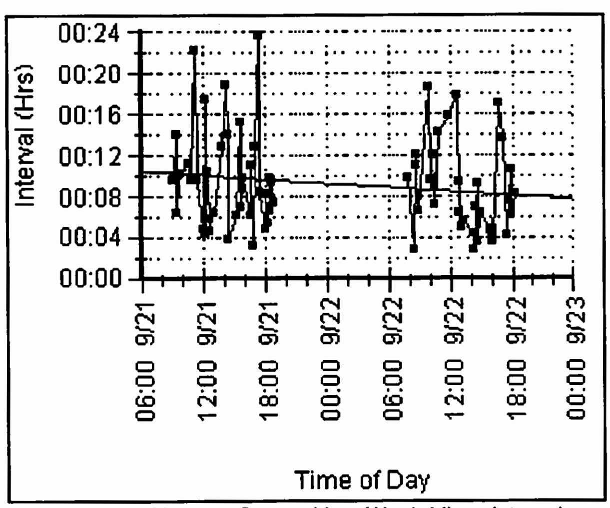

Figure 12: Veteran Geyser Very Weak Minor Intervals vs Time, 21-22 September 1992

VETERAN GEYSER - 1991-92

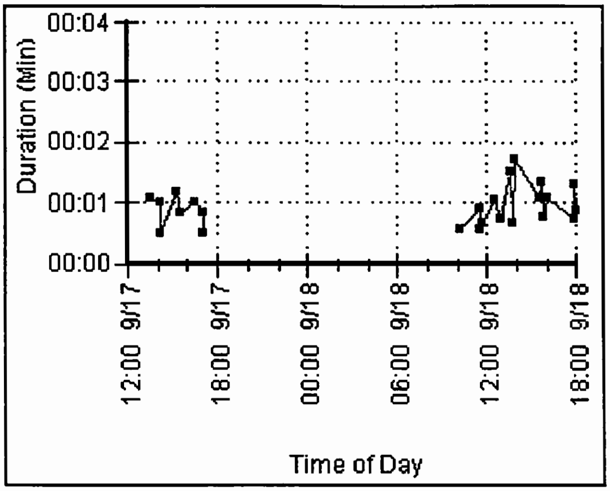

Figure 13: Veteran Geyser Very Weak Minor Durations vs Time, 17-18 September 1991

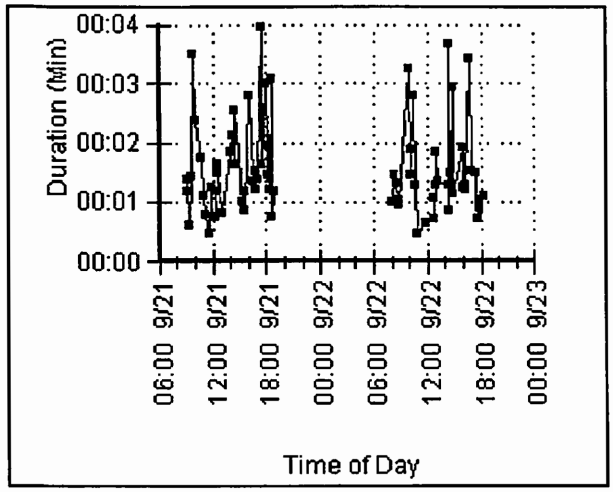

Figure 14: Veteran Geyser Very Weak Minor Durations vs Time, 21-22 September 1992

the very weak minor intervals were slightly shorter. Weak minor intervals ranged from 3m to 17m16s, with most between 4m and 12m. The very weak minor intervals ranged from 2m10s to 23m42s, with most between 3m and 14m. The distribution was fairly broad, with a peak between 4m and 6m. The longer intervals were scattered, and had no discernible pattern.

The duration of most weak minors and very weak minors was around 1m. The range in durations for very weak minors was 29s to 3m58s, with most between 30s and 2m0s. A few very weak minors lasted more than 2m, but over 90% lasted less than 2m. Weak minor durations ranged from 29s to 5m14s, with most in the 1m5s to 2m15s range.

Generally speaking, the durations of the eruptions decreased with decreasing eruption power. Figure 15 shows the duration distributions for the various types of eruptions. Major eruptions lasted between 3m and 8m, most minor eruptions lasted between 2m and 3m, and weak minor and very weak minor eruptions tended to last for less than 2m.

Pauses

Each Veteran Geyser eruption cycle includes a pause. The pauses are interesting to observe as they are such a contrast to the otherwise nearly constant activity of Veteran.

It was clear during my observations that the pause following a major eruption was both longer and more complete (in the sense of being a full stop of all activity) than the pauses following less powerful eruptions. Figure 16 shows the pause durations separated by the type of eruption and sorted by pause duration. The vertical axis represents the pause duration in minutes; the horizontal axis has one vertical bar for each eruption, sorted in order of increasing duration. The pause duration is clearly related to the power of the eruption.

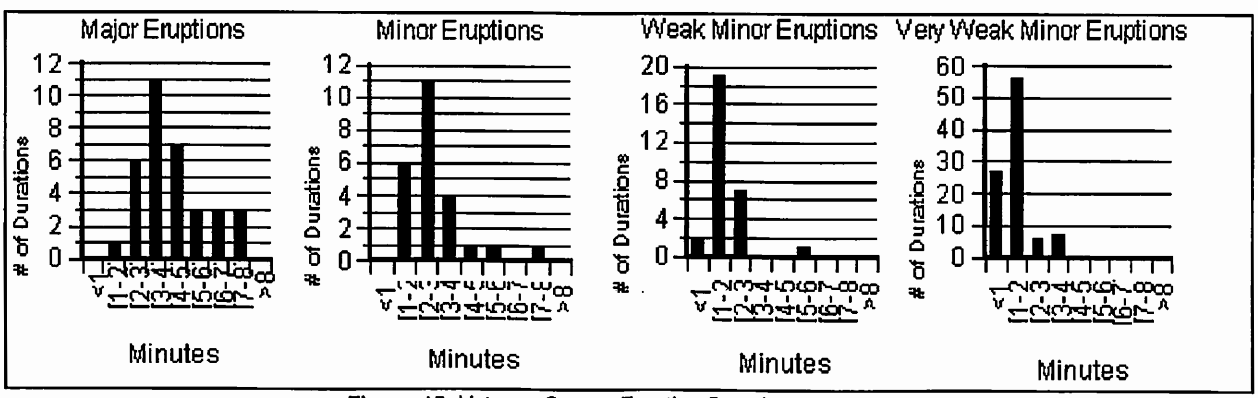

Figure 15: Veteran Geyser Eruption Duration Histograms

VETERAN GEYSER - 1991-92

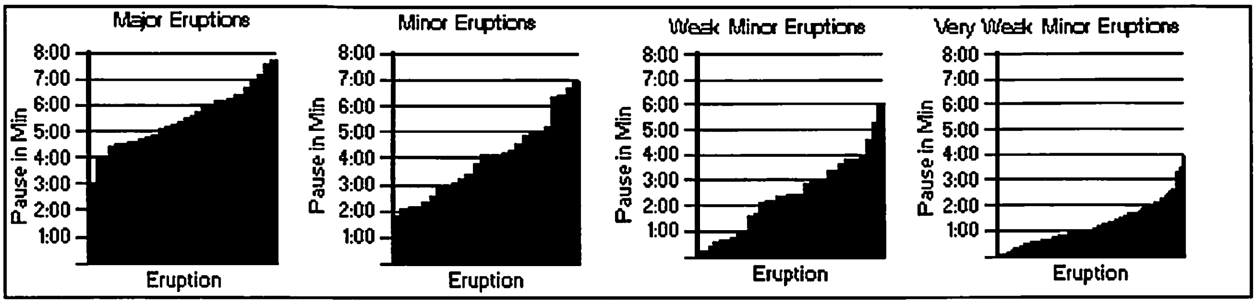

Figure 16: Veteran Geyser Pause Durations

Figure 17 is another visualization of the same data. This figure compares the distribution histograms of the pause durations. The shift in pause duration to shorter pauses as the strength of the eruption declined is again evident. In all cases the distribution peaked sharply, and the peak duration decreases from about 4m for major eruptions to less than 2m for very weak minor eruptions.

Pauses following major eruptions were periods of true quiet, with no audible boiling for much of the pause. The mean pause following a major eruption was 5m29s; the pauses ranged from 3m0s to 7m45s. Following a minor eruption the mean pause was 4m0s, with a range from 1m50s to 6m54s. Weak minor eruptions were followed by a mean pause of 2m26s, with a range from 0m13s to 6m01s; most were less than 4m in duration. Very weak minor eruptions were followed by still shorter pauses, averaging 1m15s and ranging from just 0m03s to 3m55s; most were less than 3m0s in duration.

Figure 16 shows the pause length plotted as a function of the preceding eruption's duration. There is a fairly wide scatter, but the general tendency for longer pauses following longer eruptions is evident. The line shown is a least squares line fitted to the data. The pause duration is given by the equation:

$$\textit{Pause} = 0.922 \times \textit{Duration} + 27.7$$

where:

Pause is the pause length in seconds
Duration is the duration of the preceding eruption in seconds.

The R^2 value for the fit is 0.586.

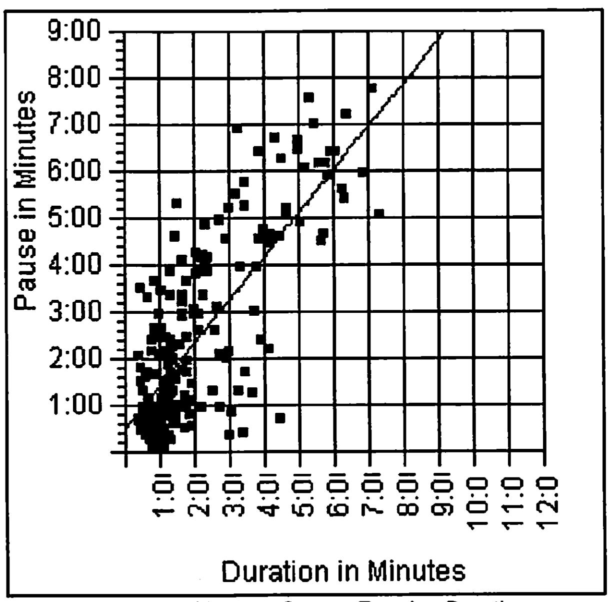

Figure 18: Veteran Geyser Eruption Duration vs Subsequent Pause

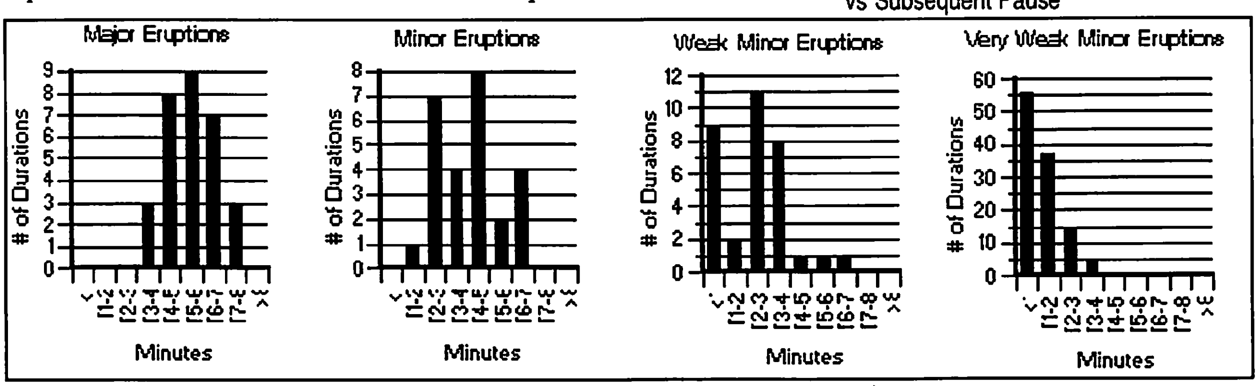

Figure 17: Veteran Geyser Pause Duration Distribution

VETERAN GEYSER - 1991-92

Overall Patterns

Figure 19 through Figure 22 show the daily activity for Veteran on the four days covered by this study. The chart for 17 September 1991 shows a strong increase in activity between 1300 and 1500, marked by five minor eruptions and three major eruptions in a period of about two hours. No such strong concentration was evident on the next day. On both days, activity tended to increase during the interval between major eruptions. The long periods shown as normal play following most major eruptions contrast with the periods of normal play punctuated by very weak minor eruptions on the two charts from 1992. This may be more an artifact of more careful observation and classification of activity than any real change in activity.

The 1992 charts (Figure 21 and Figure 22) show a clear trend of increasing activity throughout the interval. There is a definite increase in activity level during the afternoon of 22 September 1992, from about 1330 to 1700. The graphs suggest that a cycle with a period of perhaps 12 hours is present in the 1992 data, and one with a longer period may be present in the 1991 data. A longer stretch of continuous data would be necessary to make a clear determination.

Observing Veteran Geyser

Earlier sections of this paper discussed the activity of Veteran Geyser. The patterns are complicated, and one tends at first to make copious notes. After a considerable period of observation, I determined that the complete pattern can be captured by recording just three times for each cycle: the start of normal play after the pause, the eruption start, and the eruption end. These three times, along with the type of eruption, fully describe the cycle.

The transition from normal play to an eruption is difficult to describe clearly. The simplest advice I can offer is to watch several cycles. The sound and power of the main vent activity are the best indicator of the eruption start.

CONCLUSIONS

Based on six days of intensive observation, I conclude that Veteran Geyser has changed its behavior significantly since 1984. The "Auxiliary Vent" displays no activity other than slow steaming now, and the progression of activity through the cycle has changed also.

In 1991 and 1992, on most days, the major eruptions tended to occur at relatively constant intervals. I saw one day of inactivity in August 1992, when the strongest activity was the occasional very weak minor eruptions.

The gradual increase in activity during the afternoon of 22 September 1992 and the series of closely spaced, decreasing interval major eruptions on 15 August 1991 suggest a long term cyclic variation in Veteran's behavior. The long term cycles, if present, must have a period of at least ten hours, so a much longer continuous observation period is needed to find such a variation. Since Veteran Geyser is located in a relatively inconvenient spot for long term observation, some form of automatic sensing appears to be the most effective means of obtaining the needed data.

The period of inactivity in August 1992 may have been induced (or ended) by one of the basin wide disturbances common at Norris. Another worthwhile project would compare the activity in Veteran before and after one of the disturbances. A comparison of this nature could be done based on four to six hours of continuous observation every few days, assuming that the activity remains as constant as the activity observed in September 1991 and September 1992.

DATA

The record of observations that form the basis for this report is available from the author on request. The data consists of eight pages of tables, and is omitted for brevity.

REFERENCES

Bryan 1986 *The Geysers of Yellowstone*, T. Scott Bryan, Colorado Associated University Press, 1986

Paperiello 1984 *Report on the NORRIS GEYSER BASIN for 1984*, Rocco Paperiello, GOSA Press, 1984

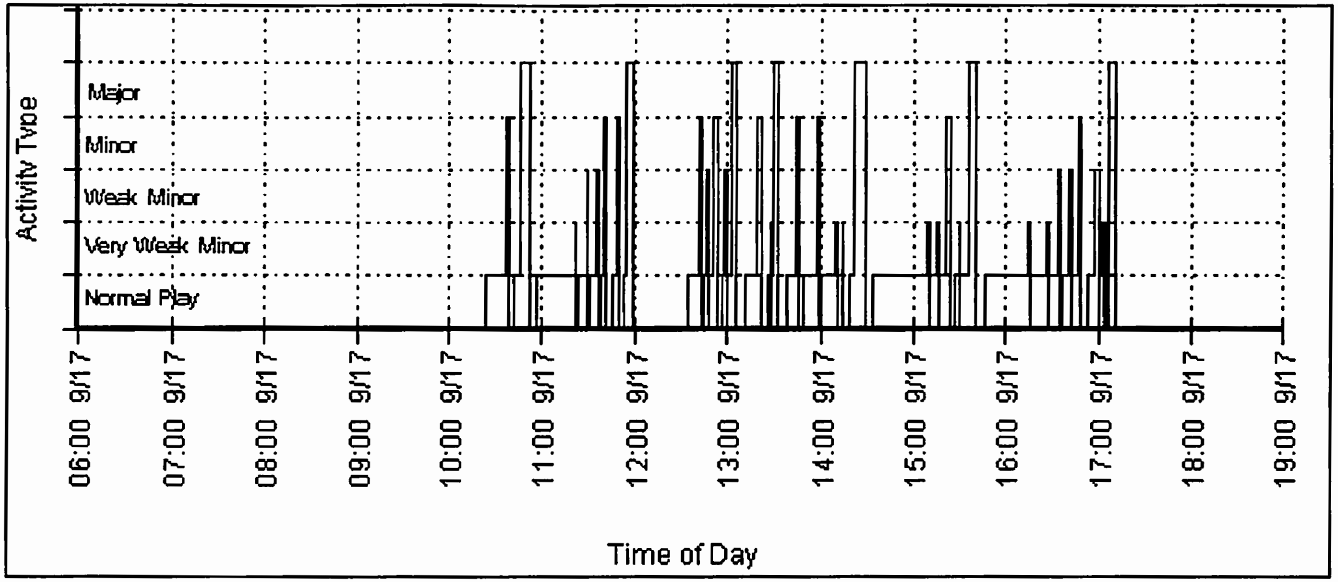

Figure 19: Veteran Geyser Activity, 17 September 1991

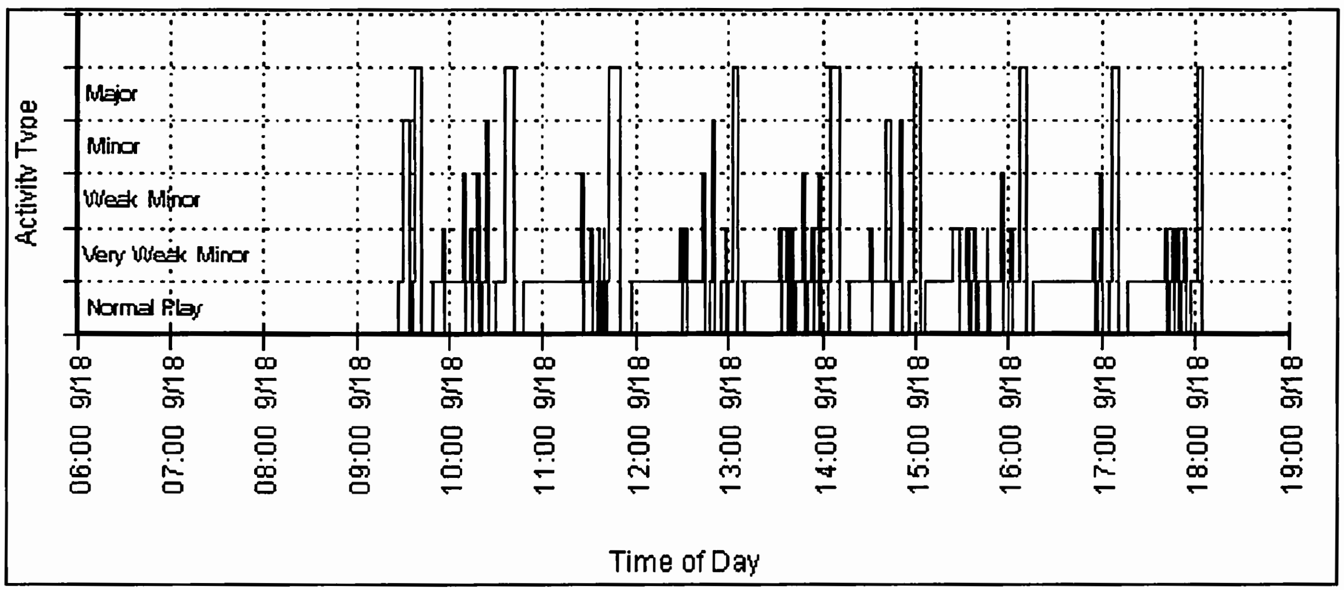

Figure 20: Veteran Geyser Activity, 18 September 1991

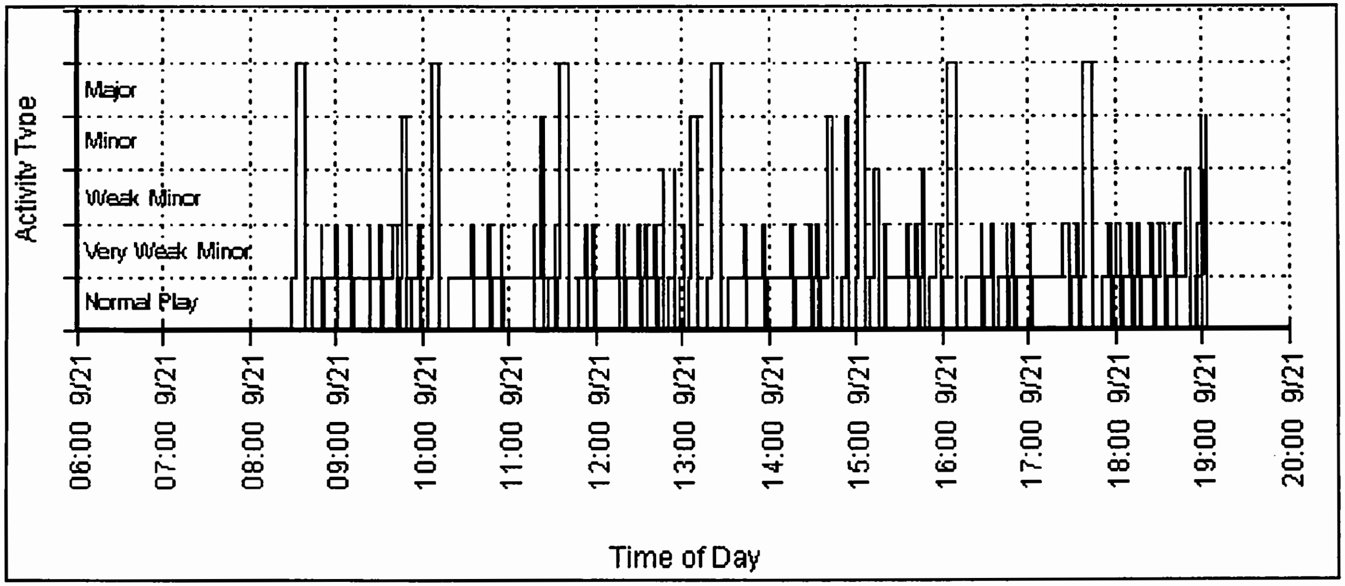

Figure 21: Veteran Geyser Activity 21 September 1992

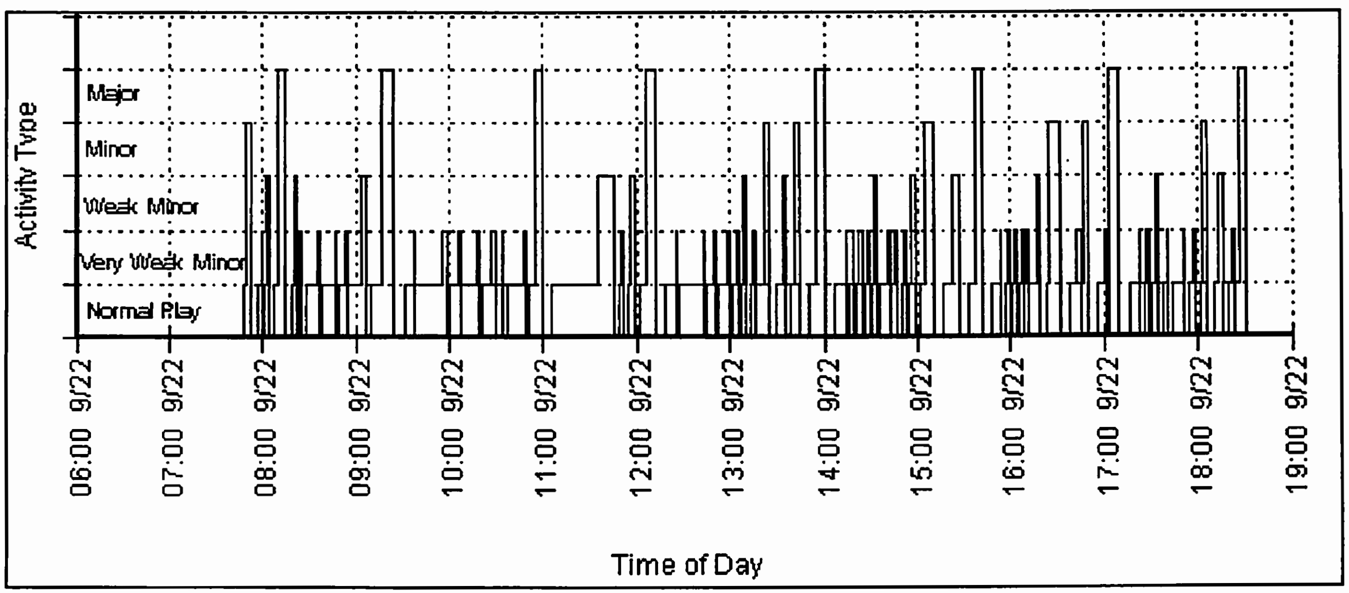

Figure 22: Veteran Geyser Activity, 22 September 1992

VETERAN GEYSER ERUPTION DATA - 1991-92

Normal Play		--- Eruption ---		---- Pause -----		--------------- Interval ---------------				Eruption
Start	Duration	Start	Duration	Start	Duration	Cycle	Major	Minor	Weak Minor	Type
Thursday, 15/Aug/91										
10:15:00	5:00	10:20:00	3:14	10:23:14	4:50					Major
12:19:11	2:04	12:21:15	4:57	12:26:12	3:53	2:04:11	2:01:15	2:01:15		Major
14:15:50	5:10	14:21:00	4:21	14:25:21	4:59	1:56:39	1:59:45	1:59:45		Major
15:49:55	3:27	15:53:22	7:35	16:00:57	3:03	1:34:05	1:32:22	1:32:22		Major
16:04:00	0:00	16:04:00	6:36	16:10:36	2:04	0:14:05	0:10:38	0:10:38		Major
16:12:40	0:00	16:12:40	2:37	16:15:17	1:46	0:08:40	0:08:40	0:08:40		Major
16:17:03	0:00	16:17:03	2:19	16:19:22	1:33	0:04:23	0:04:23	0:04:23		Major
16:20:55	0:00	16:20:55	3:08	16:24:03	1:17	0:03:52	0:03:52	0:03:52		Major
16:25:20	0:00	16:25:20	4:10	16:29:30	2:00	0:04:25	0:04:25	0:04:25		Major

VETERAN GEYSER ERUPTION DATA - 1991-92

Normal Play		--- Eruption ---		---- Pause ----		---------- Interval ----------				Eruption
Start	Duration	Start	Duration	Start	Duration	Cycle	Major	Minor	Weak Minor	Type
Tuesday, 17/Sep/91										
10:17:48	2:57	10:20:45	1:25	10:22:10	1:50					Very Weak Minor
10:24:00	12:50	10:36:50	2:08	10:38:58	2:57	0:06:12				Minor
10:41:55	3:38	10:45:33	5:45	10:51:18	4:37	0:17:55		0:08:43		Major
10:55:55	25:35	11:21:30	0:50	11:22:20	0:10	0:14:00				Very Weak Minor
11:22:30	6:31	11:29:01	0:29	11:29:30	0:25	0:26:35			0:07:31	Weak Minor
11:29:55	4:35	11:34:30	1:50	11:36:20	1:40	0:07:25			0:05:29	Weak Minor
11:38:00	1:00	11:39:00	2:40	11:41:40	3:05	0:08:05		0:53:27		Minor
11:44:45	4:15	11:49:00	1:20	11:50:20	2:20	0:06:45		0:10:00		Minor
11:52:40	1:50	11:54:30	4:15	11:58:45	4:39	0:07:55	1:08:57	0:05:30		Major
12:35:00	6:30	12:41:30	1:46	12:43:16	1:44					Minor
12:45:00	2:00	12:47:00	0:37	12:47:37	0:39	0:10:00			0:05:30	Weak Minor
12:48:16	2:57	12:51:13	2:17	12:53:30	3:21	0:03:16		0:09:43		Minor
12:56:51	1:39	12:58:30	1:07	12:59:37	0:13	0:08:35			0:07:17	Weak Minor
12:59:50	2:55	13:02:45	3:30	13:06:15	5:45	0:02:59	1:08:15	0:11:32		Major
13:12:00	7:30	13:19:30	2:12	13:21:42	4:08	0:12:10		0:16:45		Minor
13:25:50	1:25	13:27:15	1:05	13:28:20	0:00	0:13:50			0:07:45	Very Weak Minor
13:28:20	1:10	13:29:30	3:15	13:32:45	5:30	0:02:30	0:26:45	0:10:00		Major
13:38:15	6:45	13:45:00	1:17	13:46:17	1:50	0:09:55		0:15:30		Minor
13:48:07	9:38	13:57:45	1:00	13:58:45	2:05	0:09:52		0:12:45		Minor
14:00:50	8:55	14:09:45	1:00	14:10:45	0:15	0:12:43			0:12:00	Very Weak Minor
14:11:00	3:00	14:14:00	0:30	14:14:30	3:30	0:10:10			0:04:15	Very Weak Minor
14:18:00	3:45	14:21:45	6:23	14:28:08	5:22	0:07:00	0:52:15	0:24:00		Major
14:33:30	35:55	15:09:25	1:00	15:10:25	0:35	0:15:30				Very Weak Minor
15:11:00	3:45	15:14:45	1:10	15:15:55	0:05	0:37:30			0:05:20	Very Weak Minor
15:16:00	5:30	15:21:30	1:43	15:23:13	2:57	0:05:00		0:59:45		Minor
15:26:10	3:05	15:29:15	0:50	15:30:05	0:05	0:10:10			0:07:45	Very Weak Minor
15:30:10	6:05	15:36:15	4:40	15:40:55	5:05	0:04:00	1:14:30	0:14:45		Major
15:46:00	28:45	16:14:45	0:50	16:15:35	0:10	0:15:50				Very Weak Minor
16:15:45	10:45	16:26:30	1:00	16:27:30	0:05	0:29:45			0:11:45	Very Weak Minor
16:27:30	6:00	16:33:30	1:57	16:35:27	0:33	0:11:45			0:07:00	Weak Minor
16:36:00	4:40	16:40:40	1:20	16:42:00	0:15	0:08:30			0:07:10	Weak Minor
16:42:15	4:15	16:46:30	2:20	16:48:50	4:50	0:06:15		1:10:15		Minor
16:53:40	3:50	16:57:30	2:15	16:59:45	0:55	0:11:25			0:11:00	Weak Minor
17:00:40	1:50	17:02:30	0:50	17:03:20	0:10	0:07:00			0:05:00	Very Weak Minor
17:03:30	1:30	17:05:00	0:30	17:05:30	0:35	0:02:50			0:02:30	Very Weak Minor
17:06:05	0:45	17:06:50	3:30	17:10:20	5:13	0:02:35	1:30:35	0:20:20		Major

VETERAN GEYSER ERUPTION DATA - 1991-92

Normal Play		--- Eruption ---		---- Pause -----		--- Interval ---				Eruption
Start	Duration	Start	Duration	Start	Duration	Cycle	Major	Minor	Weak Minor	Type
Wednesday, 18/Sep/91										
9:21:00	3:10	9:24:10	1:25	9:25:35	1:00					Weak Minor
9:26:35	3:45	9:30:20	4:10	9:34:30	2:10	0:05:35				Minor
9:36:40	0:55	9:37:35	5:03	9:42:38	6:37	0:10:05		0:07:15		Major
9:49:15	6:25	9:55:40	0:40	9:56:20	1:09	0:12:35				Very Weak Minor
9:57:29	11:46	10:09:15	1:05	10:10:20	0:40	0:08:14			0:13:35	Weak Minor
10:11:00	2:30	10:13:30	0:35	10:14:05	1:18	0:13:31			0:04:15	Very Weak Minor
10:15:23	2:27	10:17:50	1:20	10:19:10	2:10	0:04:23			0:04:20	Weak Minor
10:21:20	2:20	10:23:40	1:42	10:25:22	4:06	0:05:57		0:46:05		Minor
10:29:28	5:47	10:35:15	5:37	10:40:52	6:08	0:08:08	0:57:40	0:11:35		Major
10:47:00	37:15	11:24:15	1:30	11:25:45	0:45	0:17:32				Weak Minor
11:26:30	4:40	11:31:10	0:55	11:32:05	3:37	0:39:30			0:06:55	Very Weak Minor
11:35:42	0:48	11:36:30	0:35	11:37:05	0:40	0:09:12			0:05:20	Very Weak Minor
11:37:45	1:23	11:39:08	0:41	11:39:49	1:41	0:02:03			0:02:38	Very Weak Minor
11:41:30	0:45	11:42:15	7:11	11:49:26	7:45	0:03:45	1:07:00	1:07:00		Major
11:57:11	31:34	12:28:45	0:57	12:29:42	0:03	0:15:41				Very Weak Minor
12:29:45	2:20	12:32:05	1:02	12:33:07	0:03	0:32:34			0:03:20	Very Weak Minor
12:33:10	10:05	12:43:15	1:50	12:45:05	2:25	0:03:25			0:11:10	Weak Minor
12:47:30	1:45	12:49:15	2:05	12:51:20	3:47	0:14:20		1:07:00		Minor
12:55:07	2:53	12:58:00	0:45	12:58:45	1:05	0:07:37			0:08:45	Very Weak Minor
12:59:50	3:05	13:02:55	3:21	13:06:16	3:57	0:04:43	1:20:40	0:13:40		Major
13:10:13	22:47	13:33:00	0:35	13:33:35	0:55	0:10:23				Very Weak Minor
13:34:30	2:33	13:37:03	1:32	13:38:35	0:55	0:24:17			0:04:03	Very Weak Minor
13:39:30	0:40	13:40:10	0:40	13:40:50	1:40	0:05:00			0:03:07	Very Weak Minor
13:42:30	4:40	13:47:10	1:22	13:48:32	0:58	0:03:00			0:07:00	Weak Minor
13:49:30	4:00	13:53:30	1:43	13:55:13	1:45	0:07:00			0:06:20	Very Weak Minor
13:56:58	0:50	13:57:48	1:22	13:59:10	3:50	0:07:28			0:04:18	Weak Minor
14:03:00	1:27	14:04:27	6:52	14:11:19	5:56	0:06:02	1:01:32	1:01:32		Major
14:17:15	13:15	14:30:30	0:55	14:31:25	0:40	0:14:15				Very Weak Minor
14:32:05	8:18	14:40:23	2:37	14:43:00	2:35	0:14:50		0:35:56		Minor
14:45:35	3:30	14:49:05	2:17	14:51:22	4:11	0:13:30		0:08:42		Minor
14:55:33	3:42	14:59:15	3:45	15:03:00	3:00	0:09:58	0:54:48	0:10:10		Major
15:06:00	17:15	15:23:15	4:30	15:27:45	0:40	0:10:27				Very Weak Minor
15:28:25	4:50	15:33:15	1:05	15:34:20	1:09	0:22:25			0:10:00	Very Weak Minor
15:35:29	1:55	15:37:24	1:21	15:38:45	1:38	0:07:04			0:04:09	Very Weak Minor
15:40:23	5:12	15:45:35	0:47	15:46:22	0:42	0:04:54			0:08:11	Very Weak Minor
15:47:04	7:46	15:54:50	1:05	15:55:55	3:25	0:06:41			0:09:15	Weak Minor
15:59:20	1:55	16:01:15	1:05	16:02:20	0:38	0:12:16			0:06:25	Very Weak Minor
16:02:58	3:52	16:06:50	3:54	16:10:44	4:31	0:03:38	1:07:35	1:07:35		Major
16:15:15	39:30	16:54:45	1:45	16:56:30	0:30	0:12:17				Very Weak Minor
16:57:00	2:30	16:59:30	1:32	17:01:02	5:16	0:41:45			0:04:45	Weak Minor
17:04:32	1:46	17:06:18	5:07	17:11:25	4:52	0:07:32	0:59:28	0:59:28		Major
17:16:17	24:58	17:41:15	0:46	17:42:01	1:39	0:11:45				Very Weak Minor
17:43:40	1:50	17:45:30	0:45	17:46:15	0:15	0:27:23			0:04:15	Very Weak Minor
17:46:30	1:10	17:47:40	1:20	17:49:00	1:15	0:02:50			0:02:10	Very Weak Minor
17:50:15	2:43	17:52:58	0:53	17:53:51	2:29	0:03:45			0:05:18	Very Weak Minor
17:56:20	4:24	18:00:44	4:01	18:04:45	4:43	0:06:05	0:54:26	0:54:26		Major

VETERAN GEYSER ERUPTION DATA - 1991-92

Normal Play		--- Eruption ---		---- Pause -----		--------------- Interval ----------------				Eruption Type
Start	Duration	Start	Duration	Start	Duration	Cycle	Major	Minor	Weak Minor	
Monday, 21/Sep/92										
8:30:00	2:20	8:32:20	6:05	8:38:25	4:50					Major
8:43:15	6:50	8:50:05	0:45	8:50:50	0:50	0:13:15				Very Weak Minor
8:51:40	8:00	8:59:40	1:10	9:00:50	0:43	0:08:25			0:09:35	Very Weak Minor
9:01:33	8:13	9:09:46	1:23	9:11:09	1:33	0:09:53			0:10:06	Very Weak Minor
9:12:42	11:01	9:23:43	0:37	9:24:20	0:20	0:11:09			0:13:57	Very Weak Minor
9:24:40	5:23	9:30:03	1:26	9:31:29	1:55	0:11:58			0:06:20	Very Weak Minor
9:33:24	6:41	9:40:05	3:30	9:43:35	1:42	0:08:44			0:10:02	Very Weak Minor
9:45:17	1:39	9:46:56	2:24	9:49:20	4:08	0:11:53		1:14:36		Minor
9:53:28	3:40	9:57:08	2:22	9:59:30	3:55	0:08:11			0:10:12	Very Weak Minor
10:03:25	3:12	10:06:37	5:31	10:12:08	6:58	0:09:57	1:34:17	0:19:41		Major
10:19:06	15:00	10:34:06	1:24	10:35:30	0:53	0:15:41				Very Weak Minor
10:36:23	8:53	10:45:16	1:44	10:47:00	1:10	0:17:17			0:11:10	Very Weak Minor
10:48:10	6:38	10:54:48	1:06	10:55:54	0:56	0:11:47			0:09:32	Very Weak Minor
10:56:50	20:10	11:17:00	0:47	11:17:47	0:31	0:08:40			0:22:12	Very Weak Minor
11:18:18	3:47	11:22:05	1:43	11:23:48	3:10	0:21:28		1:15:28		Minor
11:26:58	4:39	11:31:37	0:29	11:32:06	1:30	0:08:40			0:09:32	Very Weak Minor
11:33:36	1:46	11:35:22	6:16	11:41:38	5:35	0:06:38	1:28:45	0:13:17		Major
11:47:13	5:57	11:53:10	0:49	11:53:59	0:23	0:13:37				Very Weak Minor
11:54:22	3:38	11:58:00	1:15	11:59:15	1:15	0:07:09			0:04:50	Very Weak Minor
12:00:30	15:01	12:15:31	1:11	12:16:42	0:47	0:06:08			0:17:31	Very Weak Minor
12:17:29	2:20	12:19:49	0:45	12:20:34	0:42	0:16:59			0:04:18	Very Weak Minor
12:21:16	8:59	12:30:15	1:38	12:31:53	0:55	0:03:47			0:10:26	Very Weak Minor
12:32:48	2:02	12:34:50	1:10	12:36:00	0:30	0:11:32			0:04:35	Very Weak Minor
12:36:30	4:06	12:40:36	1:29	12:42:05	1:33	0:03:42			0:05:46	Very Weak Minor
12:43:38	3:06	12:46:44	1:15	12:47:59	2:27	0:07:08			0:06:08	Weak Minor
12:50:26	4:14	12:54:40	1:05	12:55:45	2:25	0:06:48			0:07:56	Weak Minor
12:58:10	2:55	13:01:05	0:50	13:01:55	2:22	0:07:44			0:06:25	Very Weak Minor
13:04:17	2:07	13:06:24	4:22	13:10:46	6:40	0:06:07		1:31:02		Minor
13:17:26	3:43	13:21:09	5:40	13:26:49	4:28	0:13:09	1:45:47	0:14:45		Major
13:31:17	11:22	13:42:39	1:21	13:44:00	1:00	0:13:51				Very Weak Minor
13:45:00	10:30	13:55:30	1:50	13:57:20	1:56	0:13:43			0:12:51	Very Weak Minor
13:59:16	15:10	14:14:26	2:08	14:16:34	2:34	0:14:16			0:18:56	Very Weak Minor
14:19:08	9:16	14:28:24	1:37	14:30:01	0:58	0:19:52			0:13:58	Very Weak Minor
14:30:59	1:18	14:32:17	2:33	14:34:50	1:16	0:11:51			0:03:53	Very Weak Minor
14:36:06	4:26	14:40:32	3:53	14:44:25	6:22	0:05:07		1:19:23		Minor
14:50:47	2:40	14:53:27	2:06	14:55:33	4:15	0:14:41		0:12:55		Minor
14:59:48	2:24	15:02:12	3:48	15:06:00	3:57	0:09:01	1:41:03	0:08:45		Major
15:09:57	3:33	15:13:30	2:55	15:16:25	2:05	0:10:09				Weak Minor
15:18:30	1:07	15:19:37	1:00	15:20:37	0:40	0:08:33			0:06:07	Very Weak Minor
15:21:17	13:38	15:34:55	1:10	15:36:05	0:00	0:02:47			0:15:18	Very Weak Minor
15:36:05	5:52	15:41:57	0:51	15:42:48	2:08	0:14:48			0:07:02	Very Weak Minor
15:44:56	1:49	15:46:45	1:40	15:48:25	3:21	0:08:51			0:04:48	Weak Minor
15:51:46	4:47	15:56:33	2:47	15:59:20	2:04	0:06:50			0:09:48	Very Weak Minor
16:01:24	2:56	16:04:20	5:20	16:09:40	7:33	0:09:38	1:02:08	1:02:08		Major
16:17:13	10:38	16:27:51	0:33	16:28:24	0:54	0:15:49				Very Weak Minor
16:29:18	4:42	16:34:00	1:20	16:35:20	3:20	0:12:05			0:06:09	Very Weak Minor

VETERAN GEYSER ERUPTION DATA - 1991-92

Normal Play		--- Eruption ---		---- Pause -----		---------------- Interval ----------------				Eruption Type
Start	Duration	Start	Duration	Start	Duration	Cycle	Major	Minor	Weak Minor	
Monday, 21/Sep/92 (cont.)										
16:38:40	6:18	16:44:58	1:12	16:46:10	1:29	0:09:22			0:10:58	Very Weak Minor
16:47:39	0:31	16:48:10	1:32	16:49:42	2:18	0:08:59			0:03:12	Very Weak Minor
16:52:00	8:58	17:00:58	1:23	17:02:21	1:24	0:04:21			0:12:48	Very Weak Minor
17:03:45	20:55	17:24:40	3:58	17:28:38	2:23	0:11:45			0:23:42	Very Weak Minor
17:31:01	2:08	17:33:09	1:39	17:34:48	2:18	0:27:16			0:08:29	Very Weak Minor
17:37:06	1:47	17:38:53	6:04	17:44:57	6:23	0:06:05	1:34:33	1:34:33		Major
17:51:20	5:23	17:56:43	1:26	17:58:09	0:48	0:14:14				Very Weak Minor
17:58:57	2:35	18:01:32	3:01	18:04:33	0:21	0:07:37			0:04:49	Very Weak Minor
18:04:54	4:53	18:09:47	1:57	18:11:44	1:27	0:05:57			0:08:15	Very Weak Minor
18:13:11	2:04	18:15:15	1:27	18:16:42	1:30	0:08:17			0:05:28	Very Weak Minor
18:18:12	6:57	18:25:09	1:12	18:26:21	2:08	0:05:01			0:09:54	Very Weak Minor
18:28:29	3:20	18:31:49	3:04	18:34:53	0:50	0:10:17			0:06:40	Very Weak Minor
18:35:43	5:27	18:41:10	0:45	18:41:55	0:40	0:07:14			0:09:21	Very Weak Minor
18:42:35	6:16	18:48:51	2:27	18:51:18	3:50	0:06:52			0:07:41	Weak Minor
18:55:08	1:11	18:56:19	1:10	18:57:29	0:00	0:12:33			0:07:28	Very Weak Minor
18:57:29	2:21	18:59:50	3:03	19:02:53	?:??	0:02:21		1:20:57		Minor

VETERAN GEYSER ERUPTION DATA - 1991-92

Normal Play		--- Eruption ---		---- Pause -----		--------------- Interval ---------------				Eruption Type
Start	Duration	Start	Duration	Start	Duration	Cycle	Major	Minor	Weak Minor	
Tuesday, 22/Sep/92										
7:47:00	2:20	7:49:20	3:06	7:52:26	4:37					Minor
7:57:03	2:04	7:59:07	1:00	8:00:07	0:46	0:10:03			0:09:47	Very Weak Minor
8:00:53	1:05	8:01:58	2:00	8:03:58	3:03	0:03:50			0:02:51	Weak Minor
8:07:01	2:17	8:09:18	4:28	8:13:46	4:36	0:06:08		0:19:58		Major
8:18:22	2:33	8:20:55	0:37	8:21:32	1:34	0:11:21				Weak Minor
8:23:06	0:37	8:23:43	1:27	8:25:10	1:58	0:04:44			0:02:48	Very Weak Minor
8:27:08	8:38	8:35:46	1:19	8:37:05	1:49	0:04:02			0:12:03	Very Weak Minor
8:38:54	7:51	8:46:45	1:01	8:47:46	0:29	0:11:46			0:10:59	Very Weak Minor
8:48:15	5:08	8:53:23	0:58	8:54:21	0:57	0:09:21			0:06:38	Very Weak Minor
8:55:18	8:36	9:03:54	2:15	9:06:09	3:49	0:07:03			0:10:31	Weak Minor
9:09:58	7:36	9:17:34	6:25	9:23:59	7:10	0:14:40	1:08:16	1:08:16		Major
9:31:09	6:01	9:37:10	0:26	9:37:36	0:37	0:21:11				Very Weak Minor
9:38:13	17:34	9:55:47	3:16	9:59:03	1:18	0:07:04			0:18:37	Very Weak Minor
10:00:21	4:57	10:05:18	1:27	10:06:45	0:35	0:22:08			0:09:31	Very Weak Minor
10:07:20	10:05	10:17:25	1:53	10:19:18	1:06	0:06:59			0:12:07	Very Weak Minor
10:20:24	5:55	10:26:19	2:47	10:29:06	0:55	0:13:04			0:08:54	Very Weak Minor
10:30:01	3:34	10:33:35	1:16	10:34:51	1:59	0:09:37			0:07:16	Very Weak Minor
10:36:50	10:55	10:47:45	0:29	10:48:14	1:46	0:06:49			0:14:10	Very Weak Minor
10:50:00	4:59	10:54:59	4:40	10:59:39	5:10	0:13:10	1:37:25	1:37:25		Major
11:04:49	29:51	11:34:40	10:48	11:45:28	2:24	0:14:49				Weak Minor
--- break ---										
11:47:52	2:34	11:50:26	0:39	11:51:05	2:45				0:15:46	Very Weak Minor
11:53:50	2:30	11:56:20	2:03	11:58:23	2:56	0:05:58			0:05:54	Weak Minor
12:01:19	5:25	12:06:44	5:54	12:12:38	5:53	0:07:29	1:11:45	1:11:45		Major
12:18:31	6:43	12:25:14	1:01	12:26:15	0:33	0:17:12				Very Weak Minor
12:26:48	16:19	12:43:07	0:43	12:43:50	0:32	0:08:17			0:17:53	Very Weak Minor
12:44:22	5:08	12:49:30	1:04	12:50:34	2:05	0:17:34			0:06:23	Very Weak Minor
12:52:39	6:17	12:58:56	1:17	13:00:13	1:32	0:08:17			0:09:26	Very Weak Minor
13:01:45	2:13	13:03:58	1:51	13:05:49	0:55	0:09:06			0:05:02	Very Weak Minor
13:06:44	1:58	13:08:42	1:23	13:10:05	2:24	0:04:59			0:04:44	Weak Minor
13:12:29	1:49	13:14:18	1:22	13:15:40	0:59	0:05:45			0:05:36	Very Weak Minor
13:16:39	5:19	13:21:58	2:47	13:24:45	4:56	0:04:10		1:15:14		Minor
13:29:41	3:54	13:33:35	1:43	13:35:18	2:54	0:13:02			0:11:37	Weak Minor
13:38:12	2:27	13:40:39	3:19	13:43:58	6:54	0:08:31		0:18:41		Minor
13:50:52	4:03	13:54:55	5:58	14:00:53	6:23	0:12:40	1:48:11	0:14:16		Major
14:07:16	6:18	14:13:34	1:01	14:14:35	0:24	0:16:24				Very Weak Minor
14:14:59	2:56	14:17:55	1:16	14:19:11	1:02	0:07:43			0:04:21	Very Weak Minor
14:20:13	0:35	14:20:48	3:40	14:24:28	1:14	0:05:14			0:02:53	Very Weak Minor
14:25:42	2:01	14:27:43	0:52	14:28:35	1:37	0:05:29			0:06:55	Very Weak Minor
14:30:12	1:23	14:31:35	1:27	14:33:02	2:13	0:04:30			0:03:52	Weak Minor
14:35:15	5:35	14:40:50	1:30	14:42:20	0:34	0:05:03			0:09:15	Very Weak Minor
14:42:54	1:34	14:44:28	2:56	14:47:24	1:59	0:07:39			0:03:38	Very Weak Minor
14:49:23	1:34	14:50:57	1:08	14:52:05	2:09	0:06:29			0:06:29	Very Weak Minor
14:54:14	1:13	14:55:27	2:23	14:57:50	3:58	0:04:51			0:04:30	Weak Minor
15:01:48	2:56	15:04:44	5:01	15:09:45	6:25	0:07:34		1:09:49		Minor
15:16:10	5:50	15:22:00	5:14	15:27:14	6:01	0:14:22			0:17:16	Weak Minor

VETERAN GEYSER ERUPTION DATA - 1991-92

Normal Play		--- Eruption ---		---- Pause -----		--------------- Interval ---------------				Eruption
Start	Duration	Start	Duration	Start	Duration	Cycle	Major	Minor	Weak Minor	Type
Tuesday, 22/Sep/92 (cont.)										
15:33:15	4:15	15:37:30	4:33	15:42:03	6:14	0:17:05	1:42:35	0:32:46		Major
15:48:17	4:43	15:53:00	1:05	15:54:05	2:37	0:15:02				Very Weak Minor
15:56:42	0:56	15:57:38	1:55	15:59:33	0:48	0:08:25			0:04:38	Very Weak Minor
16:00:21	2:05	16:02:26	1:14	16:03:40	1:20	0:03:39			0:04:48	Very Weak Minor
16:05:00	1:47	16:06:47	1:13	16:08:00	0:56	0:04:39			0:04:21	Very Weak Minor
16:08:56	1:29	16:10:25	1:17	16:11:42	0:21	0:03:56			0:03:38	Very Weak Minor
16:12:03	4:53	16:16:56	1:29	16:18:25	4:34	0:03:07			0:06:31	Weak Minor
16:22:59	2:17	16:25:16	7:21	16:32:37	5:01	0:10:56		0:47:46		Minor
16:37:38	4:45	16:42:23	3:27	16:45:50	0:23	0:14:39			0:17:07	Very Weak Minor
16:46:13	1:06	16:47:19	3:03	16:50:22	5:10	0:08:35		0:22:03		Minor
16:55:32	5:27	17:00:59	1:31	17:02:30	0:59	0:09:19			0:13:40	Very Weak Minor
17:03:29	0:32	17:04:01	5:51	17:09:52	6:08	0:07:57	1:26:31	0:16:42		Major
17:16:00	6:57	17:22:57	0:24	17:23:21	2:03	0:12:31				Very Weak Minor
17:25:24	1:46	17:27:10	1:30	17:28:40	1:39	0:09:24			0:04:13	Very Weak Minor
17:30:19	2:04	17:32:23	2:06	17:34:29	2:55	0:04:55			0:05:13	Weak Minor
17:37:24	2:33	17:39:57	0:43	17:40:40	3:18	0:07:05			0:07:34	Very Weak Minor
17:43:58	6:38	17:50:36	0:54	17:51:30	2:39	0:06:34			0:10:39	Very Weak Minor
17:54:09	2:44	17:56:53	1:01	17:57:54	2:56	0:10:11			0:06:17	Very Weak Minor
18:00:50	1:29	18:02:19	2:58	18:05:17	4:31	0:06:41		0:58:18		Minor
18:09:48	4:02	18:13:50	1:50	18:15:40	3:38	0:08:58			0:11:31	Weak Minor
18:19:18	2:47	18:22:05	1:06	18:23:11	0:55	0:09:30			0:08:15	Very Weak Minor
18:24:06	2:46	18:26:52	4:12	18:31:04	4:26	0:04:48	1:22:51	0:24:33		Major

The Geysers of Iceland
A Summary from November 1993

by Mike Keller

Abstract
Without any pretense of descriptions or interpretations on the basis of only brief observations, active geysers were seen in each of eight Icelandic thermal areas during November 1993. This table presents these basic findings.

Area Name	Geyser Name	Interval	Duration	Height (feet)
Haukadalur	Strokkur	5-18 min	seconds	20-55
	Smithur	active	long	3-4
	Opherrishola	15-40 min	1-6 min	6-15
Mithdalur	Laugarvatn	8-10 min	30-45 sec	3-12
Torfastathir	Reykholtshver	9-11 min	4-6 min	1-2
Hruni	North Basahver	seconds	seconds	1-4 (fine spray)
	unnamed	1-2 min	10-20 sec	inches
Reykir in Ölfus	Gosi II (artificial)	hours	hours	2-5
	Bogi I (artificial)	30 min	2-6 min	25
	Bogi II (artificial)	30 min	2-6 min	15-25
	Svarthi	6-9 hrs	15 min	8
	Bathstafuhver	60-80 min	3 min	15
	unnamed	seconds	seconds	3
Borgarfhartharsysla	Arhver	hours	hours	2
	Sturlureykir	hrs to days	hours to days	8
	Dynk (spouter)	constant	constant	4-6
	unnamed	1-4 min	seconds	2
	unnamed	12-16 min	3-6 min	4
	unnamed (spouter)	constant	constant	1
Reykjahverfi	Uxahver	seconds	seconds	3-7
Unnamed area near Vik	unnamed	minutes	seconds	3

Totalnumber of obsedrved natural geysers = 16.

Geyser Activity at Nakama Springs, Savusavu, Vanua Levu, Fiji

Historic and Modern Observations of Geyser Activity

T. Scott Bryan
all photos by the author

Abstract

The historic nature of geyser activity among the Nakama Springs at Savusavu, Fiji has been revealed by a review of published literature and several personal communications. In summary, intermittent boiling and small-scale geyser action have been observed on numerous occasions over the past 150+ years, but geysers of large size were seen only during one brief episode during 1878.

Introduction

The region at and near the town of Savusavu, on Vanua Levu in the Fiji Islands, comprises one of the smaller and least known geyser fields in the world. The location is shown on Figure 1. The Nakama Springs ("Burning Water"), immediately adjacent to the town, are the largest and most active of the spring groups. Others of boiling temperatures and possible historic geyser activity are located as far as several kilometers from the town. Eruptions of uncertain nature, but possibly due to submerged geysers, have also been noted beneath the water of Savusavu Bay.

As a part of the research preliminary to a planned 1993 excursion to Savusavu, I made contact with Mr. Peter Rodda, a member of the Mineral Resources Department of Fiji who has done extensive geothermal work at Savusavu, and Mr. Hector MacDonald, the General Manager of the Mantani Kavika (Kontiki) Resort. Both provided personal accounts of hot spring activity, and Mr. Rodda additionally sent photocopies of several old published works of limited availabil-ity. A summary of the observations conducted through the years is provided below, followed by my personal observations of June 1993.

Historic Records of Hot Spring and Geyser Activity at Nakama Springs

1840

Wilkes [1845] wrote the first known description of the Nakama Springs. In 1840, there were five springs, each occupying craters 18 to 24 inches across and having water temperatures of about 210°F. He wrote, "...eruptions were induced by the natives for the purpose of boiling food: taro or yams were placed into the springs which were not boiling; then they were covered with leaves and grass... It [sic?] boils up to a height of eight or ten inches." One of the springs was not used for cooking, being kept sacred to the spirit which inhabited the area. Wilkes did not mention any degree of intermittent activity other than the cooking–induced boiling.

1863

Cumming [1881] noted that Chief Tui of Wainunu attempted to plug and cover the springs, which were cited as 15 in number. The

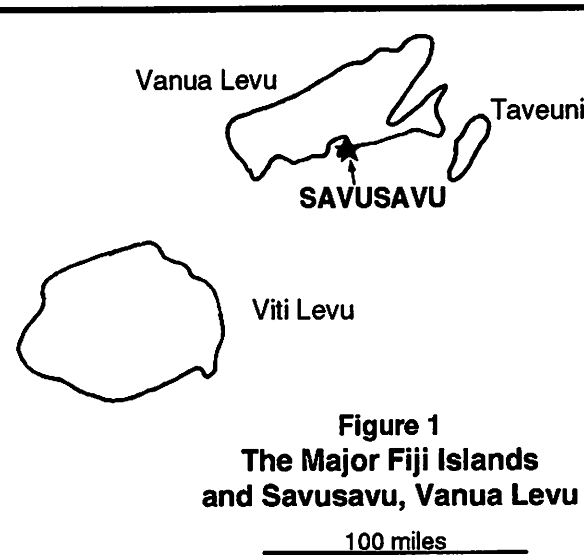

Figure 1
The Major Fiji Islands and Savusavu, Vanua Levu

reason for this provides an interesting historical story, especially when one recalls that the Fijians were notorious as ceremonial cannibals until well into the 19th Century. The springs were owned by an old woman warrior who was captured by the Chief. "She was past seventy, and must have been very tough and smoke–dried, but as in her younger days she had been a regular Joan of Arc, leading her tribe to battle, and herself fighting hand to hand with a hatchet... So he had her cooked with the sixteen men, and made a great feast, and then to spite the people, before leaving the district, he attempted to choke up all the springs, in which amiable effort he partially succeeded."

1876

In May, according to Kleinschmidt [1879], there were four springs. The largest measured 3 by 4 feet and spouted continuously; when not retarded by stones, leaves and grass, the play reached "about the height of a man." The other springs were smaller in size but were intermittent, boiling up to 1 foot high with durations of around 20 minutes. The intervals were not stated but were said to be longer in dry weather.

1876

In August, Cumming [1881] noted only three springs, but recorded intermittent activity in each, the highest of the springs "making a fountain 2 to 3 feet high."

1878 (date unknown, probably early)

Horne [1881] described "three or four springs", all boiling up to 1 foot high. Nothing was said about intermittency.

1878 (date unknown but after the above)

Mr. A. H. Barrack (then owner of the springs) along with other long-time residents stated that for a time span of "1 to 2 months" the springs were active as geysers, withintervals of 10 to 20 minutes; durations of 10 to 20 minutes; and heights, "at an angle of 40 to 60 feet." Then the springs "gradually resumed their normal level." [Guppy, 1903] The number of springs involved in this action was not stated.

1884

In his "The World's Geyser Regions," Peale [1884] referred to the Savusavu springs as "*pseudo* geysers." Somewhat earlier in that paper he wrote: "Almost all the constantly boiling springs have periods of increased activity, and those which spout only a few feet into the air have been classed as *pseudo* geysers" [italics his]. The nature of this statement implies that Peale's information about the Nakama Springs was of either variable perpetual spouting and/or geysers smaller than some unspecified size limit.

1898

Guppy visited the springs himself and found them "boiling briskly" to a height of several inches *without* periodicity. The "principle springs were 5 or 6 in number."

1921

In September, two springs were "boiling briskly to a height of one foot," with temperatures of 100°C. A third spring had a water temperature of only 79°C. [Wright, 1922] There was no observed periodicity to the boiling.

1955

In December, 1955, some (two?) of the springs were intermittent and boiling vigorously, Spring No. 3 (see Figure 2 for the location of this and all following spring numbers) playing to a height of 18 inches. The total period was about 2 hours with durations of "slightly less than 15 minutes." As No. 3 erupted, the water level in nearby Spring No. 1 gradually dropped until water from the adjacent stream was able to flow into its crater; the eruption in No. 3 ceased a short while later. A few months earlier, when visited by Harvey alone, the total eruptive period was only 15 minutes. [Banwell and Harvey, 1956]

1956

Between 30 April and 2 May, Healy [1960] noted intermittent action in Springs No. 3 and No. 4, as had been noted by earlier authors, as well as in Spring Nos. 5, 7, and 9, which had not been previously noted as periodic. He declined to refer to any of the springs as geysers. The activity of all was in concert, indicating a relatively close subsurface connection. The total period of the activity was in excess of $1\frac{3}{4}$ hours. The action consisted of a vigorous boiling to a height of about 6 inches.

In a 1978 personal communication, Healy stated: "Your enquiry... aroused some discussion in this office [New Zealand Geological Survey, Rotorua, New Zealand]. Using the definition by Allen and Day, I would say that No. 3 spring is a geyser which behaves as an intermittent spring. In a case like that, one can only describe the action and suggest a name, which I seem to have avoided doing. Maybe I would have called it a small intermittent geyser."

1956

During a return visit in September, Banwell and Harvey [1956] found the springs active about as they had been for Healy earlier in the year, except the total period was now only around 30 minutes. There was discharge from spring vent complex No. 5.

1957

Between 7 and 10 April, Bartholomew [1957] found that the discharge and boiling was intermittent in Springs No. 3 and 4 (the same as Nos. 3 and 1 respectively of Healy [1960], and this report). The recorded periods were of 50, 58 and 61 minutes. Bartholomew also noted that after a full day of continuous rain there was no periodicity; after two dry days, the periods averaged 47 minutes, and after four dry days the period had increased to an average of 62 minutes. (This reflects Kleinschmidt's [1879] statment of longer intervals during dry weather.) These periods were roughly one half occupied by vigorous boiling as the crater of No. 3 filled. The durations, given as 10 minutes, consisted of violent boiling with discharge from both No. 3 and 4. In company with the geysers, No. 5 (the same as my numbers 9–11) boiled but did not discharge, and No. 1 drained during the eruption as it had during 1955.

1958

On an unstated date, about 3 kilometers north–northeast of the town of Savusavu, three or four "water spouts up to 30 meters high occurred for a period of several hours." [Cox, 1980] Some felt that this might have been an 'atmospheric phenomenon', but the event is quite similar to another which definitely was geothermal in 1961 (below).

1961 and since

During each visit in 1961, 1965, and 1966, Rodda found only steady boiling and discharge with no indications of periodicity. [Rodda, 1992]

1961

Both Cox [1980] and Rodda [1992] state that at Easter time, several springs, two or three at a time, were active as large geysers at a shallow water spot in Savusavu Bay, eight kilometers due west of the town. They were vigorous enough to play through the sea water and produce water spouts 15 meters high. The active episode lasted about three days, during which the periods of the features averaged 2h 15m with durations of 10 to 15 minutes. In 1963, a hydrographic survey of the bay was unable to find any temperature anomaly in the area!

1975

It is probably significant that Rodda paid visits to Savusavu during the 1960s and 1980s (above, and below under 1992), but evidently not at all during the 1970s. He claimed to have never observed intermittent action at Savusavu, yet Cox [1980] did see periodic springs in 1975 and 1976.

The action was described as follows (note that the numbers of Cox do not correspond to those of earlier researchers): Spring No. 2

bubbled up to 10 centimeters with "occasional slight eruptions"; Spring No. 4 discharged only at the time of "intermittent, more vigorous bubbling"; Spring No. 5 discharged continuously but "occasionally rises to a height of 20 centimeters." Springs No. 1, 3, and 6 all erupted 10 to 15 centimeters high but apparently as perpetual spouters.

The site of Spring No. 8 was a gravel area which intermittently hissed with steam, and a bubbling sound could be heard at depth. A small pit was dug at the site and "three vents in the bottom of the pit discharged water which began to boil vigorously to a height of 10 centimeters... The water level in pit No. 8 was seen to rise with the incoming tide."

Note that Cox did not provide interval or duration time data for any feature.

Cox also observed perpetual(?) bubbling and boiling in Springs No. 3 and 4 among the Nakama Creek Springs, about 100 meters from the Nakama Springs proper, and minor bubbling in several small pools at the Savusavu Beach Springs on the shore of the bay adjacent to town.

1992

MacDonald [1992] wrote in a personal communication that "we have a second geyser in the sea, which I can show you during your visit." Peter Rodda followed by stating that "this is probably another constantly boiling spring" as he is not aware of any true geyser activity in the Savusavu area since the 1961 episode (a statement contradicted by Cox's studies of the 1970s). In fact, this feature turned out to be a warm spring (definitely not a geyser) at Nacekoro, also known as Reva, on the south shore of the Sasvusavu Peninsula.

Observations of June 15, 1993

The Nakama Springs are a classic example of the indistinct difference between small geyser versus boiling or perpetually spouting spring. This matter of definition is more fully discussed in the concluding section of this paper, and it is noted that neither Healy

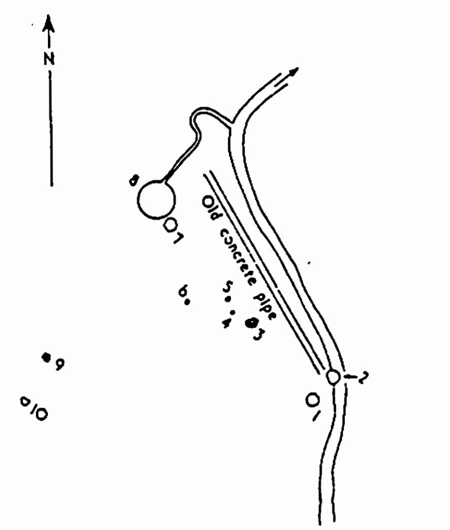

Figure 2a
Map of Healy [1960]

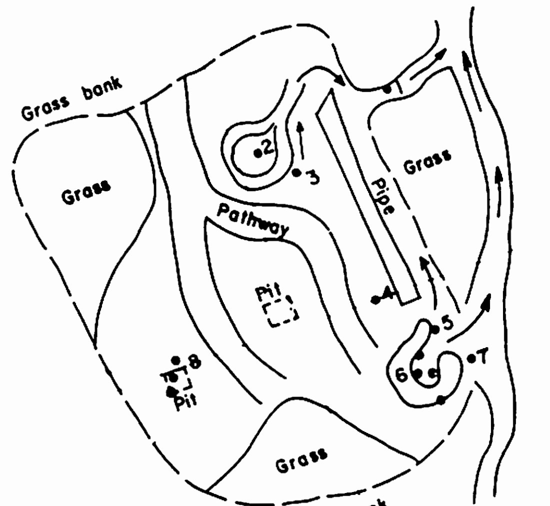

Figure 2b
Map of Cox [1980]

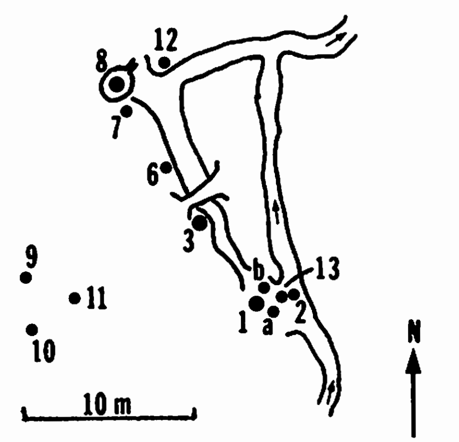

Figure 2c
Map of Bryan [1993, this study]

[1960] nor Cox [1980] referred to any of these springs as geysers. It was only later, when pressed for a clarification, that Healy [1978] called his spring No. 3 a "small intermittent geyser," and it is my interpretation of other written descriptions that leads to the identification of several Nakama Spring features as geysers during years past.

Those observations and interpretations plus mine inthis study are summarized by Table I. (Note that different authors have utilized different numbering schemes. I have chosen to follow that of Healy [1960], as his work is the earliest that I am aware of to have identified and described all existing springs.)

A number of changes among both the Nakama Springs themselves and their surroundings have taken place since 1956 and/or 1975. Figure 2 presents the original maps of Healy [1960] for 1956, Cox [1980] for 1975, and Bryan [1993] for this study. The originals have been resized from their published scales, and then rotated so that all have "north up" orientations. The major differences seen are:

• No trace of the concrete pipe shown by both Healy and Cox can be seen. Instead, its approximate route is now followed by a substantial trench bisected by a 'bridge" of gravel.

• The pathway shown by Cox, and visible in a photograph in that work as a constructed walkway, no longer exists in any form.

• The spring complex that I have labeled as Nos. 1, 1a, 1b, and 13, which are now distinct as four clearly separate features, were indicated as a single feature by both Healy and Cox. In fact, Healy described his No. 1 as a pool, 3 by 2 feet in dimensions. Cox noted three openings for this one feature, and described it as surrounded by a circular stone and concrete wall of which there is now no trace. Also, per Banwell and Harvey [1956], this spring was at or below the level of the stream; it is now elevated at least one foot above the stream. My interpretation of these charges is that the original crater was filled in with rocks, probably to improve the springs' use as a cooking facility.

• Healy's Nos. 4 and 5, and perhaps also No. 6, disappeared between 1956 and 1975. The sites of all three might be beneath the gravel "bridge" across the trench and, if so, my No. 6 is a new feature.

The activity observed during a 1h 45m visit to Nakama Springs on June 15, 1993 was:

No. 1 — Perpetual Spouter

The vent of this spring is filled with gravel and it was only at times of maximum vigor that there was any pool of standing water. At other times No. 1 consisted of vigorous boiling and jetting from among the rocks, reaching as high as 1 meter on one brief occasion. Although there were substantial variations in the strength of the boiling, that this activity is truly perpetual is supported by a native who used No. 1 to cook cassava while I was there, stating that he used it rather than another spring (No. 8) because it is constant.

Note that this spring plus Springs No. 1a and No. 1b of this paper were identified as a single feature by all previous authors (it was No. 4 of Banwell and Harvey [1956] and Bartholomew [1957], No. 1 of Healy [1960], and No. 6 of Cox [1980]), at which times it was a pool lying at or below the level of the stream. Banwell and Harvey first and then Healy described a relationship between this spring and spring No. 3: the activity and water level of No. 1 would decrease as the eruption increased at No. 3. Eventually stream water was able to flow into No. 1, and the eruption in No. 3 then quit only moments later. During the intervening years, the crater of the old spring No. 1 has been filled with rocks so that the three now-separate vents lie well above the level of the stream. The effect on No. 3's is unknown.

No. 1a — Geyser

This was active as a true geyser. Intervals ranged from as little as 10 seconds to as long as a full minute, during which no water was visible among the rocks occupying the crater. Eruptions began abruptly, superheated water boiling between the rocks and reaching full height within a few seconds of the onset of the play, which lasted roughly 30 seconds. The maximum height was 70 centimeters.

No. 1b — Geyser

This spring, at a slightly higher elevation than No. 1 or No. 1a, had a crater filled with smaller stones but was otherwise similar in appearance to geyser No. 1a. Its intervals ranged from 5 to 30 seconds, and durations from 10 to 60 seconds. The height was rather constant at 30 centimeters.

No. 2 — Spring

This feature acted as a perpetual spouter for Healy [1960] and was a site of considerable discharge for Cox [1980]. In 1993, No. 2 was visible as a small hole in the stream bed from which water was discharged strongly enough to produce a spot of steamy upwelling through the stream water. This activity did not visibly vary in strength.

No. 3 — Geyser

Spring No. 3 has behaved as a geyser for every observer but Rodda since at least 1955. The activity is cyclic. Banwell and Harvey [1956] witnessed complete periods of activity to range from 15 minutes to 2 hours; Healy [1960] found a complete cycle to be longer than 1¾ hours. I was at Nakama Springs for just 1¾ hours. During that time, the water level in No. 3 gradually rose to overflow. As it did so, the degree of bubbling in the small (12-15 cm diameter) pool increased until some splashes a few centimeters high took place. For the last half hour of observations, No. 3 behaved as a "small intermittent geyser"— I can readily see why Healy [1978] used that term, and why Cox [1980] stated that this discharged only at "the time of intermittent, more vigorous bubbling." Leading from No. 3 was a considerable runoff channel (which would flow water into No. 1) lined with greenish algae. These observations imply that spring No. 3 was undergoing a long-term cyclic behavior and that a more substantial eruption might have been seen with a longer observation.

No. 4, No. 5, ?No. 6 — Nonexistent

No trace of the earlier Spring No. 4 or No. 5 could be found. Their site might lie beneath the gravel "bridge" across the trench just north of No. 3.

No. 6 — Intermittent spring

The No. 6 of this study is probably different from that of Healy, especially given that Cox showed no feature in this area. Dry on arrival, this spring was bubbling and discharging a trickle of water by the time of my departure. Its appearance made it clear that greater activity never took place.

No. 7 — Perpetual spouter

Although there were slight variations in the force of the boiling,during my visit this spring was the most constant of the Nakama Springs in its action. The height of the spouting was about 10 centimeters.

No. 8 — Variable perpetual spouter; possible geyser

Surrounded by a circular concrete wall and drained by a concrete discharge channel, this spring behaved as a widely variable perpetual spouter at a water level below overflow throughout my visit. Also, the dirt area beyond the concrete channel showed no sign of recent water runoff. However, the Fijian who described No. 1 as constant declined to use No. 8 for cooking because "it changes too much." Cox [1975] noted "occasional slight eruptions" here. Play observed during my visit ranged from near zero to as much as 50 centimeters high.

No. 9 — Intermittent spring

This spring was only a steamy muddy depression during my observations. That this occasionally filled with water (probably when nearby No. 10 had eruptions) was both implied by algae and statements by two Fijians on different occasions.

No. 10 — Geyser

This spring was probably spring No. 10 of Healy, and might be the "No. 8 pit" of Cox. Like No. 9, it was dry but hissing steam throughout my visit. Unlike No. 9, however, there is a runoff channel. The Fijian native who described the activity of No. 1 and No. 8 stated that this was active as a geyser, playing perhaps 30 centimeters high about one time per day.

No. 11 — Subterranean bubbler

In an observation apparently identical to that of Cox for his No. 8, a loud bubbling could be heard beneath the gravel fill of a shallow depression. Intervals were typically 5 to 10 seconds long and the duration only a second or two. The nature of the sound implied that the water level was only a few centimeters below ground level.

No. 12 — Seep

A small perpetual spouter for Cox, no feature was identified at this site by Healy and for me it was little more than a seep with discharge sufficient to saturate a patch of ground with warm water.

No. 13 — Geyser

I almost missed seeing this geyser, which was not identified by Healy and might be No. 5 of Cox. However, it was actually the most vigorous true geyser at Nakama Springs, made smaller by a large boulder atop its vent. The quiet intervals of 30 seconds to more than 10 minutes were punctuated by frequent brief overflows. The eruptions, which lasted only a few seconds each, jetted water nearly horizontally from under the boulder outward as far as 60 centimeters into the stream; my judgement was that, had the boulder not been in place, the play would have been true bursting (rather than boiling) to more than 1 meter high.

Discussion and the Future of the Nakama Springs

Given the large geyser eruptions that were described for 1878 and the intermittent action seen during the 1950s, 1970s, and in 1993, the Nakama Springs fully merit their identification as a geyser field.

The classic definition of "geyser" reads: "A geyser is a natural hot spring characterized by intermittent discharge of water ejected turbulently and accompanied by a vapor phase."

Many aspects of this definition are ambiguous. As it stands, for No. 1a, No. 1b, and No. 3 as described here to be called true geysers rather than similar erupting springs (such as variable perpetual spouters) might be questionable to some. However, No. 10 and No. 13 undergo long totally non–eruptive quiet intervals, and in my opinion cannot be described as other than true geysers.

Therefore, although these geysers are of very small size compared to those of the world's better known geyser fields such as Yellowstone and New Zealand, the fact that the Nakama Springs do include true geysers makes the locality rare indeed. A liberal educated guess places geysers at no more than 45 places on Earth. The Nakama Springs deserve better treatment than they have received.

Studies conducted by the Department of Natural Resources of the Fiji government have indicated that the Nakama Springs and vicinity hold enough potential energy for a geothermal powerplant sufficient to satisfy the electrical needs of all of the greater Savusavu region, and perhaps for all of Vanua Levu island. However, such a use would thoroughly destroy the Nakama Springs.

During my visit to Savusavu, several people expressed interest in the preservation and interpretation of the Nakama Springs. One proposal is to utilize the natural discharge (which totals about 10 liters per minute) for a small public bathing facility. That would require some construction in the area, but could also clear and clean the area of trash and numerous old works of construction. The springs would still exist, and could still be used for cooking. The hot runoff would be captured for bathing use rather than simply flowing to the nearby sea, and the springs themselves could be made more attractive and interpreted for the rare variety of thermal features among them. I would encourage a use such as this.

Acknowldegements

I thank Mr. Peter Rodda of the Department of Natural Resources for providing me with numerous references and personal recollections on the historical activity at the Nakama Springs; Mr. Hector MacDonald, General Manager of the Konitki Resort, for driving me to Nacekoro and Nakama; Mr. Tony Hoskins, primary shareholder of the Kontiki Resort, for discussing thoughts and plans about the future of the Nakama Springs; and perhaps above all the several Fijian natives who took the time to hold brief but open discussions about the spring activity.

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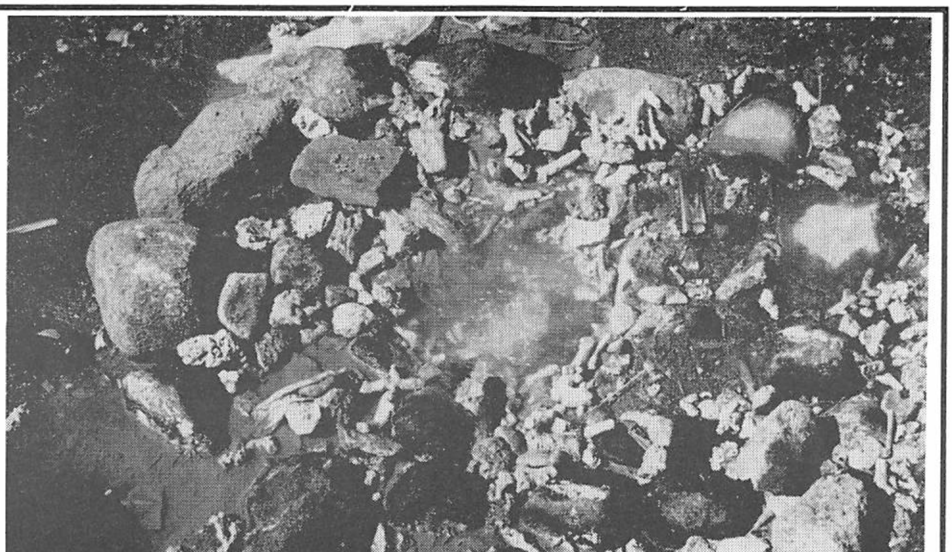
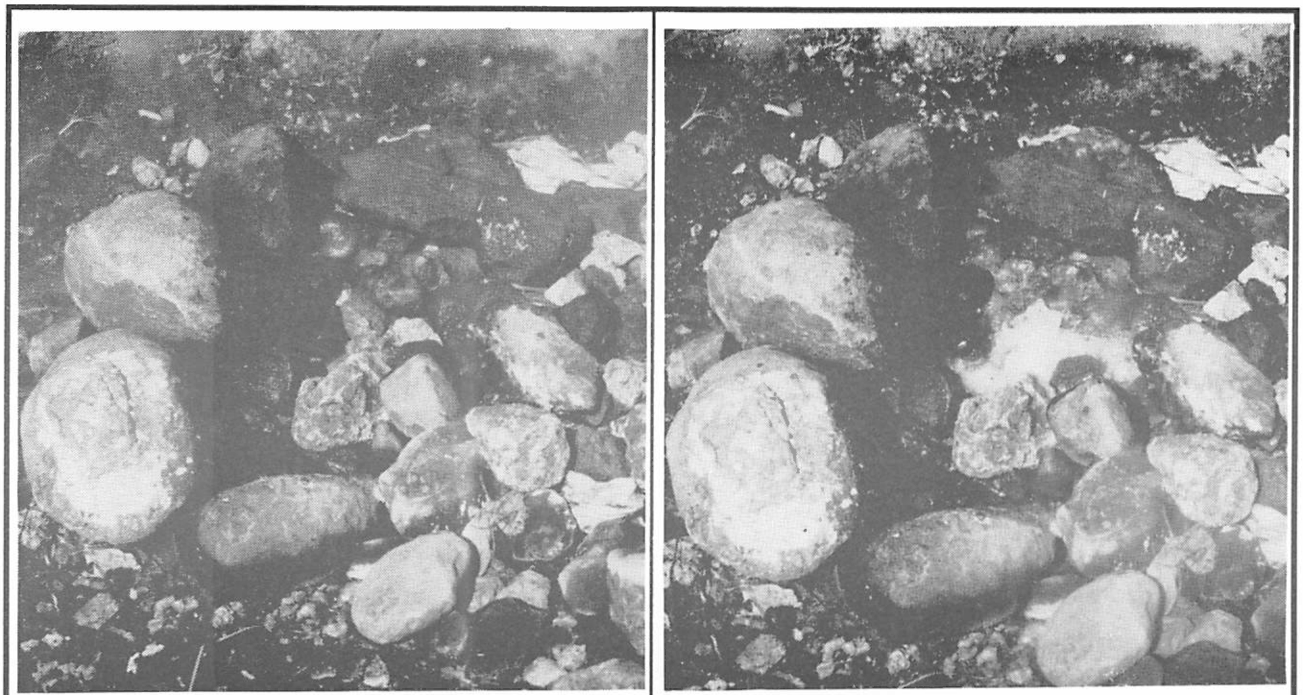


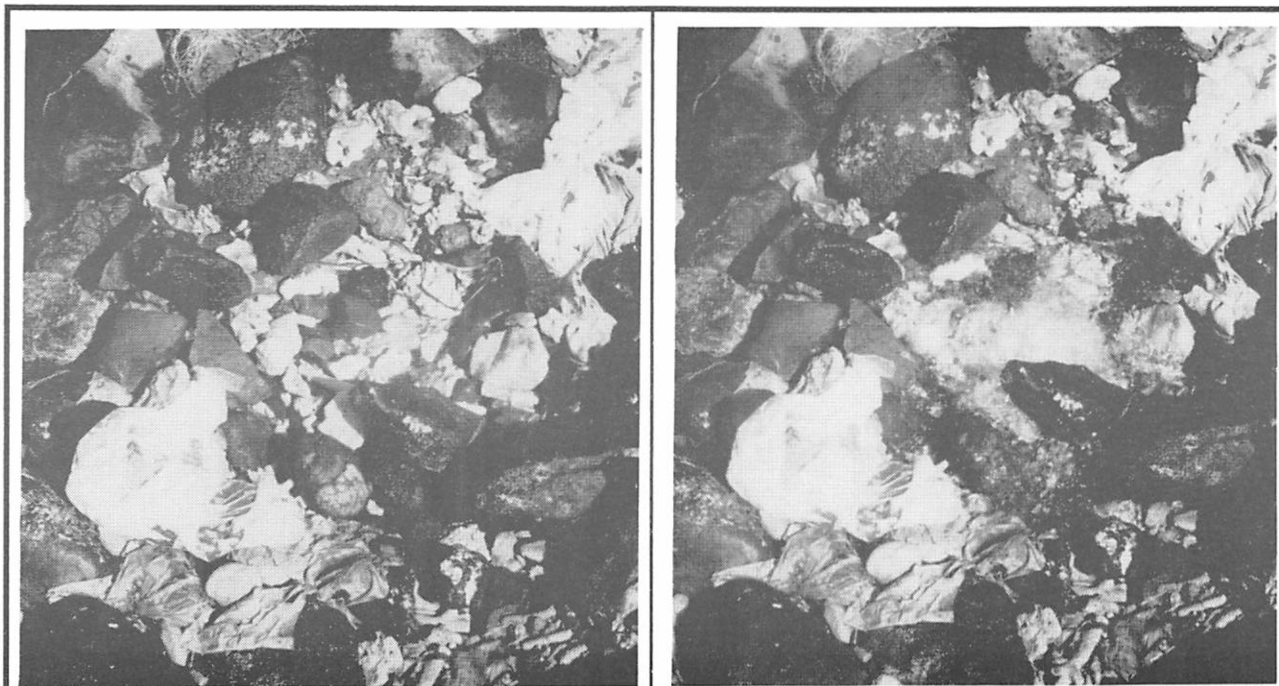
Spring No. 3. During part of my observations, this spring acted as a geyser a few centimeters high. As shown here, the water level was still about 3 centimeters below overflow; runoff would drain to the lower left.

An overview of the **Nakama Springs** at Savusavu, Fiji. Spring No. 8 lies within the concrete ring in the foreground; Spring No. 1 complex shows as slight steam near the upper right of the photo. This distance of less than 60 feet between them is the maximum dimension of the hot spring area.

Spring No. 1 complex. No. 1 is in eruption toward the upper right. No. 1a is partially surrounded by large rocks at the upper left while No. 1b is near the lower right.



Spring No. 1a. These comparitive photos taken from the same position show No. 1a not in eruption (left) and in eruption (right). The round boulder to the lower left is approximately 30 centimeters in diameter. Note the position in the photograph at the top of the previous page.



Spring No. 1b. These comparitive photos taken from the same position show No. 1b not in eruption (left) and in eruption (right). A plastic bag at the lower left can also be seen in the photograph at the top of the previous page.

Table I

Hot Spring Activity at Nakama Springs, Savusavu, Vanua Levu, Fiji

Spring Identity and Year of Study			Observed Activity			
Bryan, 1993	**Healy, 1956**	**Cox, 1975**	**Bryan**	**Healy**	**Cox**	**Comments per Bryan, 1993**
1	1	6	perpetual spouter	perpetual spouter	perpetual spouter	Substantial variations in force, height
1a	(with #1)	dot on map	**geyser**	perpetual spouter	perpetual spouter	I=10–60s; D≈30s; H=20–70cm
1b	(with #1)	dot on map	**geyser**	perpetual spouter	perpetual spouter	I=5–30s; D=10–60s; H=20–30cm
2	2	7	upwelling	perpetual spouter	spring	Vigorous steady upwelling in stream
3	3	4	**geyser**	**geyser**	**geyser**	Cyclic; not seen at full level; see text
none	4	none		**geyser**		Feature has disappeared
none	5	none		**geyser**		Feature has disappeared
6	6	none	spring	intermittent spring		#6 of Bryan, Healy probably different
7	7	3	perpetual spouter	perpetual spouter	perpetual spouter	Slight variations in force, discharge
8	8	2	perpetual spouter	perpetual spouter	**geyser**	Highly variable activity, possible geyser
9	9	none	intermittent spring	**geyser**		Empty during obs.; intermitt. per native
10	10	"No. 8 pit"?	**geyser**	spring	boiled when dug	Ditto; long–period geyser per native
11	none	8	subterranean		subterranean	Intermittent bubbling sounds at depth
12	none	1	seep		perpetual spouter	Tiny, luke warm discharge
13	none	5?	**geyser**		**geyser**	I=30s to >10m; D=secs; H to 70cm horiz.
Total Number of Geysers Observed			**5**	**4**	**3**	

The Geysers of New Zealand
A Summary

by T. Scott Bryan

Abstract

The thermal areas on the North Island of New Zealand were visited between June 4 and 10, 1993. The following is a summary of the observations.

Introduction

Most reports I'd received through the years implied or specified that only 12 to 15 geysers remained active among all of New Zealand's thermal areas. It turns out that those numbers involved some guesswork for one thing. More important is this. It seems that the most important point to both the proprietors of the various thermal areas and the geologists who do studies among them is that geysers are present. An actual count of how many there are is of little importance.

With the guidance of Ron Keam (Department of Physics, University of Auckland), Ted Lloyd (Rotorua District Geologist retired, New Zealand Geological Survey), and Brad Scott (New Zealand Institute of Geological and Nuclear Sciences, Wairakei), I was able to meet with these proprietors and their guides in an effort to learn the true situation. In total I was among these areas for seven days (June 4-10), and here's what I found.

Whakarewarewa

This, the best known area just outside the city of Rotorua, contained at least 10 active geysers, including well-known Pohutu, Prince of Wales Feathers, Kereru, Waikorohihi, and Mahanga. Perhaps most significant was an eruption by a small geyser, Ororea (or something nearby that name). In an area that had not seen eruptions for several years because of the geothermal drawdown due to wells in Rotorua, it and several nearby springs were extremely vigorous. This is taken as an indication of recovery since legal rulings that have limited the geothermal production. All told, in-cluding some features not actually seen to erupt but which had the signs of activity, Whaka probably contains at least 14 active geysers.

Waimangu Valley–Lake Rotomahana

Geysers have always been relatively minor members of Waimangu-Rotomahana—excepting, of course, Waimangu itself, but it's been gone since 1904. I only saw three geysers erupt within Waimangu Valley, but I was assured that one other vent there is also a geyser. Both Taha Roto and Iodine Spring, recently active as geysers, are presently acting as perpetual spouters. I also feel that several of the many vents among the Nga Puia O Te Papa complex could be geysers. Along Lake Roto-mahana I saw numerous spouting features, and Brad stated that at least four are geysers. Thus, the current total geyser count here is at least 8.

Waiotapu

Waiotapu is a strongly acid area known for its col-lapse craters, mud pots, acid lakes, hydrothermal explosions, and huge Champagne Pool. Three geysers were seen, however: one in a steam phase, one sputtering from a tiny crack, and one full one day and refilling the next. In addition, two other geysers probably exist. Away from the tourist track, I did not visit them, but they have been active on many of the visits by local geologists.

Waikite Valley

This is a small group of springs, but according to geologist Ashley Cody, one of them is a small geyser. Its deposits apparently include aragonite travertine! This is also the site of Puakohurea, which probably destroyed itself with huge explosive eruptions in the 1980s.

Te Kopia

There is one geyser at Te Kopia. It is a mud spring among a number of *bona fide* mud pots, but it has been active as a true geyser since at least the early 1950s. It has been seen to approach 100 feet high in the past, but the best I saw reached perhaps 12 feet.

Orakei Korako

This was a wonderful surprise. Even though the majority of its springs and geysers were drowned beneath Lake Ohakuri in 1961, I saw 9 geysers erupt, 1 in what I later learned was preplay, and was told by proprietor Tim Boddy about 6 others known active and still another 6 possible— a total of 16 and possibly 22 geysers is significant to say the least. On top of that, I am convinced that a longer observing time would have revealed several additional geysers, and I feel that a total 30 is possible. The largest of the geysers are Diamond, Cascade, and Sapphire.

Wairakei

We didn't even visit Wairakei, although we did pause long enough to gaze up along the steam pipes toward was was once probably the most concentrated basin of large geysers anywhere. Wairakei has, of course, been totally destroyed by the geothermal drilling adjacent to "Geyser Valley," as have the geysers that once existed at The Spa closer to the city of Taupo.

Tokaanu

At the south end of Lake Taupo and so well removed from the other areas, Tokaanu is the site of Taumatapuhipuhi Geyser, once large but rare and now just 3 feet high but playing every 4 to 8 minutes. Teretere, a superheated pool, probably has in-frequent eruptions.

Geyser Observations

Specific observations and comments are presented on the following pages. Readers must remember that this is based on only seven days among the hot springs. However, too, none of the five New Zealanders who have seen this tabulation has yet to change anything in it!

The Geysers of New Zealand

Locality	Observed By Me	Reported by Others	Minimum Total	Possible Additional
Whakarewarewa	9	1	10	4
Waimangu-Rotomahana	3	5	8	several
Waiotapu	3	2	5	unknown
Waikite Valley	0	1	1	probably 0
Te Kopia	1	0	1	probably 0
Orakei Korako	10	6	16	6
Tokaanu	1	0	1	1
TOTALS	**27**	**15**	**42**	**10+**

THE GEYSERS OF NEW ZEALAND

No	Name	Observed in eruption	Rpt by Others	Comments
Geysers at Whakarewarewa				
1	Kereru	X		Brief splashes only; large infrequent eruptions not seen
2	Prince of Wales Feathers	X		Only brief pauses following Pohutu
3	Pohutu	X		Very vigorous, I≤1h; D=5-20m; H to 40 meters
4	Waikorohihi	X		Erratic, H to 4 meters
5	Mahanga (Boxing Glove)	X		Cyclic; when active I=min; D=5-15s; H≥5 meters
6	UNN vent behind Puapua	X		Subterranean eruptions heard
7	Korotiotio-Waiparu complex	X		One periodic vent seen; activity shifts frequently among many vents
8	Ororea (name?)	X		One eruption witnessed, D>4m, H≈1 meter
9	UNN vent within Te Hinau Crater	X		Subterranean beneath collapse rubble; also recently observed by B.J. Scott
10	Pareia			Fresh sinter within vent implies recent activity
11	Parekohoru		X	Rare explosive eruptions; recent activity implied by B. J. Scott
12	351			These vents in vigorous eruption, H as great as 2 meters, throughout visit
13	352			of ≈10 minutes. With historically known geyser activity and lying near Ororea,
14	Moutere (name?)			these and other openings are all potentially if not now active as geysers.
Geysers at Waimangu				
1	UNNG (Dog Tongue Spring?)	X		Not noticed on June 5, i.e. on June 10; identity by name uncertain
2	Taha Roto			Presently active as perpetual spouter
3	UNNGs (area #2/011)			Probably the site of "2 or 3" geysers recently noted by B.J. Scott
4	"Outlet Spouter" (#2/007)	X		i.e. to H≈50 cm on June 5; bubbling below overflow on June 10
5	Nga Puia O Te Papa complex			Numerous eruptive vents, quite probably some as geysers with observation
6	Iodine Geyser		[X]	Presently perpetual spouter?; geyser, I=10-12m in 1990-91
7	Warbrick Terrace, back spr (#7/006)		X	Per Keam; i.e. each time seen by me
8	Warbrick Terrace, bottom spr	X		Single interval of ≈1 1/2 minutes observed; H=10-20 cm
10	on Rotomahana		X	Per B.J. Scott, at least 4 active geysers along Lake Rotomahana shoreline
11	on Rotomahana		X	Ditto.
12	on Rotomahana		X	Ditto.
13	on Rotomahana		X	Ditto

Geysers at Waiotapu

1	Lady Knox	[X]		Artificial, soaped daily at 10:15am
2	#69 of Lloyd	X		i.e., H≈30 cm on June 6; steam phase on June 10
3	#70 of Lloyd		X	Full and ov. on June 6, empty on June 10; in 1958, I≥12h
4	#77, or #82, or vicinity of Lloyd	X		Observed to fill suddenly, splash H≈15 cm on June 6
5	#134 of Lloyd		X	Active on every visit by Lloyd and/or Keam
6	? near #134		X	Usually active when visited by Keam

Geysers at Orakei Korako

1	Diamond	X		Near steady to H≤2 meters; about daily to 8 meters per Tim Boddy
2	UNNG in bush	X		Two eruptions seen, possible I≈1h; H=1-1 1/2 meters at start, then smaller
3	Cascade	X		Difficult to see within cavern. I=few min; D=1-2m
4	Sapphire	X		Three eruptions seen, probably I= few 10s of min; D=1-2m; H≈2 meters
5	Geyser below Sapphire	X		New to Lloyd and Keam. I=min; D=1-2m; H≈30 cm
6	Geyser west of Sapphire	X		New to Lloyd and Keam. I unk; D≈1m; H≈1 meter
7	"Lloyd's Dark Patch"		X	New to Lloyd and keam. Brief eruption seen by Lloyd during visit with me
8	"Stick Pile Cone"	X		New to Lloyd and Keam. I short; D short; H≈20 cm
9	UNNG inside red cavern	[X]		Fresh, pearly sinter in damp runoff channel out of cavern
10	Subterranean at Gold. Fleece	X		Visible splashing at ≈2 meter depth stopped after Keam walked away
11	New geyser in old crater		X	West of Artist's Palette, reported by Tim Boddy. H to 2 meters
12	New geyser in old crater		X	Ditto, H to 2 meters
13	UNNG on slope west of Cascade		X	New in January 1992 per Tim Boddy. No details, not seen.
14	Soda Fountain (My Lady's Lace)	[X]		Active, within interval when seen. Action reported to be like Shell Spring.
15	UNNG upstream from jetty		X	Infrequent, reported by Tim Boddy
16	UNNG upper lake area		X	Reported by Tim Boddy. Active naturally, often soaped by boaters. H≈2 meters
17	Kurapai		X	Eruptions discussed by Lloyd, Keam, and Boddy
18	Crater east end of Artists Palette	[X]		Historically known, surroundings wet and clean. I say yes, Lloyd says no.
19	Wairiri		[X]	Active only with low barometric pressure; last? seen in 1991? per Tim Boddy
20	Near #2 above	[X]		Hidden in bushes; possibly intermittent spring only
21	Near fallen tree on Artists Palette	[X]		Possibly a variable perpetual spouter rather than geyser
22	Hidden vent near #8 above	[X]		Intermittent steam and noise from thoroughly hidden vent

Geysers at Waikite Valley

1	Paukohurea		[X]	Explosive eruptions of late 1980s probably destroyed plumbing
2	UNNG		X	Deposits carbonate(?) sinter; believed by Ashley Cody to be geyser

Geyser at Te Kopia

1	"Te Kopia Mud Geyser"	X		I=min; D=secs; H=1-3 meters. My video perhaps only motion pictures showing

Geysers at Tokaanu

1	Taumatapuhipuhi	X		I≈4-8m; D≈20s; H to 1 meter. Far smaller, much more frequent than historically
2	Teretere			Not seen. Superheated, thumping and signs of wash surrounding

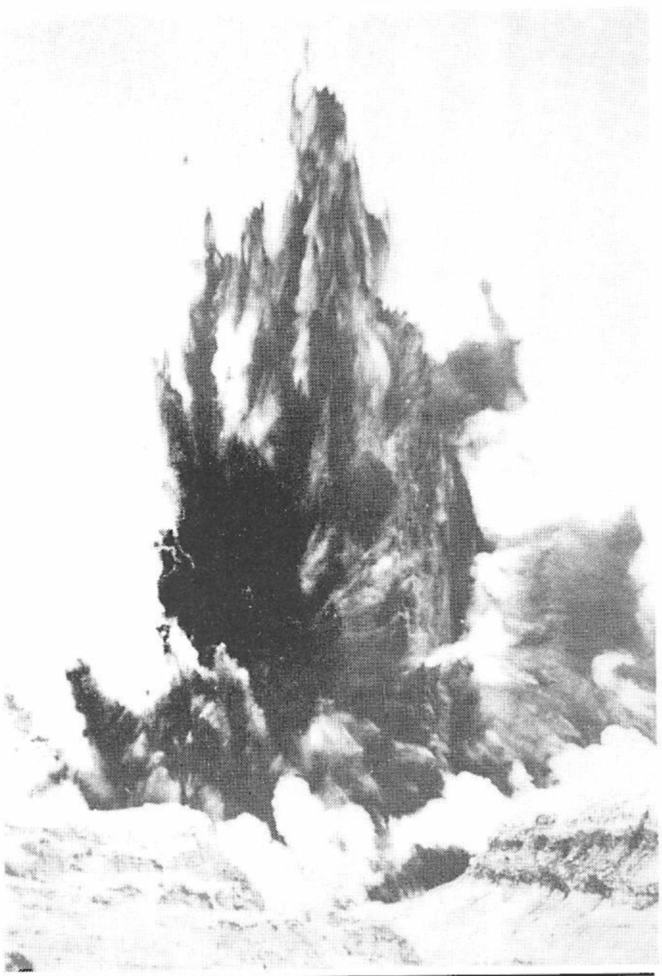
NOTES

One of the remarkable concerted eruptions by Morning Geyser (right) and Fountain Geyser (center), joined by Clepsydra Geyser (left) in August 1991. The relationships between these geysers are discussed in this issue of *The GOSA Transactions*. Photo by Lynn Stephens.

Notes

Monument Geyser, also known as Thermos Bottle, did indeed spout water at one time. This photo, perhaps by Haynes, is labeled in Scott Bryan's collection as "NPS photo #8042–6."

Notes



New Zealand's Waimangu Geyser. Little is left to be said. Perhaps Ron Keam or another New Zealand reader will be able to identify the source of this photo, which is on display in the Old Faithful Visitor Center courtyard.

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