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Giant Geyser
June 7, 1997
photo by
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The Geyser Observation
and Study Association

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photo by Mary Ann Moss

Roderick A. Hutchinson
March 5, 1947 - March 3, 1997

Rick at Cinder Pool

This volume is dedicated to Rick Hutchinson,
. . . to the love that Rick had for Yellowstone Park,
. . . to the love that Rick had for all the things that made Yellowstone his park,
. . . and to all those who loved, and those who will love the park, as much as he did.

Rick Hutchinson in the "Thermal Boat" on Morning Glory Pool

photo by Charlie Goldberg

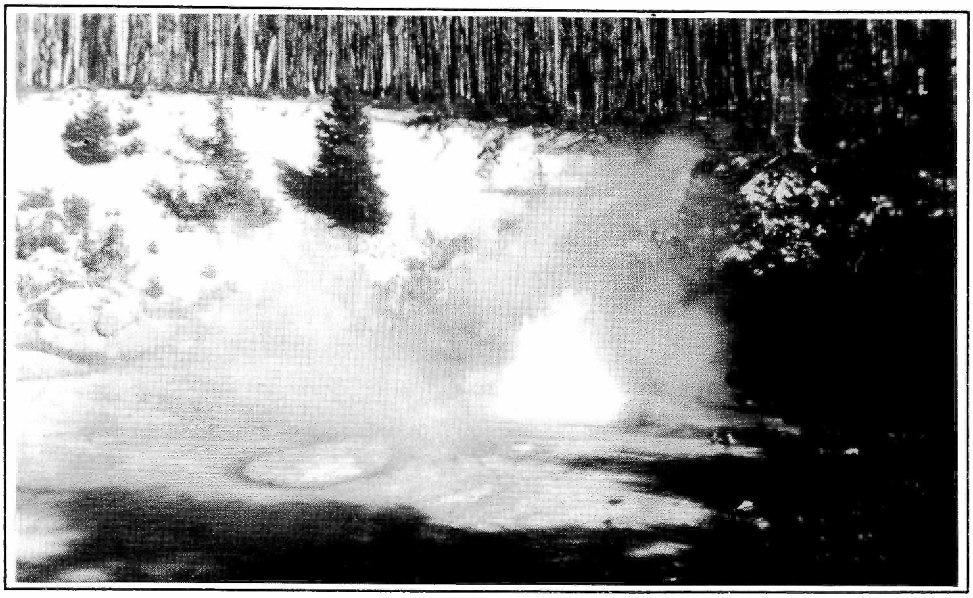
A Photo Display

Contributors: T. Scott Bryan, Douglas Colin, Carlton Cross, Genean Dunn, David Goldberg, Mike Keller, Dan Miller, David Monteith, Rocco Paperiello, David Stark

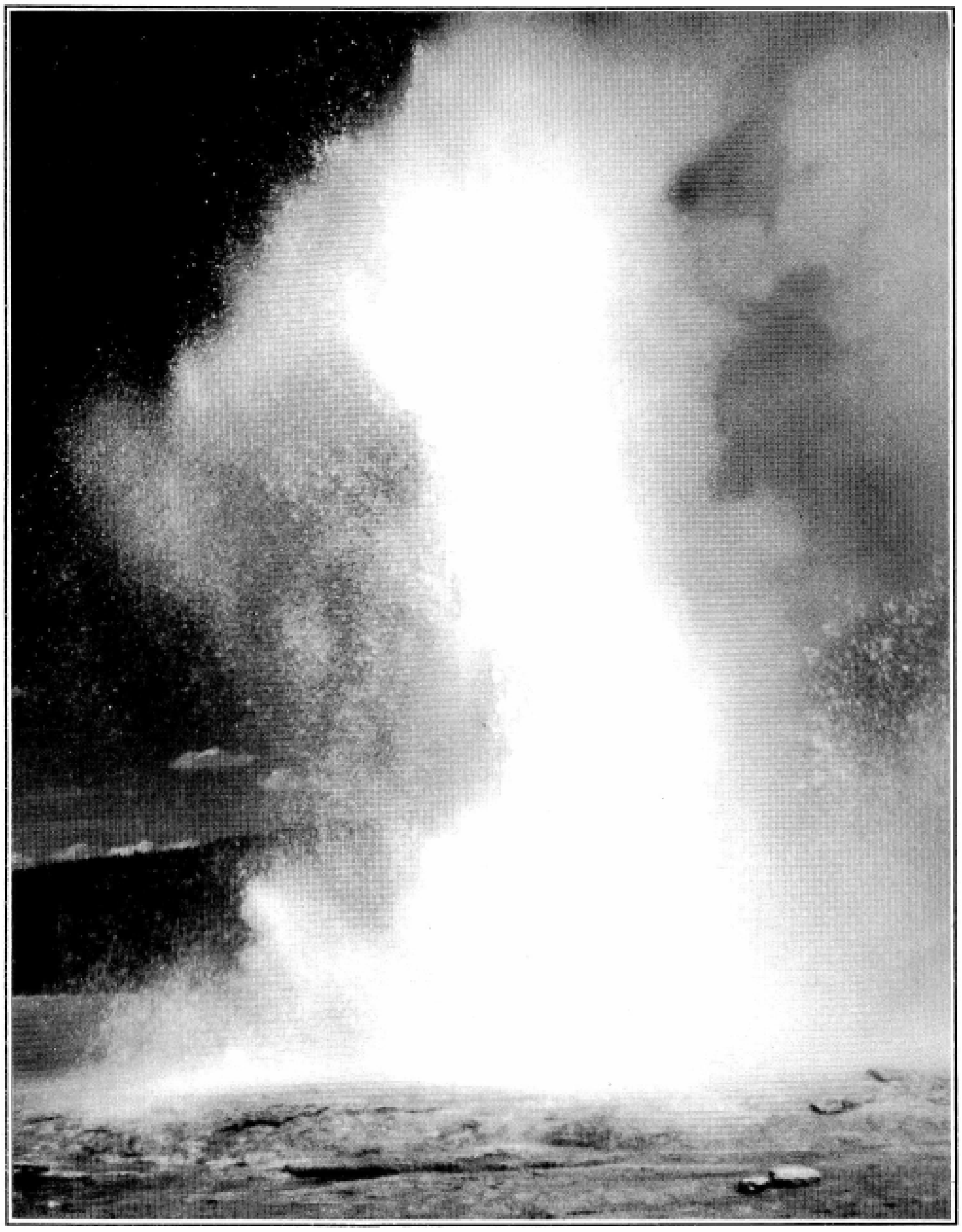
Grand Geyser
August 1992
photo by
David Stark

Opal Pool
photo by
Geneane Dunn

Artemisia Geyser
1990
photo by
Dan Miller



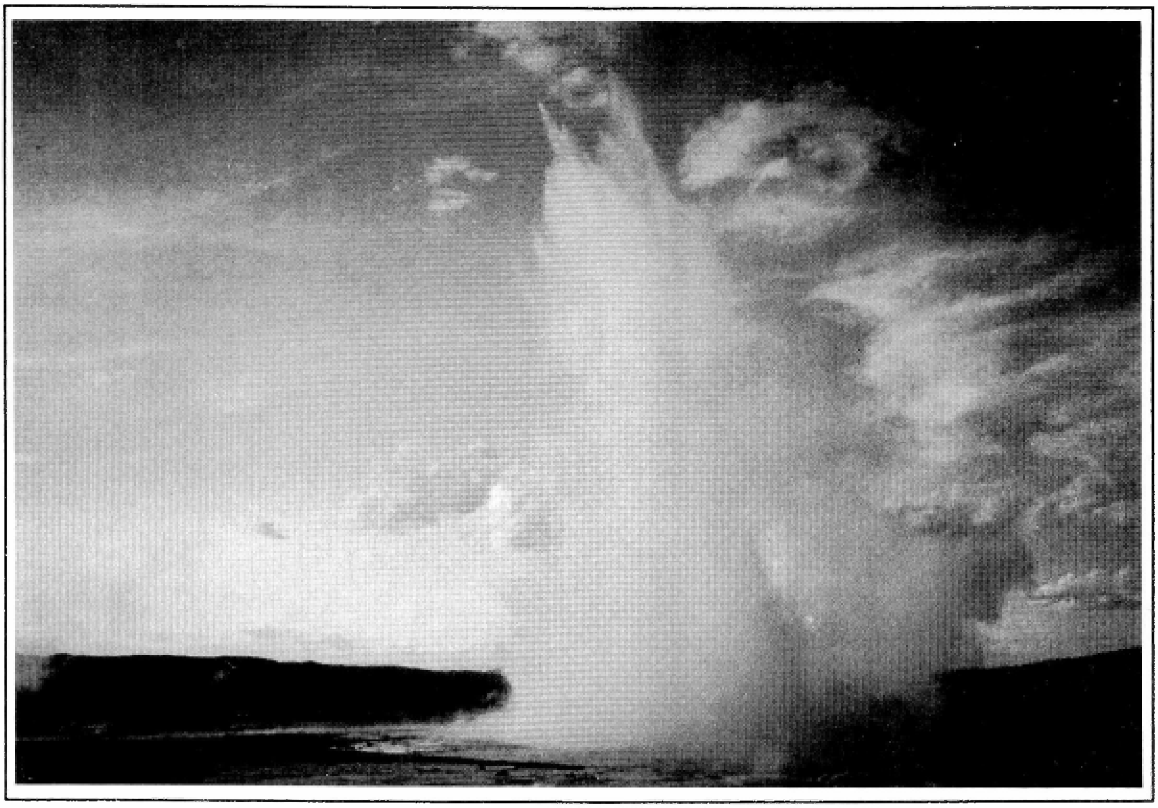
Monarch Geyser
photo by
David Monteith



Fountain Geyser
August 1992
photo by
David Starck

Drain Geyser
photo by
Mike Keller

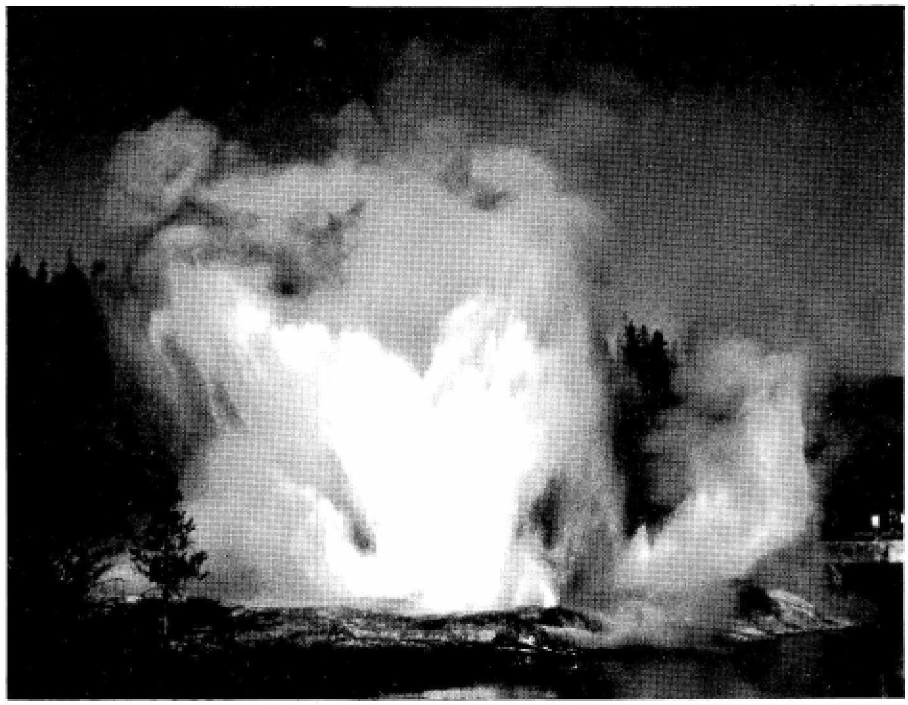
Ledge Geyser
July 22, 1994
photo by
David Monteith



unnamed geyser erupting from a vent within Deep Blue's basin, photo by Mike Keller

Atomizer Geyser photo by Rocco Paperiello

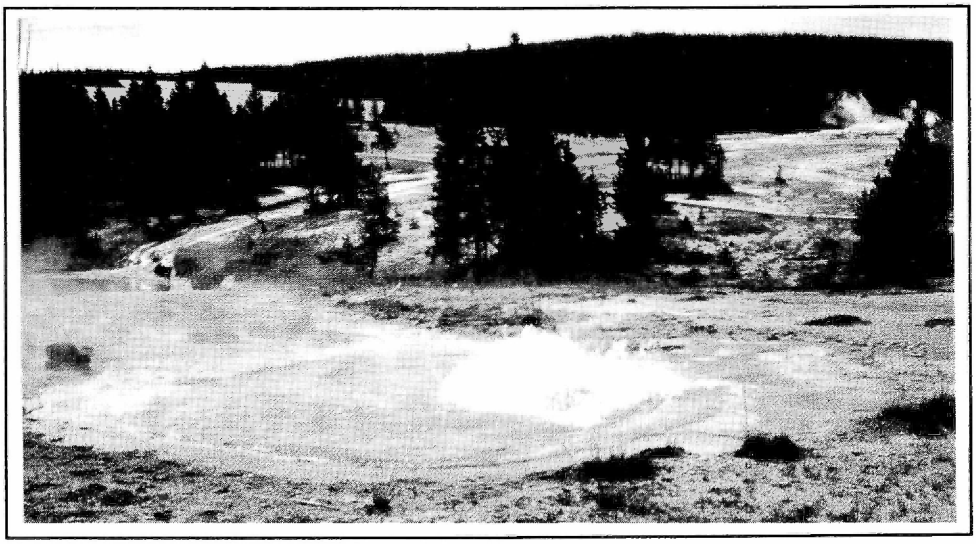
Fan and Mortar Geysers
photo by
Jack Hobart

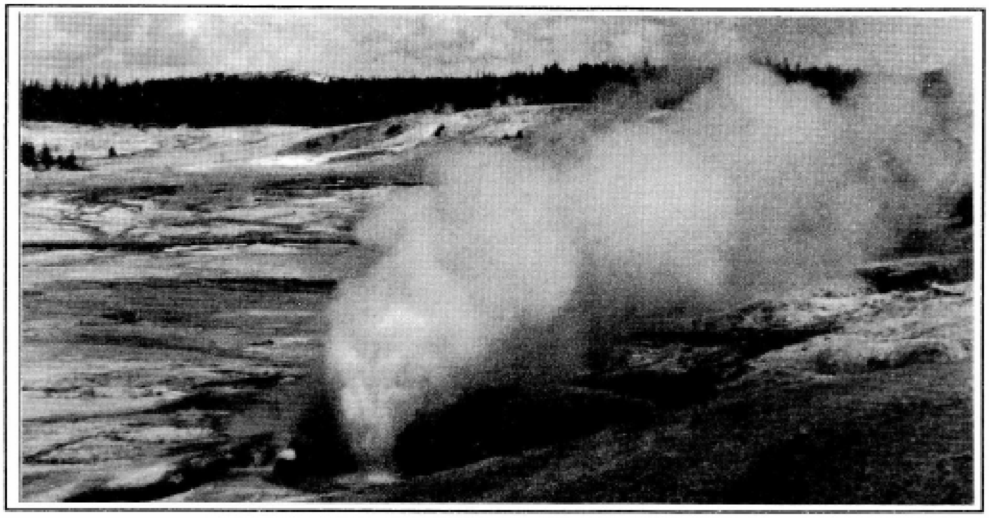


Jewel Geyser
August 1992
photo by
David Starck

Splendid Geyser
July 7, 1996
photo by
Douglas Colin
Nov 5, 1941 - Apr 20, 1997

Bronze Spring
July, 1990
photo by
T. Scott Bryan





Dark Cavern Geyser
April 20, 1994
photo by
David Monteith

Fan and Mortar Geysers
August 1992
photo by
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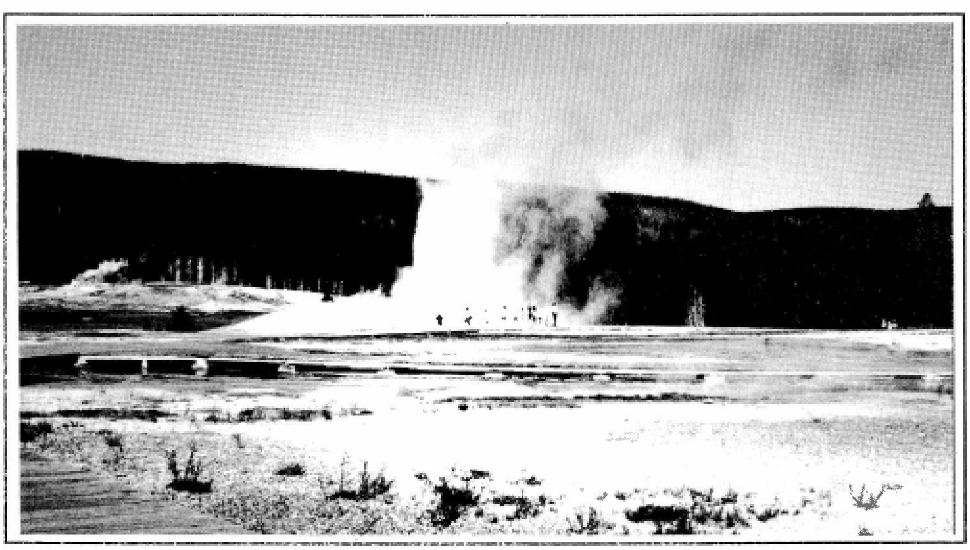
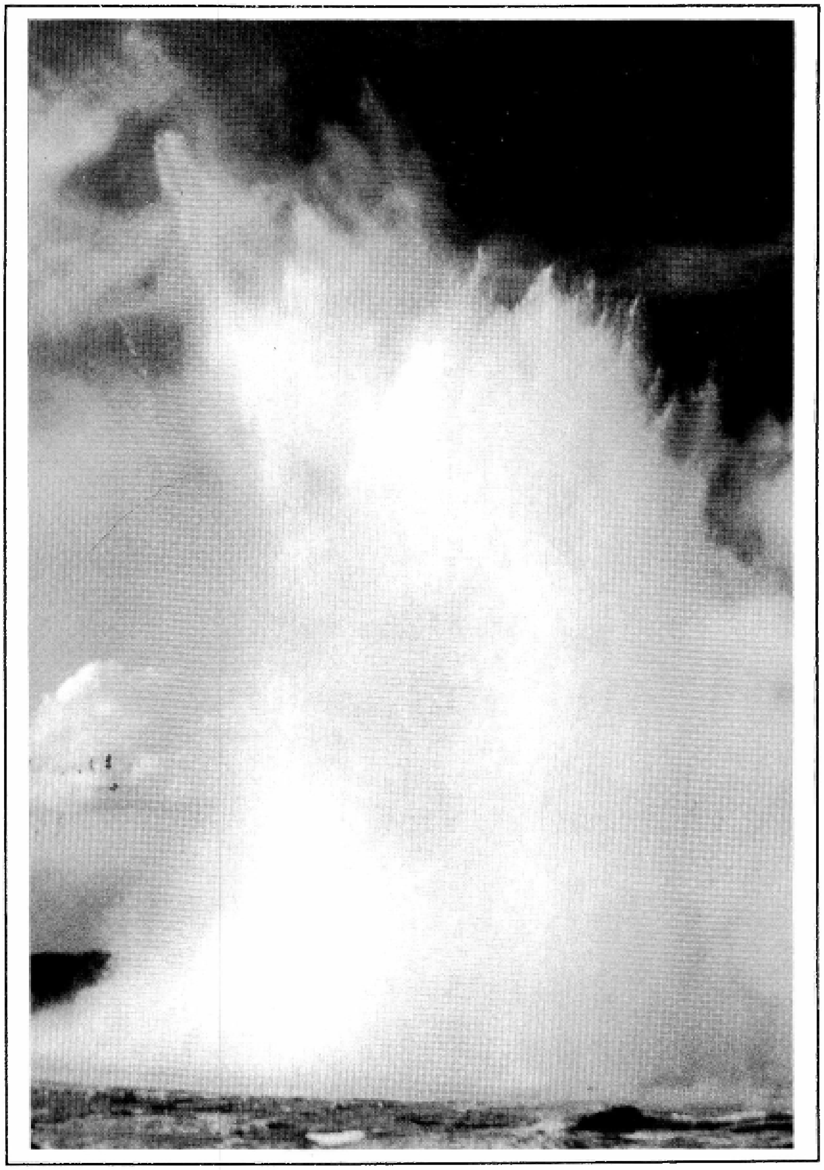
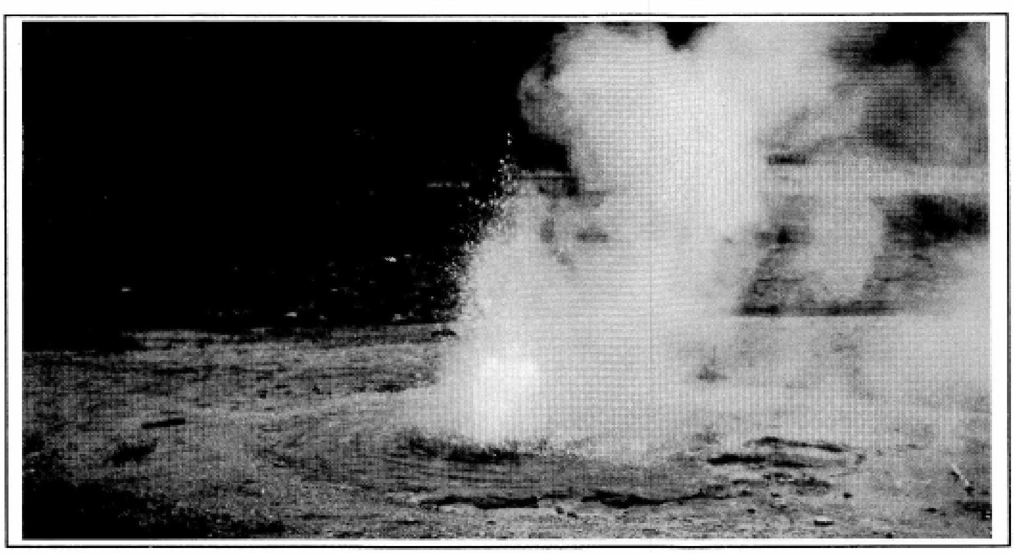
Pink Cone Geyser
photo by
David Starck



Big Cub Geyser
1987
photo by
Phil Landis

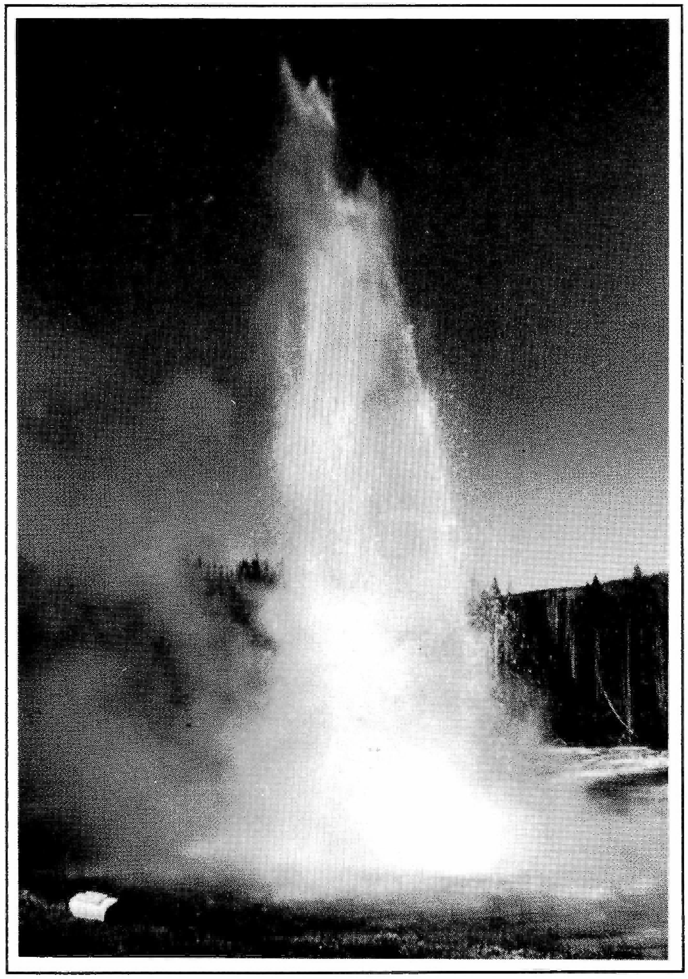
Morning Geyser
1982
photo by
Rocco Paperiello



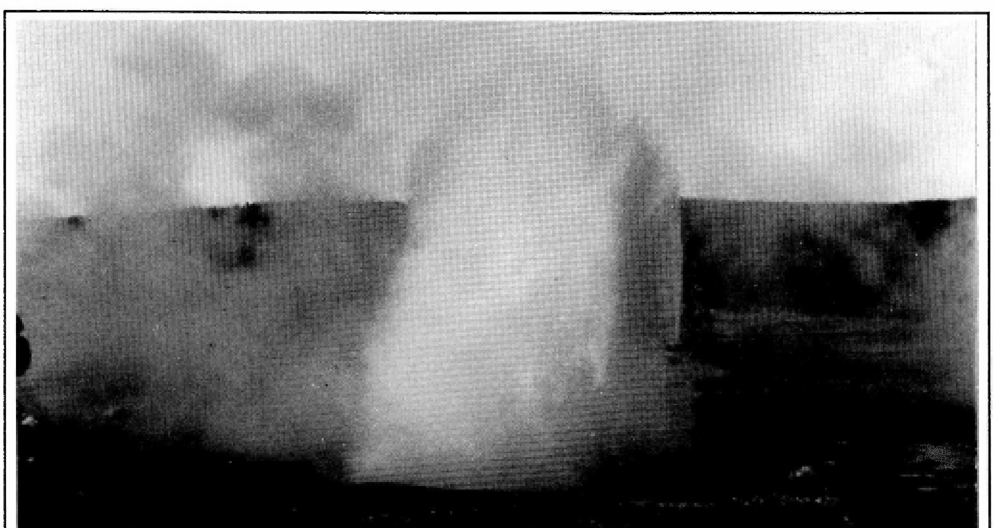


Pebble Spring
photo by
Rocco Paperiello

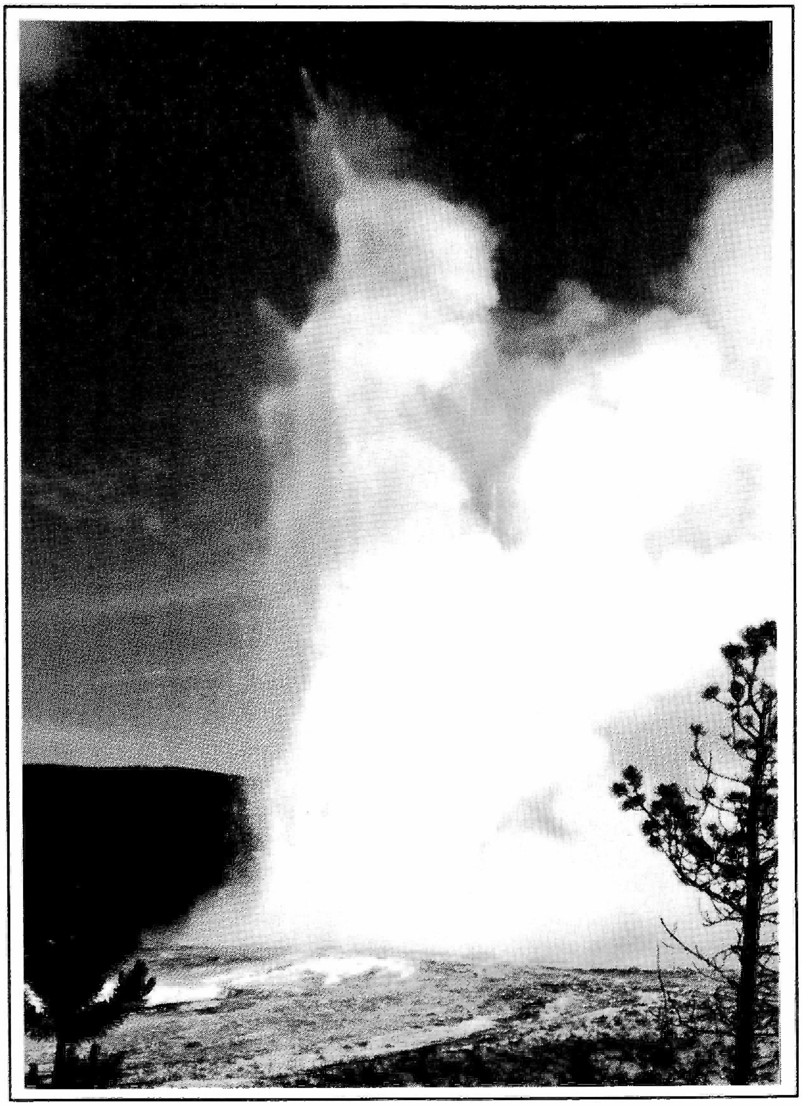
unnamed geyser
by Ragged Spring
photo by
Rocco Paperiello



Spa Geyser
August 1, 1990
photo by
David Goldberg



"Collapse Geyser"
photo by
Rocco
Paperiello



Giantess Geyser 1993 photo by Carlton Cross

Patterns in the intervals between eruptions of Giantess Geyser

H.Koenig

Abstract: During the early 1980s, Giantess Geyser erupted about once a week. After the Borah Peak earthquake of 1983, it reverted to its historical activity of infrequent eruptions. Before the earthquake, there was a pronounced tendency for longer intervals to result in the strong, steam-phase eruptions, while short intervals tended to be aborted eruptions. Since the earthquake there have been series of from one to three eruptions a few weeks apart, with several months to a year between the starts of series.

Location and Setting

Giantess Geyser is located at the summit of Geyser Hill in the Upper Geyser Basin of Yellowstone National Park. It is a large, deep pool known for having infrequent, but powerful eruptions [Marler 1973] . During most of its history, eruptions occurred only once or twice a year, yet during the period 1979-1983 it erupted with unprecedented frequency. For the first ten months of 1983 the average interval length was less than a week.

Until 1969, eruptions of Giantess were of one of two types, called a "steam phase" and "water phase"[Marler 1973] (pg. 298). Both types of eruptions begin identically, but about thirty to forty-five minutes into the eruption, the steam-phase type eruption quickly shifts from water jets to powerfully ejected steam. Water phase eruptions typically last from 24 to 36 hours, while a steam phase eruption usually lasts about 12 hours.

In 1969, Marler first noted a third type of eruption, now called a mixed phase [Hutchinson 1983], pg.17. This eruption begins like a steam phase eruption, but about three to six hours into the eruption, the eruption reverts to a water phase type of eruption. The total duration is similar to that of the water-phase.

The fourth type of eruption is the aborted, and was first observed on 20 March 1982 [Hutchinson 1983] (pg.14). These are weak water phase eruptions, and typically lasted only one to six hours. Since the Borah Peak earthquake of 1983, aborted eruptions have not been observed.

Finally, it needs to be noted that Giantess can be induced into erupting. Reports of induced eruptions date back to the 1920s. As described by Martinez [Martinez 1976], some persons claimed that the eruption of 06 August 1976 was induced by a bar of soap. The eruption of 10 May 1990 was induced by the addition of about 5kg. of dry ice, in what was described as an attempt to cause heavy boiling activity in Giantess believed necessary to stimulate activity in nearby but dormant Beehive Geyser. [U.S 1990] , [N.P.S 1990], [Billings Gazette 1990]. The full effects of induced eruptions is unknown, but it is interesting to note that in 1990 it was two months before Giantess erupted again.

The data used for this paper comes from a variety of sources. Prior to 1959, the primary sources are observations reported in [Marler 1973], [Whittlesey 1988] and [Keller 1994]. Since 1959, observations are derived from the many logbooks that have been kept at the Old Faithful Visitor Center[O.F.V.C. Logs 1959-1996]. The 472 known or inferred eruptions of Giantess are listed in the appendix to this report.

From the information uncovered by Keller, it seems likely that Giantess has been under year-round observation since at least the early 1920s, except possibly the war years of the early 1940s. Even prior to that, there are numerous reports of wintertime activity. But unless there was specific information on observations, or lack of eruptions, it is assumed that prior to the 1920s observations were only made during the summer season.

Modes of Activity

The frequency of Giantess eruptions falls into one of three classes, or modes. Each mode is characterized by the interval and type of eruptive activity exhibited during that time.

Mode 1: Infrequent series

The most common mode for Giantess since its discovery has been infrequent series of from one to three eruptions. The eruption of a Mode 1 series has usually been a steam-phase or strong mixed-phase eruption. Later eruptions in the series were usually weaker mixed-phase or water-phase eruptions.

Intervals during Mode 1 activity ranges from as short as seven days, to over one thousand days (nearly three years). The longer intervals are those that precede the first eruption of a series, while the shorter intervals typically are those between the subsequent eruptions of the series.

1864	1		1897	7*	1	1932	3	1	1967	1	1
1865			1898	0	1	1933	0	1	1968	2	1
1866			1899	1	1	1934	2	1	1969	7	2
1867			1900	0	1	1935	1	1	1970	4	1
1868			1901	1	1	1936	1	1	1971	2	1
1869			1902	2	1	1937	1	1	1972	3	1
1870	1	1	1903	2	1	1938	2	1	1973	5	1
1871	0	1	1904	14	2	1939	0	1	1974	8	2
1872	1	1	1905	13	2	1940	1	1	1975	12	2
1873	1	1	1906	12	2	1941	0	1	1976	13	2
1874	0	1	1907	13	2	1942	1	1	1977	8	2
1875	1	1	1908	24	3	1943	0	1	1978	0	1
1876	1	1	1909			1944	1	1	1979	5	1
1877	0	1	1910			1945	1	1	1980	13	1->3
1878	1	1	1911			1946	1	1	1981	23	3
1879	0	1	1912			1947	5	1	1982	35	3
1880	2	1	1913			1948	2	1	1983	40	3->1
1881	1	1	1914			1949	2	1	1984	1	1
1882	3	1	1915			1950	3	1	1985	4	1
1883	4	1	1916			1951	1	1	1986	2	1
1884	2	1	1917			1952	3	1	1987	4	1
1885	≥1 ?	1	1918			1953	1	1	1988	3	1
1886	2	1	1919	8	3	1954	1	1	1989	7	2
1887	4	1	1920	6	2	1955	3	1	1990	4	1
1888	2	1	1921	2	1	1956			1991	2	1
1889	3	1	1922	3	1	1957			1992	1	1
1890			1923	≥1	1	1958	1	1	1993	4	1
1891	1	1	1924	1	1	1959	3	1	1994	2	1
1892			1925	2	1	1960	1	1	1995	3	1
1893	4	1	1926	8	1	1961	4	1	1996	1	1
1894			1927	2	1	1962	2	1	1997†	1	1
1895	12*	3	1928	2	1	1963	4	1			
1896	14*	3	1929	7	1	1964	0	1			
			1930	4	1	1965	1	1			
			1931	1	1	1966	2	1			

* Summer season only

† as of 01 Jul 1997

Observed Eruptions
Table 1

Mode 2: Infrequent isolated activity

In this mode Giantess erupts with greater frequency than in Mode 1, on average every one to two months. The eruptions do not seem to come as part of distinct series. This mode has appeared on a number of occasions, most recently during the mid-1970s. Also, the activity of 1989 might have been an attempt to shift to Mode 2.

Many of the eruptions during the Mode 2 activity of the 1970s were of the mixed-phase type, possibly indicating that this mode might be just a long Mode 1 type series.

Mode 3: Frequent activity

This modes has been observed thrice, during 1895-1986, in 1908, and again from 1980 until the Borah Peak earthquake at the end of October 1983. The last Mode 3 eruption was the second after the earthquake, beginning on 10 November 1983. It was followed by a 340-day interval. This mode is characterized by two to four eruptions of Giantess per month. The activity during the 1980s seemed to most observers to be lacking in strength, as if Giantess needed a long period of time to gain strength. These observations are supported by the numerous mixed-phase and water-phase eruptions. It was also during the 1980s activity that aborted eruptions were first observed. At times it every other eruption was an aborted-type, followed in less than a week by another, stronger eruption.

Relation of steam-type eruptions to series

Since the 1982 Borah Peak earthquake, Giantess has been in Mode 1, except for a brief period in 1989 when it seemed to exhibit Mode 2 type behavior. Listed in Table 2 are the eruptions that have occurred between the earthquake and 01 July 1997. For each eruption is listed the eruption type, if known, the interval between it and

Date	Type	Interval	Series Int.
10 Nov 1983		11d	
15 Oct 1984	**Steam**	**340d**	**340d**
18 Jan 1985	Water	95d	
11 Feb 1985	Water	24d	
31 May 1985	**Steam**	**108d**	**227d**
09 Jul 1985	Mixed	38d	
26 Jun 1986	**Mixed**	**352d**	**390d**
15 Jul 1986	Steam	18d	
17 Feb 1987	**Steam**	**217d**	**235d**
14 Mar 1987	Mixed	25d	
04 Apr 1987	Mixed	20d	
12 Dec 1987	**Steam**	**259d**	**304d**
08 Jul 1988	**Steam**	**157d**	**157d**
28 Aug 1988	Mixed	51d	
18 Sep 1988	Water	21d	
27 May 1989	**Mixed**	**251d**	**323d**
07 Jun 1989	Mixed	11d	
24 Jun 1989	Mixed	16d	
19 Jul 1989	Water	24d	
15 Sep 1989	Mixed	39d	
04 Nov 1989	Mixed	50d	
10 May 1990	**Induced**	**187d**	**187d**
29 Jun 1990	**Mixed**	**61d**	**61d**
12 Jul 1990	Mixed	12d	
05 Nov 1990		**116d**	**128d**
19 May 1991	**Steam**	**195d**	**195d**
09 Jun 1991	Water	21d	
25 Mar 1992	**Steam**	**290d**	**301d**
04 May 1993	**Mixed**	**405d**	**405d**
12 Jun 1993	Mixed	39d	
19 Jul 1993	Water	37d	
02 Aug 1993	Water	14d	
11 Jul 1994	**Steam**	**343d**	**433d**
01 Oct 1994	Mixed	82d	
18 Jan 1995	**Steam**	**109d**	**191d**
28 Sep 1995	**Mixed**	**253d**	**253d**
09 Nov 1995	Mixed	43d	
13 Oct 1996		**339d**	**382d**
10 Apr 1997		**179d**	**179d**

Eruptions of Giantess since Borah Peak Earthquake (as of 01 Jul 1997)
(with series start in **bold-face**)
Table 2

Steam	8
Water	28
Mixed	22
Aborted	13
Steam after Aborted	3
Water after Aborted	7
Mixed after Aborted	2
Aborted after Aborted	1
Unknown	14
Total	**98**

Observed Eruption Types
1981-1983
Table 3

the previous eruption, and, if applicable, the interval between the start of eruption series. A new series is arbitrarily considered to have began when over 100 days elapsed between eruptions. By this classification, of the eighteen eruptions that began a series, nine were steam-phase types, five were mixed, three were unknown and one induced. The mixed phase eruption of 04 May 1993 had a duration of 43h30m, which is unusually long for its type. Typical mixed-phase eruptions last from 24 to 30 hours. The 26 June 1986 mixed-phase eruption was followed by the only steam-phase eruption that didn't begin a series.

Two of the steam-phase eruptions that began series also deserve comment, as they showed some unusual behavior. The eruptions of 19 May 1991 and 11 July 1994, while steam-phase at the start, late in the eruption evolved into mixed-phase type water/steam bursts, in effect blurring the line between mixed-phase and steam-phase eruptions.

Relation of interval to eruption type

During the 1980s Mode 3 activity, after an aborted type eruption, Giantess would typically erupt within four to six days. Because of the short durations of aborted-type eruptions, and the short intervals following them, they have been excluded from the analysis of variance of the intervals preceding an eruption, presented in Table 4. This analysis clearly shows that relationships exists between the various eruption types and the intervals preceding them when the preceding eruption was not an aborted-type.

Steam-phase eruptions and aborted eruptions resulted from longer and shorter intervals, respectively. Mixed-type and water-type eruptions are possibly related, as both their means and standard deviations are similar. In addition, the "mixed vs. water" category is the only one not significant at the 95% confidence level.

The data for 1983 through 1994 (Table 5) also shows a relationship between interval and eruption type, although not as strong. Again, the steam-phase eruptions were preceded by the longest intervals, while the shortest intervals preceded the water-type eruptions

Note on the statistics

An Analysis of Variance (ANOVA) is a statistical test used to determine if the values of grouped are are significantly different between the groups. Significance at the 95% level means that the results show would, if random, occur in less than one in twenty such sets of data. The "Fisher PLSD" and "Scheffé F-test" are two

	DF	Σ Squares	Mean Square
Between Groups:	3	371944.755	123981.585
Within Groups:	37	662735.898	9746.116
Total	40	1034680.653	

FTest = 12.721 (p=0.0001)

Group	Count	Mean	Std.Dev	Std.Err
Steam	8	434.375	121.318	42.892
Mixed	22	295.182	95.667	20.396
Water	28	255.25	105.505	19.939
Aborted	14	171.5	71.773	19.182

Comparison	Mean Diff.	Fisher PLSD	Scheffe F-test
Steam/Mixed	139.193	81.341*	3.888*
Steam/Water	179.125	78.983*	6.828*
Steam/Aborted	262.875	87.319*	12.032*
Mixed/Water	39.932	56.131	0.672
Mixed/Aborted	123.682	67.357*	4.476*
Water/Aborted	83.75	64.489*	2.239

* Significant at 95%

One Factor ANOVA of Eruption Types vs. Interval (1981-1983)
(excluding eruptions following aborted types)
Table 4

standard tests which when given the means and standard deviations of sets of data, measure the degree to which the data are not random [Brownlee 1965].

In effect, the significant results from Table 4 and Table 5 show that the grouping being tested (determined prior to calculating the tests) are probably real, and not just coincidence.

	DF	Σ Squares	Mean Square
Between Groups:	2	80257882.436	40128941.218
Within Groups:	30	199493205.564	6653106.852
Total	27	279851088	

FTest = 6.032 (p=0.0063)

Group	Count	Mean	Std.Dev	Std.Err
Steam	10	4965.7	2578.451	815.378
Mixed	16	2198.875	3022.396	755.599
Water	7	811.429	675.069	255.152

Comparison	Mean Diff.	Fisher PLSD	Scheffe F-test
Steam/Mixed	2766.825	2123.722*	3.54*
Steam/Water	4154.271	2596.25*	5.341*
Mixed/Water	1387.446	2387.404	0.7094

* Significant at 95%

One Factor ANOVA of Eruption Types vs. Interval (1984 - 1994)
Table 5

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Eruptions of Giantess Geyser — 1864 - 1997

Year	Date	Time	Interval
1864	-----		
1865			
1866			
1867			
1868			
1869			
1870	19 Sep		
1871	- none -		
1872	18 Aug	18:56	
1873	-----		
1874	- none -		
1875	21 Aug	09:00	
1876	-----		
1877	- none -		
1878	27 Aug	08:30 ie	
1879	- none -		
1880	-- Sep		
	-- Oct		≈21d
1881	-----		
1882	06 Aug	20:00	
	13 Aug	15:30	6d19h
	26 Aug	03:30	12d12h
1883	22 Aug	09:00	
	02 Sep		11d
	11 Sep		9d
	20 Sep		9d
1884	25 Aug	16:15	
	12 Sep		
1885	active ?		
1886	17 Aug		
	27 Aug		
1887	-- Jan		
	24 Jun	16:00 ie	
	28 Aug		
	-- Sep		
1888	26 Aug	08:00	47d
	24 Sep [or 25 Sep]		30d
1889	19 Jun ?		
	02 Jul		
	20 Jul ?		
	03 Aug	01:20	
	30 Aug	01:20	27d
1890			
1891	10 Jun	16:30	
1892			
1893	17 Jul	18:30	
	31 Jul	13:30	14d
	26 Aug	08:00	25d19h
	18 Sep	17:10	23d09h
1894			
1895	01 Jul	17:10	
	12 Jul	15:00	11d22h
	18 Jul	20:00	6d05h
	27 Jul	16:30	8d21h
	04 Aug	14:30	7d22h
	11 Aug	01:30	6d11h
	21 Aug	01:30	10d00h
	27 Aug	04:30	6d03h
	04 Sep	01:30	7d21h
	10 Sep	06:30	6d05h
	20 Sep	15:00	10d09h
	29 Sep	20:00	9d05h
1896	08Jun	17:00	
	20 Jun	21:30	12d05m
	29 Jun	16:30	8d19h
	07 Jul	16:30	8d00h
	11 Jul	17:00	4d01h
	19 Jul	04:30	7d12h
	23 Jul	09:30	4d05h

Year	Date	Time	Interval
	08 Aug		16d
	18 Aug		10d
	27 Aug		9d
	06 Sep		10d
	14 Sep		8d
	24 Sep		10d
	01 Oct		7d
1897	01 Jun		
	12 Jun		11d
	22 Jun		10d
	02 Jul		10d
	12 Jul		10d
	28 Aug	18:30	47d
	07 Sep	04:00	9d10h
1898	- none -		
1899	04 Jul		
1900	- none -		
1901	07 Jul		
1902	13 Aug	04:20	

1903	24 Nov		
	12 Dec		18d
1904	19 Jan		38d
	07 Feb		19d
	16 Mar		38d
	26 Apr		41d
	10 Jun		45d
	01 Jul		21d
	04 Aug		34d
	21 Aug	20:15	17d
	08 Sep	18:25	17d22h
	24 Sep	06:00	15d12h
	13 Oct		19d
	29 Oct		16d
	14 Nov		16d
	11 Dec		27d
1905	17 Jan		37d
	01 Feb		16d
	01 Mar		28d
	13 Mar		13d
	28 Mar		15d
	16 May		49d
	26 May		10d
	21 Jun		26d
	17 Jul		26d
	02 Oct		
	05 Nov		
	15 Nov		10d
	14 Dec		29d
1906	01 Jan		18d
	01 Feb		31d
	28 Mar		49d
	03 Apr		6d
	13 May		40d
	24 Jun		42d
	17 Jul		23d
	28 Aug		42d

Notes: If an eruption is know to exist for a given year, but no further details are known, a '-----' is show in the date column. If the month is given, but not a date, then '-- *mon*' is shown. When all records indicate there weren't any eruptions for a year, '- none -' is shown. Many times prior to the 1960s rounded times, anywhere from the nearest 5 minutes to the half hour. 'ie' : first observed " in eruption". Time zone changes are noted if known.

Year	Date	Time	Interval
	02 Oct		35d
	20 Nov		49d
	07 Dec		17d
	24 Dec		14d
1907	06 Jan		8d
	22 Jan		14d
	05 Feb		14d
	16 Feb		11d
	01 Mar		13d
	03 Apr		33d
	24 Apr		22d
	10 May		15d
	27 May		17d
	22 Jun		26d
	13 Nov		
	03 Dec		20d
	14 Dec		12d
1908	08 Jan		24d
	04 Feb		27d
	12 Feb		8d
	22 Feb		10d
	02 Mar		9d
	26 Mar		24d
	04 Apr		9d
	10 May		36d
	24 May		14d
	07 Jun		14d
	17 Jun		10d
	04 Jul		17d
	14 Jul		10d
	23 Jul		9d
	06 Aug		14d
	17 Aug		11d
	01 Sep	18:00	15d
	12 Sep		11d
	24 Sep		12d
	08 Oct		14d
	20 Oct		12d
	03 Nov		14d
	14 Nov		
	25 Nov		
1909			
1910			
1911			
1912			
1913			
1914			
1915			
1916			
1917			
1918			
1919	20 Jun	12:00	
	30 Jun	07:30	9d20h
	05 Jul	10:00	
	11 Jul	06:45	5d21h
	21 Jul	14:30	10d08h
	28 Jul	10:30	5d21h
	03 Aug	08:00	5d21h
	16 Sep		
1920	25 May		
	27 Jun		33d
	28 Jul		31d
	24 Aug		27d
	15 Sep		22d
	28 Sep		13d
1921	-- Jul		
	-- Oct		
1922	02 Feb		
	04 Jun		142d

Year	Date	Time		Interval
	02 Jul			28d
1923	"active"			
1924	-- Aug			
1925	29 Oct			
	01 Dec			33d
1926	late Jan			
	12 Feb			
	20 Mar	09:30		
	-- Apr			
	24 May			
	14 Sep	10:00		
	01 Dec			48d
	29 Dec			28d
1927	30 Jul	13:00		213d
	21 Oct			
1928	02 Jul			
	09 Sep		"Induced"	
1929	14 Jan	15:15 ie		127d
	04 Feb			21d
	-- Apr			≈70d
	17 Jun	11 22:30		≈63d
	02 Jul	20:00		14d21h
	28 Aug			57d
	10 Nov			74d
1930	17 Jun	11:30		
	03 Jul	10:30		
	28 Aug	05:00		
	17 Sep	22:00		
1931	13 Sep	22:00		
1932	02 Jun			263d
	23 Jul	06:00ie		51d
	07 Dec			137d
1933	- none -			
1934	29 Jan	14:40		418d
	early Aug			
1935	22 Sep	23:00		
1936	≈14 Dec			
1937	03 Sep	04:00ie		≈263d
1938	30 May	≈04:00		269d
	03 Sep	≈04:00		96d
1939	- none -			
1940	25 Sep	20:30		753d
1941	- none -			
1942	10 Jul	15:45		653d
1943	- none -			
1944	01 Sep	≈02:45		784d
1945	09 Aug	early am		342d
1946	20 May	early am		284d
1947	"spring"			
	09 Jun			
	22 Jun			13d
	11 Jul			19d
	30 Jul			19d
1948	17 Jul	09:40		

1949	03 Aug	08:15		
	22 Dec	10:00		141d02h
1950	-----			
	02 Jul			

1951	30 Aug			
1952	11 Feb			165d
	07 Apr			56d
	03 Sep			149d
1953	05 Sep	11:00		367d
1954	29 Nov	≈12:15		450d
1955	30 May	early am		183d
	06 Jul	early am		37d
	07 Aug	early am		32d

Year	Date	Time		Interval
1956				
1957				
1958	23 Sep			
1959	-- Mar			
	-- May			
	17 Aug	23:47		
1960	19 Feb			186d
1961	03 Feb			350d
	21 Jun	17:35	Steam	138d
	19 Jul	23:30		28d06h
	15 Sep	09:45		47d05h
1962	31 Jul	17:03		319d07h
	19 Sep	15:00	Steam	49d22h
1963	**18 May**			**244d**
	26 Sep	14:14	Steam	130d09h
	10 Oct	early am	Water	14d16h
	17 Oct	10:15	Water	7d06h
	-- Nov			
1964	- none -			
1965	-- Sep			
1966	01 Mar			
	24 Mar			23d
1967	03 May	08:50	Water	405d
1968	28 Jan	09:15		270d00h
	03 May	early am	Water	95d20h
1969	13 Mar			314d
	28 Jun	07:00ie	Steam	107d
	12 Jul	≈08:00	Mixed	14d01h
	28 Jul	08:25	Steam	16d01h
	12 Aug	am	Steam	14d15h
	15 Sep	07:20ie		35d03h
	03 Dec	12:50		78d05h
1970	13 Feb	11:05	Water	71d22h
	20 Feb	08:50ie	Water	6d22h
	01 Aug	10:00	Steam	162d01h
	28 Aug	am	Water	27d20h
1971	02 Nov	15:05 ie		52d09h
	12 Nov			≈10d
1972	07 Jun	17:21		≈208d
	23 Jul	22:40		46d05h
	15 Dec	midday		≈144d12h
1973	19 Feb	08:10ie		≈58d
	23 May	07:50 ie		93d00h
	02 Aug	07:30 ie		70d 23h
	11 Sep	09:45	Steam	40d02h
	06 Nov	am ie	Steam	≈55d22h
1974	07 Jan	16:18	Water ?	≈62d10h
	19 Jan	09:50ie	Water ?	11d18h
	18 Feb	09:10 ie	Water	29d23h
	16 May	15:55	Water	87d07h
	10 Jul	≈09:47	Mixed	54d18h
	31 Oct	05:16	Water	112d19h
	29 Nov	16:33ie		29d11h
	08 Dec	am		≈8d12h
1975	12 Mar	21:06		≈94d16h
	28 Mar	05:59ie		15d09h
	14 May	16:02		47d10h
	29 Jun	08:22		45d16h
	10 Jul	01:25 ie	Steam	11d17h
	02 Aug	05:05 ie	Steam	23d04h
	15 Aug	16:33 ns		13d11h

	-----			
	19 Dec	09:30 ie	Steam	
1976	20 Jan	08:57 ie	Water	28d
	03 Mar	15:40 ie	Water	43d07h
	31 Mar	20:10 ns	Mixed	28d05h
	02 May	08:20	Water	31d12h

Year	Date	Time		Interval
	06 Aug	08:06	Steam (Induced?)	97d00h
	29 Aug	08:16	Mixed	23d00h
	09 Sep	11:25	Mixed	11d03h
	16 Sep	09:48 ie	Water	6d22h
	14 Oct	15:00	Mixed	28d05h
	07 Nov	09:00 ie	Steam	33d19h MST
	≈17 Nov			≈10d
	12 Dec	≈12:30	Mixed	≈25d
	24 Dec	08:45	Steam	≈11d20h
1977	13 Jan	early am	Mixed	≈19d21h
	18 Jan	10:18	Water	≈5d04h
	05 Feb	12:52	Water	18d03h
	18 Feb	11:55	Water	12d23h
	27 Mar	19:00 ie	Steam	37d07h
	07 May	23:31	Steam	41d04h MDT
	18 May	20:28	Steam	10d21h
	26 Aug			100d
1978	- none -			
1979	11 Jan			502d18h MST

1980	19 Feb	23:17	Steam	
	11 May	16:34	Mixed	81d16h MDT
	17 Aug	17:13	Steam	98d01h
	31 Aug	08:52	Mixed	13d16h
	22 Sep	05:37	Steam	20d21h
	29 Sep	02:09	Mixed "Induced"	6d21h
	11 Oct	19:35	Steam	12d17h
	21 Oct	16:55	Steam	9d21h
	31 Oct	08:53 ie	Water ?	9d16h
	11 Nov	09:16	Steam	11d01h MST
	24 Nov	12:14		13d03h
	16 Dec	04:56	Mixed ?	21d17h
	28 Dec	08:48	Water	8d04h
1981	14 Jan	10:54	Steam	17d02h
	23 Jan	13:12	Steam	9d02h
	04 Feb	08:00ie		11d20h
	23 Feb	17:03	Steam	19d09h
	08 Mar	11:19	Mixed	12d18h
	20 Mar	02:57	Water	11d16h
	02 Apr	01:35	Mixed	12d23h
	23 Apr	09:40	Water	21d08h
	04 May	08:30 ie	Water	10d23h
	25 May	19:30	Steam	21d11h
	12 Jun	04:04	Mixed	17d09h
	23 Jun	05:49	Water ?	11d02h
	04 Jul	21:12 ie	Mixed	1d15h
	19 Jul	10:57	Water	14d14h
	01 Aug	21:36	Mixed	13d11h
	16 Aug	10:41	Mixed	14d13h
	06 Sep	19:39	Mixed	21d09h
	17 Sep	17:37	Water	10d22h
	08 Oct	03:28		20d10h
	21 Oct	08:50 ie		13d05h
	27 Nov			37d
	12 Dec	≈08:00		15d
1982	12 Jan	09:05	Water	18d10h
	30 Jan	21:00	Water	18d12h
	09 Feb	00:15	Water	9d03h
	01 Mar	11:08	Mixed	20d11h
	15 Mar	01:07	Steam	13d14h
	20 Mar	07:56	Abort	5d07h
	21 Mar	16:37	Water	1d09h
	29 Mar	01:17		7d09h
	03 Apr	00:50		5d00h
	08 Apr	09:39	Water	5d09h
	12 Apr	21:32	Water	4d12h

Year	Date	Time		Interval
	18 Apr	08:11	Water	5d11h
	29 Apr	11:15	Mixed	11d02h MDT
	07 May	09:56	Water	7d23h
	15 May	20:12	Mixed	8d10h
	25 May	15:44	Water	9d20h
	01 Jun	11:42	Abort	6d20h
	10 Jun	12:47	Water	9d01h
	17 Jun	15:00	Water	7d02h
	01 Jul	14:55	Mixed	14d00h
	19 Jul	14:37	Steam	18d00h
	31 Jul	22:39	Mixed	12d08h
	18 Aug	22:33	Water	18d00h
	29 Aug	00:58	Water	10d02h
	14 Sep	18:18	Mixed	16d17h
	23 Sep	12:47	Water	8d18h
	03 Oct	11:55	Water	9d23h
	24 Oct	01:07	Steam	20d13h
	31 Oct	00:46	Mixed	7d00h
	08 Nov	06:36	Mixed	8d07h MST
	14 Nov	19:46	Water	6d13h
	01 Dec	17:13	Water	16d21h
	09 Dec	09:11	Water	7d16h
	19 Dec	22:32	Water	10d13h
	27 Dec	05:44	Water	7d07h
1983	03 Jan	08:26		7d03h
	09 Jan	17:40		6d09h
	18 Jan	21:01	Mixed	9d03h
	26 Jan	04:32	Mixed	8d08h
	04 Feb	18:47	Mixed	9d14h
	13 Feb	15:03	Abort	8d20h
	20 Feb	18:09	Water	7d03h
	08 Mar	01:55	Abort	16d08h
	12 Mar	15:58	Water	4d14h
	20 Mar	09:56	Abort	7d18h
	25 Mar	03:11		4d17h
	02 Apr	21:48		8d19h
	11 Apr	13:07		8d15h
	07 May	05:42	Steam	25d16h MDT
	13 May	06:25		6d01h
	18 May	19:43	Abort	5d13h
	21 May	23:46	Steam	3d04h
	25 May	22:32	Abort	3d23h
	31 May	02:10	Mixed	5d03h
	08 Jun	01:16	Water	7d23h
	18 Jun	22:15	Water	10d21h
	27 Jun	07:40	Abort	8d09h
	03 Jul	09:50	Water	6d02h
	10 Jul	10:21	Abort	7d01h
	13 Jul	07:21	Steam	2d21h
	19 Jul	08:06	Abort	6d01h
	22 Jul	13:03	Water	3d05h
	05 Aug	15:36	Mixed	14d03h
	11 Aug	12:41	Abort	5d21h
	17 Aug	12:56	Steam	6d00h
	26 Aug	01:45	Mixed	8d13h
	04 Sep	19:28	Mixed	9d18h
	13 Sep	19:47	Mixed	9d00h
	18 Sep	03:42	Abort	4d08h
	25 Sep	01:19	Abort	6d22h
	03 Oct	15:02	Water	3d14h
	10 Oct	12:46	Abort	6d22h
	13 Oct	21:57	Mixed	3d09h
	22 Oct	00:37	Water	8d03h
	31 Oct	08:58	Water	9d08h MST
	10 Nov	02:19		10d18h MDT
1984	14 Oct	20:06	Steam	340d17h MST
1985	18 Jan	08:50 ie	Water	95d14h
	11 Feb	23:34	Water	24d14h MDT
	31 May	22:11	Steam	108d22h

Year	Date	Time		Interval
	09 Jul	20:51	Mixed	38d23h
1986	26 Jun	22:43	Mixed	352d02h
	15 Jul	01:26	Steam	18d12h
1987	17 Feb	12:30	Steam	217d02h MST
	14 Mar	20:30 ie	Mixed	25d08h
	04 Apr	16:10 ie	Mixed	20d20h
	12 Dec	early am	Steam	259d16h
1988	08 Jul	08:58	Steam	157d05h MDT
	28 Aug	14:18	Mixed	51d05h
	18 Sep	16:31	Water	21d02h
1989	27 May	07:22	Mixed	250d15h
	07 Jun	21:01	Mixed	11d14h
	24 Jun	18:38	Mixed	16d22h
	19 Jul	00:51	Water	24d06h
	07 Aug	05:44	Mixed	19d05h
	15 Sep	08:57	Mixed	39d03h
	04 Nov	03:46	Mixed	50d20h MST
1990	10 May	07:30	Induced	187d04h MDT
	29 Jun	20:59	Mixed	60d13h
	12 Jul	20:10	Mixed	12d12h
	05 Nov	23:40		116d05h MST
1991	19 May	18:20 ie	Steam	225d18h MDT
	09 Jun	07:53	Water	20d13h
1992	25 Mar	08:05 ie	Steam	290d00h MST
1993	04 May	17:44	Mixed	405d10h MDT
	12 Jun	11:31 ns	Mixed	38d18h
	19 Jul	10:55	Water	36d23h
	02 Aug	02:06	Water	13d15h
1994	11 Jul	09:25	Steam	343d07h
	01 Oct	20:20	Mixed	82d11h
1995	18 Jan	01:17	Steam	108d05h MST
	28 Sep	02:02	Mixed	253d01h MDT
	09 Nov	09:57	Water	43d08h MST
1996	13 Oct	12:10		339d02h
1997	10 Apr	02:47		178d15h

Pre-Eruptive Behavior of Oblong Geyser

Carl M. Bender and Daniel E. Bender

ABSTRACT: This paper details a preliminary study of the pre-eruptive patterns of Oblong Geyser. Its purpose is to describe those patterns indicative of an eruption, and to propose a methodology for studying Oblong in the future.

This paper presents a preliminary study of Oblong Geyser. It is based on a small data set collected during the seven day span of August 11 - 17, 1994. During this period, we observed six eruptions of Oblong Geyser and nearly twenty hours of pre-eruptive behavior. After an eruption, the pool fills slowly, requiring about 2 hours. Once the pool is full, Oblong can display two types of behavior. One is a regular series of periodic rises and falls in the level of the pool. Each cycle lasted about 18 minutes. During the other mode, the pool can remain at a relatively unchanging level for an extended period of time. While eruptions can occur directly after a long sequence of 18-minute cycles, we observed that most begin only after one or two 18-minute cycles following the geyser's recovery from a one to two hour period of unchanging pool level.

The level of Oblong's pool is most easily judged by comparing it with the array of geyserite islands at the left side of the pool as it is faced from the boardwalk. The two front islands closest to the boardwalk become covered with water when the pool is especially full. We abbreviated this event as **IC** -- islands covered. When the water level in the pool begins to drop, abbreviated as **D**, these islands become clearly visible and both **LCO** (left channel overflow) and **RCO** (right channel overflow) cease. Times when overflow completely stops is designated by **COO** (channel overflow off). Finally, if a **DD** (deep drop) of the pool level occurs, a sinter bridge appears to connect the two front islands.

In summary, our terminology is:

LCO --- left channel overflow
RCO --- right channel overflow
IC --- sinter islands covered
COO --- channel overflow off
D --- pool level drop
DD --- pool level deep drop

Pre-Eruptive Modes

We observed two distinct modes of pool behavior in Oblong. These were:

Mode I. Level Pool --- This phase may last from one to several hours. The water level in the pool seems almost unchanging. It is high enough for continuous RCO and LCO, but not for IC. However, after careful observation, we found that the pool level actually rises extremely slowly but steadily, especially toward the end of the level pool phase. The end of the level pool is marked by a notable drop in the level of the pool, and sometimes we observe that this drop is enough to cause CO. At this point the second pre-eruptive phase begins.

Mode II. Oscillating Pool --- This phase is characterized by a cyclic rise and fall in the level of the pool. The time required to complete a cycle is remarkably constant, usually deviating only a few seconds from 18 minutes. During each cycle the water level rises slowly until it reaches a peak about 16 to 17 minutes into the cycle. Then either there is a sudden and rapid drop in the level of the pool, or the geyser erupts. It takes only about one minute for the pool to reach its nadir.

In timing the length of the cycle, it is most convenient to measure the time from D to D because the drop is so precipitous that there is little room for error. Based on the surface area of the pool, we estimate, that during a drop, the total volume of water ebbing back into the system is between 1500 and 3000 gallons, a flow amounting to 25 to 50 gallons per second.

The following data obtained on August 16 illustrates the Oscillating Pool mode:

11:23 D
11:33 COO
11:36 LCO and RCO
11:48 IC
11:49 general runoff over sinter between LC and RC

11:50 D
11:51 COO
11:57 LCO
12:00 RCO
12:06 IC
12:06 slight runoff over sinter between LC and RC
12:08 D
12:10 COO

12:13 LCO
12:18 RCO
12:25 IC
12:26 D
12:28 COO
12:31 LCO
12:35 RCO
12:43 IC
12:44 D

We observed that as this cyclic mode continues, periods may lengthen slightly and the drops may become very deep. After a deep drop (or two), if the geyser does not erupt then, it will change over to the Level Pool mode. This is illustrated by data obtained on August 17 shown in the table below. Note that the cyclic overflow period lengthened to 20 minutes and deep drops developed just before the Level Pool mode began. The resumption of the Oscillating Pool mode was back to 17 to 19 minute intervals.

D or DD	Interval (m)	COO	LCO	RCO	IC
10:41 (D)		10:43	10:45	10:45	10:57
10:59 (D)	18	11:01	11:06	11:06	none
11:18 (D)	19	11:20	11:26	11:27	11:34
11:36 (D)	18	11:38	11:46	11:48	11:53
11:55 (D)	19	11:57	12:03	12:06	12:12
12:14 (D)	19	12:15	12:20	12:21	12:30
12:32 (D)	18	12:34	12:40	12:43	12:49
12:52 (DD)	20	12:54	13:03	13:03	13:07
13:12 (DD)	20	13:13	13:28	13:29	none
15:14 (D)	122	none	---	---	---
15:23 (D)	9	15:24	15:29	15:33	15:37
15:40 (e)	17	eruption			

Table showing the timing of events during the Oscillating Pool–Level Pool–Oscillating Pool–Eruption sequence on August 17, 1994

Questions for Future Study

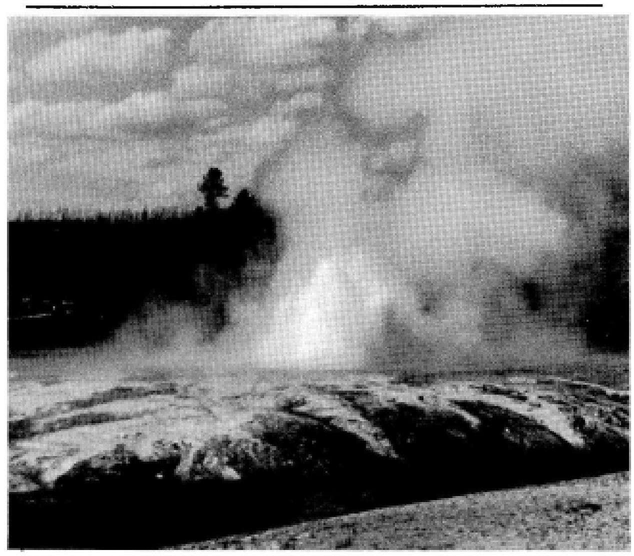
Oblong Geyser has undergone a number of dormancies and episodes of erratic activity in the past few years. This study took place during a few months during which there were relatively regular and frequent eruptions. However, all known observers during previous active phases have observed cyclic overflow. Therefore, a resumption of regular activity is likely to exhibit the same cyclic as those seen in 1994. We generated four questions to be answered by future studies:

1. Is the 18-minute cycle constant throughout a season, or does it vary either seasonally or annually? Previous observers have often discussed 20-minute cycles. Perhaps we observed unusually short interval cycles.

2. Do either eruptions or hot periods of Giant Geyser effect the pre-eruptive pattern of Oblong Geyser? We have no data whatsoever for this, but we have observed that marathon eruptions of Grotto Geyser have no apparent effect on this geyser.

3. Is it possible from detailed observation to predict the eruption time of Oblong Geyser on the basis of an overflow pattern? The amount of runoff in the channels on the sinter platform in front of Oblong did not help us to make such a prediction; we observed one eruption of Oblong after many hours of overflow, when all the channels were running heavily, but we also saw one when most of the channels were dry.

4. What kinds of temperature changes and convection currents occur in the pool during the Oscillating Pool mode, and are there any such changes during the Level Pool mode? This study will need close cooperation with government personnel as it would require significant off-trail work.



OBLONG GEYSER Paperiello Photo

Probabilistic Geyser Gazing: Sprinkler Geyser, 1992-1995

Castle Group, Upper Geyser Basin, Yellowstone National Park, Wyoming

Gordon Bower

Abstract

Historical reports characterize Sprinkler geyser as a frequent but erratic performer. Observations in recent years have shown its eruption pattern to be regular and have revealed an annual increase and decrease in the level of activity. Two uncommon statistical approaches to geyser study are applied to Sprinkler data and compared with more traditional methods.

Introduction and Historical Review

Sprinkler Geyser is perched on the west bank of the Firehole River, about 100 meters northeast of Castle Geyser. It includes a main crater two to three meters across, and numerous subsidiary vents.

The 1878 Hayden survey mapped Sprinkler but apparently recorded no details of its activity. Walter Weed probably named it in the 1880s; he also enumerated five of the small springs nearby. Around the same time, Arnold Hague reported irregular intervals and a height of "5 feet [1½ meters]. . . at times reported to be at least twice this height." There is also a 1927 reference to a "Motor Geyser" of similar description and position [Whittlesey 1988].

Marler [1973] noted that "it erupts several times daily. However, if there is any regularity it has not yet been determined. The heights of the eruptions are about 10 feet [3 meters]; their durations unknown. . . . Both it and a small vent nearer the river became noticeably more active the first few weeks following the [1959] earthquake." Bryan [1979 and 1991] said the eruptions varied in length from five minutes to several hours, but that pauses between them were consistently 20 to 40 minutes[1]. Whittlesey [1988] states, "in recent years, Sprinkler has erupted to heights of 4-15 feet [1¼-4½ meters] every 15-30 minutes for 15 minutes to 3 hours." The one thing on which all published sources concur is that Sprinkler has received little attention and almost no serious study. All sources up to 1991 also report irregular intervals but no dormancies. (However, a dormancy in the early to mid-1920s could account for the appearance of the supposedly new "Motor Geyser" at the same site.)

Stephens [1995] observed Sprinkler for two hours on 22 December 1991, seeing intervals of 24-27 minutes and durations of 8-10 minutes. She wrote, "contrary to what Marler indicates, I do seem to remember regularity when I briefly watched it." Sprinkler was in eruption less than half the time when she observed it; this seems to be quite rare.

This study found Sprinkler to have intervals of 20-30 minutes and to be in eruption half to two-thirds of time. Eruptions started suddenly and the strongest bursts, 3-4 meters high, occurred in the first few minutes of the eruption. This gradually gave way to gentle

[1] "Interval" is used in this paper to denote the time elapsed between the starts of consecutive eruptions. This is the meaning entrenched in common usage. A more formal but less widely used approach, used by Bryan [1979,1991,1995a], is to call this a "period," defining "interval" as the time from the end of one eruption to the start of the next.

splashing and tapered off into a quiet interval. No cyclic behavior on the hours-to-days scale was noted.

The 1995 edition of Bryan was revised to reflect the new activity: "In 1993 the action was quite regular, with both [end-to-start] intervals and durations around ten minutes, so that Sprinkler was in eruption about 60% of the time." He also said that Sprinkler is probably cyclic, but did not elaborate upon his remark.

Theoretical Background: Geyser Statistics and %IE

Published reports of geyser activity often include some number of summary statistics. The most commonly reported values are mean duration and interval and their respective standard deviations. Sometimes medians, quartiles, minima and maxima, confidence intervals and the like are reported — but again, the focus is on two variables, the interval and the duration.

An important question concerning geyser behavior that lends itself to statistical treatment is, "Is Geyser X more or less active now than it was last year (last month, before the earthquake, etc.)?" To perform this test, 'activeness' must be quantified. Sometimes this is easy, but not always. For instance, Little Cub Geyser's average interval dropped from 82 to 68 minutes between 1991 and 1992. . . but the average duration dropped from 11½ to 10¼ minutes, too. Little Cub became more frequent, but does this reflect more energy, or just different timing?

The simplest solution, assuming no dramatic change in height, discharge, etc., has occurred, is to compute the percentage of time in eruption, i.e., Duration ÷ Interval. There are three ways of doing this, presented below in order of preference:

1. If paired data (duration of an eruption, and the interval between that eruption and the next) exist, one can simply find D/I for each pair. The list of values obtained is then a new variable, for which mean, median, standard deviation, 95% confidence interval, etc. can be computed.

2. If there are not sufficient paired data, or only the summary statistics are available, the ratio of mean duration to mean interval can be found. The standard error of %IE can no longer be computed directly from the data, but is given by the well-known formula

[1] $se_{\%IE}=m_{\%IE}((s_D/m_D)^2+(s_I/m_I)^2)^{1/2}$

where m_D=mean duration,
m_I=mean interval,
s_D=standard deviation of duration,
s_I=standard deviation of interval.

The 95% confidence interval (hereafter, "CI") for mean %IE is then $m_D/m_I \pm 1.96 se_{\%IE}$.. All things being equal, method #1 is more powerful than #2, and is to be preferred when possible unless the unpaired observations far outnumber the paired.

3. The third situation is the one of greatest relevance to this paper. What happens if too few accurate durations and/or closed intervals have been obtained to reliably estimate the four quantities needed for the Method #2 equations? If enough "Geyser X was/was not in eruption at ___" observations ("on-off data") have been made, it may still be possible to estimate %IE.

Collection and analysis of the on-off data amounts to flipping an unfair coin, then trying to determine what its bias is. If a geyser is erupting six times out of twenty, one suspects that the geyser erupts roughly 30% of the time. There are two complications: the observations must be made at *random* times for the results to be valid, and computing the margin of error is a rather sticky mathematical problem.

The time-honored statistical shortcut is to use a normal approximation. If the geyser was erupting x times out of n observations, the mean is taken to be x/n and the standard deviation $(x(n-x)/n)^{1/2}$. For sufficiently large x and n, the 95% CI for p, percentage of time in eruption, approaches

$$[2] \quad p = \frac{x}{n} \pm \frac{1.96(x(n-x)/n)^{1/2}}{n}$$

The standard rule of thumb is to use the normal approximation to a binomial distribution only if $n>30$ and $5<x<n-5$. Within these limits, the largest possible error due to approximation is 3.5%. (When $n>30$ but $|n-x|\leq 5$, a different approximation of similar precision is available.)

However, situations where $n\leq 30$ are common. The problem of small-n CI construction has been considered by Crow [1956]. He evaluated a variety of methods (all of them involving complicated calculation) and tabulated results for an 'optimal' method proposed by Theodore Sterne. For those not interested in Crow's theoretical discussion, his tables of 90, 95, and 99%CIs are reprinted in Daniel [1990] and elsewhere.

The author has created a simplified method which approximates Crow's figures well. Consider the following 'turned-around version' of equation [2]:

$$[3] \quad np \pm z(np(1-p))^{1/2} = x$$

where $z=1.96$ for a 95% interval. This equation can be solved symbolically for p, which is given by the following expression:

$$[4] \quad p = \frac{z^2+2x}{2z^2+2n} \pm \frac{z(z^2n^2+4n^2x-4nx^2)^{1/2}}{2z^2n+2n^2}$$

For instance, a 95%CI for $x=21$, $n=25$ is $.654<p<.936$ by this approximation, as opposed to $.664<p<.943$ from Crow's tables or $.696<p<.983$ from the traditional normal approximation. The traditional method does not take into account the skewness of the binomial distribution; as a result, it yields estimates considerably too far from $p=1/2$. In contrast, the author's method includes a correction — a slight overcorrection, in fact — and will always produce values a little too close to $p=1/2$. For small n the intervals also tend to be too narrow; this can be largely corrected by replacing z by a t value with the appropriate number of degrees of freedom.

The confidence intervals in Table I were computed using [4] and $z=1.96$. When possible, figures taken from Crow are also given as confirmation of the approximation. Anyone interested in the development and justification of [4] is invited to contact the author.

Sprinkler in 1992 and 1993

When this study began in spring 1992, Sprinkler's intervals and durations were unknown. All published references indicated Sprinkler was irregular. This suggested that protracted continuous observations were likely to be frustrating. As an alternative, it was decided to periodically record whether Sprinkler was on or off, and see if a pattern emerged. Originally, the data-collection scheme was: one data point first thing in the morning, one for each hike along the Sawmill-Lion trail, and one immediately following each Turban while waiting for Grand — anywhere from 3 to 20 observations per day. Later, more frequent observations were made, taking advantage of distant but clear views of Sprinkler from much of Geyser Hill, but a single active or quiet period never was recorded as more than one point.

By the time the data were analyzed, it was clear that Sprinkler was actually quite regular. Worse yet, Sprinkler's interval was almost the same as Turban's. Abundant data had been collected — 131 observations in 1992, 221 in 1993 — but in light of what was learned in 1994 and 1995, there was no hope of these data sets fulfilling the "random sample" requirement. The statistical project seemed doomed before the first number had been crunched.

The most common type of artificial data occurred when one point was taken during and immediately after each of several consecutive eruptions, producing an "on-off-on-off-on-off-on" sequence whether the durations were 25% or 75% as long as the intervals. A filter was applied to the data to reduce bias from this source. In 1994 it was found that Sprinkler's status could be predicted about 2 cycles ahead (~50 minutes) based on a single observation, and 3 or 4 cycles ahead based on an accurate start or stop time. Hence, only data points more than an hour after the previous "on-off" observation and more than 1½ hours after a start or stop was seen were used in this paper. Sixty-two observations from 1992 and 87 from 1993 met these criteria and were deemed usable.

Sprinkler was erupting 73% of the times it was checked in 1992, yielding a 95%CI of 60-82%. It seemed to be suspiciously less active in June than in August, but given the 1992 sample sizes, the difference was not significant. The 1993 results paralleled those from 1992: 79% overall, with a 95%CI of 70-86%. Figures for spring were lower than for summer, but again the difference was too small to be significant. No differences between the 1992 and 1993 activity were detected, visually or through the analysis of the data.

Various subsets of data points from these two years were examined, but none of the differences among them was statistically significant. Table I contains summaries of each grouping. The raw data are available from the author upon request.

Data analysis did not take place until the summer of 1995. The computed CIs of 60-82 and 70-86% came as a surprise. Intuitive estimates made in 1992 and 1993 fell on the extreme low end of these CIs. A possible explanation for this difference will be considered below.

A Classical Approach:
Sprinkler in 1994 and 1995

Fifty-one closed intervals were recorded during 1994. They averaged 24m40s in length, ranging from 19 to 30 minutes, with a standard deviation of 2m34s. Including 53 inferred multiple intervals, the average was 24m22s. Twenty-eight intervals from May and June averaged nearly 26 minutes, while the 23 from July and August averaged only 23m10s. The difference between spring and summer intervals was statistically significant.

Only ten accurate durations were obtained in 1994. The range was 11 to 17 minutes, averaging 12m39s. Recorded spring durations were longer than summer ones, but there were too few data to determine if the difference was significant. The intuitive estimate made during data collection was that Sprinkler was much less active than before, erupting only half the time instead of two-thirds.

Forty-three additional intervals were recorded in May and June 1995. The mean was 26m13s, with a standard deviation of 2m23s and extrema of 19 to 33¾ minutes. Six durations of 11 to 14½ minutes, averaging 13m15s, were recorded. Summary statistics organized by month, season, and year are presented in Table II.

The spring 1995 data as a whole do not differ significantly from spring 1994. However, in 1994, May intervals were much higher than June's, and vice versa in 1995. A possible explanation for this is discussed below.

Testing the Probabilistic Method

The purpose and method of data collection in 1994 and 1995 was different from that of 1992 and 1993, focusing on intervals rather than random observations. However, in an effort to test the reliability of the probabilistic method, a sample of 53 on-off observations from 1994 was extracted, using the filtering scheme applied to the 1992-93 data. These data showed most of the same features noted in the classical analysis: greater activity in summer than spring, and noticeably less activity in 1994 than in 1992-1993. When data from all three years were pooled, the spring-summer difference was significant.

The 1994 data afford an opportunity for a head-to-head comparison of methods 1, 2, and 3 for determining %IE. Method 1, using nine paired observations, gave an estimate of 51.0%, with a 95%CI of 45.2-56.8%. Method 2, based on 10 durations and 51 intervals, produced an estimate of 51.3%, with a 95%CI of 45.4-57.2%. However, the probabilistic method estimated 62%, with a 95%CI of 48.8-74.1%.

This comparison offers reassurance that the probabilistic method was able to detect the changes that took place between 1993 and 1994. The "right" answer of 51% did fall within the 95%CI — barely. However, the estimates of %IE from this method are consistently several percentage points too high. Why? The most likely culprit is human nature: Sprinkler's status was recorded when an observer happened to look at it, and Sprinkler was more likely to attract attention when erupting than when quiescent. A well-designed data collection scheme must weed out as much observer bias as possible; the 1992 scheme gave the observer a little bit too much freedom to choose when to collect data points. As a result, the data in this paper are bound to somewhat overstate %IE.

Average Interval in 1992 and 1993

The 1992 and 1993 data were collected without knowing the pattern of Sprinkler's intervals and durations. In 1994 it became clear that Sprinkler was highly regular. Assuming Sprinkler showed the same degree of regularity in 1992 and 1993, could the average intervals for these years be extracted from the on-off data?

A statistical method known as autocorrelation can be used to search for cyclic patterns in time-series data. Traditionally, one collects a continuous series of observations, then computes the correlation coefficient between adjacent data points, between data points two time units apart, three time units apart, and so on; see Chapter 4 of Davis [1986] for a more complete discussion. A plot of correlation coefficient vs. time lag will reveal a tendency of a system to return to the same state after a fixed period of time.

This technique can be adapted to the analysis of scattered on-off data. Here is how a sample data set (16 August 1992: on at 1142, on at 1221, off at 1304, on at 1402) was processed. Sprinkler was doing the same thing at 1221 as it was 39 minutes before, so tally a score of +1 for t=39. Similarly, add one of the scores of t=140 (1142 to 1402) and t=101 (1221 to 1402), but subtract one from t=82 (1142-1304), 43 (1221-1304), and 58 (1304-1402). When enough data points have been examined, clusters of positive and negative scores emerge. Random samples produce a tidier graph, but are not necessary in order for the method to work.

Figure 1 is a rough autocorrelogram constructed from the 131 on-off observations made in 1992. (In a true autocorrelogram, the plus and minus tallies would have to be converted to some strength-of-correlation measure.) The scores were lumped into five-minute blocks. This figure shows positive scores at time lags around 30, 55, 80, and 105 minutes—1, 2, 3, and 4 intervals. Similarly, lags of 15, 35-40, 70, and 95 minutes— ½, 1½, 2½, and 3½ intervals— show negative scores. This indicates that Sprinkler's 1992 average interval was 26 or 27 minutes. The standard deviation must also have been quite low (probably 1 to 2 minutes) for the pattern to persist through four cycles.

Figure 2 is a similar plot constructed from the 1993 data, with scores lumped into three-minute blocks. There are clear maxima at

24-27 and 51 minutes, and minima at 12-15 and 36 minutes. Less distinct high (69-75, 93-102) and low (54-60, 78-90) zones alternate at longer lags. This indicates an average interval near 25 minutes. The decay of a clear pattern after two cycles suggests a higher standard deviation, perhaps 3-4 minutes.

During this study, only one duration (14 minutes) and one interval (25 minutes) were obtained in 1993. Bryan [1995a] reported durations and (end-to-start) intervals in the neighborhood of ten minutes. These observations provide confirmation of the autocorrelation results.

Seasonal Variations

Sprinkler behaved similarly in each of the four years it was observed. But in all four years, there was a tendency toward longer intervals and lower %IEs in the spring.

A possible explanation for this could be an influx of water from the Firehole River. This explanation was suggested by a sudden jump in Sprinkler's intervals around 25 May 1995 which coincided with a rise of ~15 cm in the river level. Several small seeps and spouters dot the riverbank between Sprinkler's vent and the waterline, providing a plausible entry point for river water.

A U.S. Geological Survey stream gaging station on the Madison River at West Yellowstone, Montana was the nearest source of streamflow data available. (Under normal circumstances, Firehole River flow at Upper Geyser Basin ought to be roughly proportional.) In a typical year, a flow of around 11000 L/s (400 ft^3/s) prevails from August through April. Sometime in May, this doubles, triples, or even quadruples in the space of a few days, then gradually declines to the minimum over a period of about two months. Occasional day-to-day changes of up to ±20% add 'hiccups' to this pattern. Sprinkler's springtime activity declines have roughly coincided with high water in each of the past four years. Activity fluctuations have not been observed at other times when the river level has been stable; however, significant changes could easily have gone unnoticed in the fall and winter.

Peak streamflow was 26000 L/s in 1992, 59000 L/s in 1993, and 29000 L/s in 1994. Flow returned to 11000 L/s by mid-July in 1992 and 1994, but remained at 12-14000 L/s until October 1993. The magnitude of the effect on Sprinkler does not seem to depend on the exact water level. This may indicate that water enters through a single vent, which is submerged whenever streamflow at West Yellowstone exceeds about 17000 L/s.

What volume of river water would be required to account for changes in %IE? Assume that the deep heat source for Sprinkler is constant, that the eruption consists of a mixture of deep hot water and cold shallow water, and that no heat loss occurs when an eruption is not in progress. According to Fournier [1992], water-rock equilibrium is achieved for the last time in a reservoir at roughly 200°C. Water at this temperature has a heat content of 852 kJ/kg [all thermodynamic data from Weast 1989]. Water boils at 93°C in Yellowstone; at this temperature, liquid water has a heat content of 389 kJ/kg and steam 2669 kJ/kg. If no water flashes to steam at the surface, no eruption occurs; if water rose from a 200°C reservoir to the surface with no heat loss, 20.3% would flash to steam. For simplicity's sake, assume that 10% of the water involved in Sprinkler's eruption flashes to steam at the surface, i.e., the water has a heat content of 617 kJ/kg as it nears the surface. Sprinkler's discharge is impossible to measure and difficult to estimate. Again for simplicity's sake, suppose it is 100 L/min while erupting, 0 L/min while not. Based on these estimates and that Sprinkler was in eruption 51% of the time in 1994, Sprinkler's average energy usage is 525 kW, and each 1% change in the %IE figure corresponds to a 10.3 kW change in available power. Heating 10°C river water to

93°C requires 357 kJ/kg. Therefore, the estimated influx would be 1.7 L/min for each 1% change, or a total of 10-15 L/min. This is only a ballpark estimate, but it suggests that the springs in the riverbank below Sprinkler are the right size to act as a conduit.

There are several alternative explanations. Surface water might enter the plumbing system through another route. Bryan [1992 and 1995b] has proposed an annual basin-wide increase in activity in late summer. It is also possible (but unlikely) that similar random month-to-month variations took place in all four years.

How could the river-leakage hypothesis be tested? Careful observations of Sprinkler's activity and the river level could be made (Sawmill's runoff channel is a nice "gaging station"). Water samples could be collected from Sprinkler to see if dissolved mineral concentrations become more dilute at times of high water. A careful inspection of the bank and bed of the river could be made to try to locate the vent(s) responsible.

Conclusions about the Method

The most important advantage of the probabilistic approach is the small time investment in data collection. Data collection in 1992 and 1993 combined took barely one hour, yet the average interval and the %IE could still be determined to a fair degree of accuracy. On the other hand, the analysis is difficult, a very large number of data points need to be collected to obtain high-quality results, and overcoming observer bias is a problem. In addition, it is difficult to mix this style of data collection with traditional geyser gazing.

This method is probably best suited to situations where traditional geyser gazing is impractical and a suitable sampling scheme can be used. Winter observations of the Lower Geyser Basin could be reported to the visitor center by snowcoach drivers in this way ("We saw Fountain and Till this morning, but not Kaleidoscope, White Dome, Great Fountain, or Flood") and subjected to a Sprinkler-like analysis to obtain winter season statistics. Geysers with very long durations and intervals, such as Spouter Geyser at Black Sand Basin or Palpitator Spring at Norris, might also be good candidates.

More generally, geyser gazers need to realize that recording times at which a geyser is *not* in eruption is almost as important as recording when it is. This study has carried this concept to its logical extreme. Even a logbook entry as simple as "Artemisia: no eruption during daylight hours" is much more meaningful than a blank line.

Conclusions about Sprinkler

Sprinkler is presently a small but highly regular performer, in eruption about half the time. It has changed slightly from year to year, but overall has acted similarly throughout the 1990s. A significant change in its behavior took place sometime after Marler wrote the *Inventory*, but so little attention has been paid to Sprinkler that it may never be known how, why, or when the change took place. It is hoped that such changes in the future will not pass unnoticed.

Sprinkler seems to be susceptible to an annual decrease in activity in the spring and reinvigoration in the summer. It is proposed that water leaking from the Firehole River is the cause. However, this hypothesis requires further testing. The fall-winter portion of the annual cycle is as yet unknown.

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Sprinkler Geyser 1982 Paperiello photo

TABLE 1.
Summary of Results — Probabilistic Approach

Time Period	# Off	# On	# Total	%IE est.	Confidence Interval (95%) (Crow [1956])	Approximate CI (Bower [1995])
June 92	6	7	13	54%	26.0-77.6%	29.1-76.7%
August 92	11	34	45	76%		61.3-85.8%
October 92	0	4	4	100%	47.3-100.0%	51.0-100.0%
All 92	17	45	62	73%		60.4-82.1%
May 93	4	11	15	73%	44.8-90.3%	48.0-89.1%
June 93	9	33	42	79%		64.1-88.3%
July 93	2	19	21	90%	72.4-98.3%	71.1-97.3%
August 93	3	6	9	67%	28.9-90.2%	35.4-87.9%
Spring 93	13	44	57	77%		64.8-86.2%
Summer 93	5	25	30	83%	67.6-93.2%	66.4-92.6%
All 93	18	69	87	79%		69.6-86.5%
Spring 92-93	19	51	70	73%		61.4-81.9%
Summer 92-93	16	59	75	79%		68.1-86.4%
All 92-93	35	114	149	77%		69.1-82.6%
May 94	5	9	14	64%	37.1-84.7%	38.8-83.6%
June 94	8	4	12	33%	12.3-65.4%	13.8-60.9%
July 94	2	12	14	86%	61.1-97.0%	60.1-96.0%
August 94	5	8	13	62%	32.7-83.4%	35.5-82.3%
Spring 94	13	13	26	50%	28.2-71.8%	32.1-67.9%
Summer 94	7	20	27	74%	56.3-89.0%	55.3-86.8%
All 94	20	33	53	62%		48.8-74.1%
All May	9	20	29	69%	50.0-83.4%	50.8-82.7%
All June	23	44	67	66%		53.7-75.9%
All July	4	31	35	88%		74.1-95.5%
All August	19	48	67	72%		59.9-81.0%
All Spring	32	64	96	67%		56.8-75.3%
All Summer	23	79	102	77%		68.4-84.5%
All Data	55	147	202	73%		66.3-78.4%

TABLE 2.
Summary Statistics — Sprinkler Geyser

All times in minutes

INTERVALS:	N	Min	Q-1	Med	Q-3	Max	Mean	S.D.	95%CI	N_i	$Mean_i$
May 1994	17	21	25	27	28	30	26.84	2.20	25.7-28.0	21	26.83
June 1994	11	22	23	24	25	27	24.43	1.75	23.3-25.6	32	24.03
July 1994	10	20	21¼	24	24	29	23.43	2.48	21.7-25.2	22	23.44
August 1994	613	19	23	23	24	25	22.98	1.68	22.0-24.0	29	23.69
Spring 1994	28	21	24	25¾	27	30	25.89	2.33	25.0-26.8	53	25.13
Summer 1994	23	19	23	23½	24	29	23.17	2.02	22.3-24.1	51	23.58
All 1994	51	19	23	24	27	30	24.67	2.57	23.9-25.4	104	24.37
May 1995	20	19	24	25	25¾	28	24.72	1.96	23.8-25.6	29	24.81
June 1995	23	25	26	27¼	28	33¾	27.51	1.94	26.7-28.4	31	27.41
Spring 1995	43	19	25	26	28	33¾	26.22	2.38	25.5-27.0	60	26.16
All Spring	71	19	25	26	28	33¾	26.09	2.35	25.5-26.6	113	25.68
All 1994-1995	94	19	24	25	27	33¾	25.38	2.59	24.9-25.9	164	25.02
D RATI NS:											
Spring 1994	6	11	---	13	---	17	13.33	2.06	11.1-15.5	---	---
Summer 1994	4	10	---	11½	---	13½	11.63	1.49	9.2-14.0	---	---
Spring 1995	6	11	---	14	---	14½	13.25	1.41	11.8-14.7	---	---
All 1994	10	10	11	12½	13	17	12.65	1.97	11.2-14.1	---	---
All Spring	12	11	12	13½	14	17	13.29	1.68	12.2-14.4	---	---
All 1994-1995	16	10	11	13	14	17	12.88	1.76	11.9-13.8	---	---

FIGURE 1.

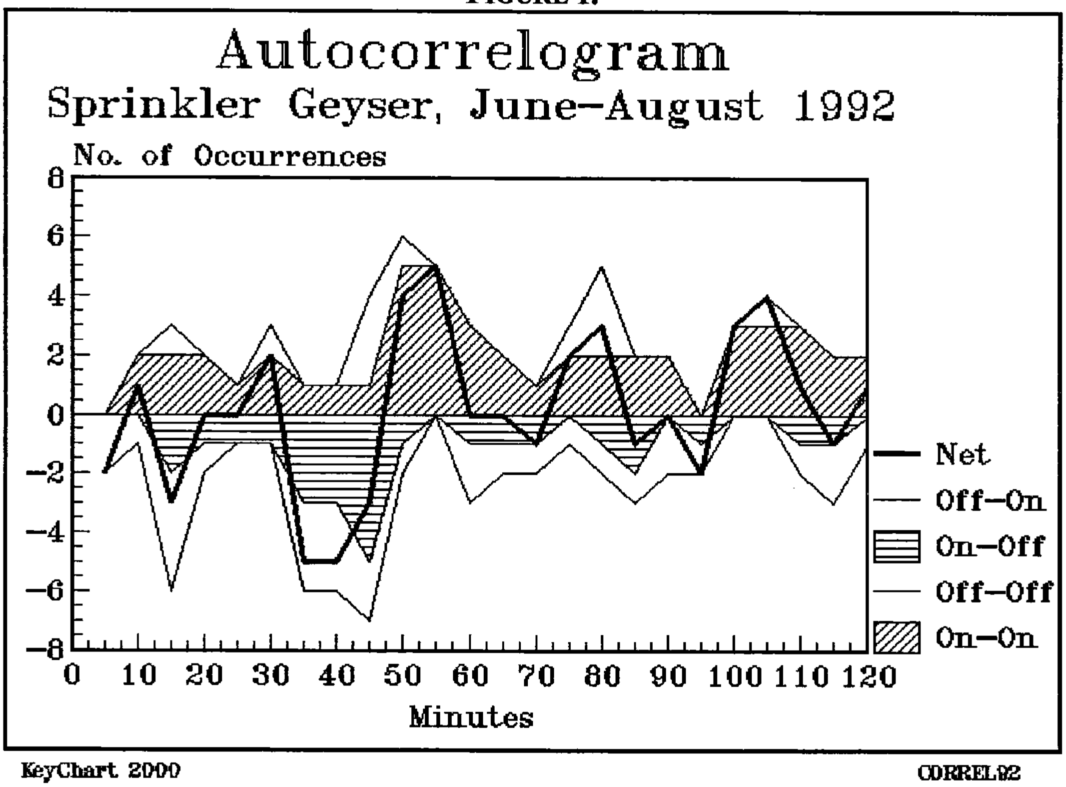
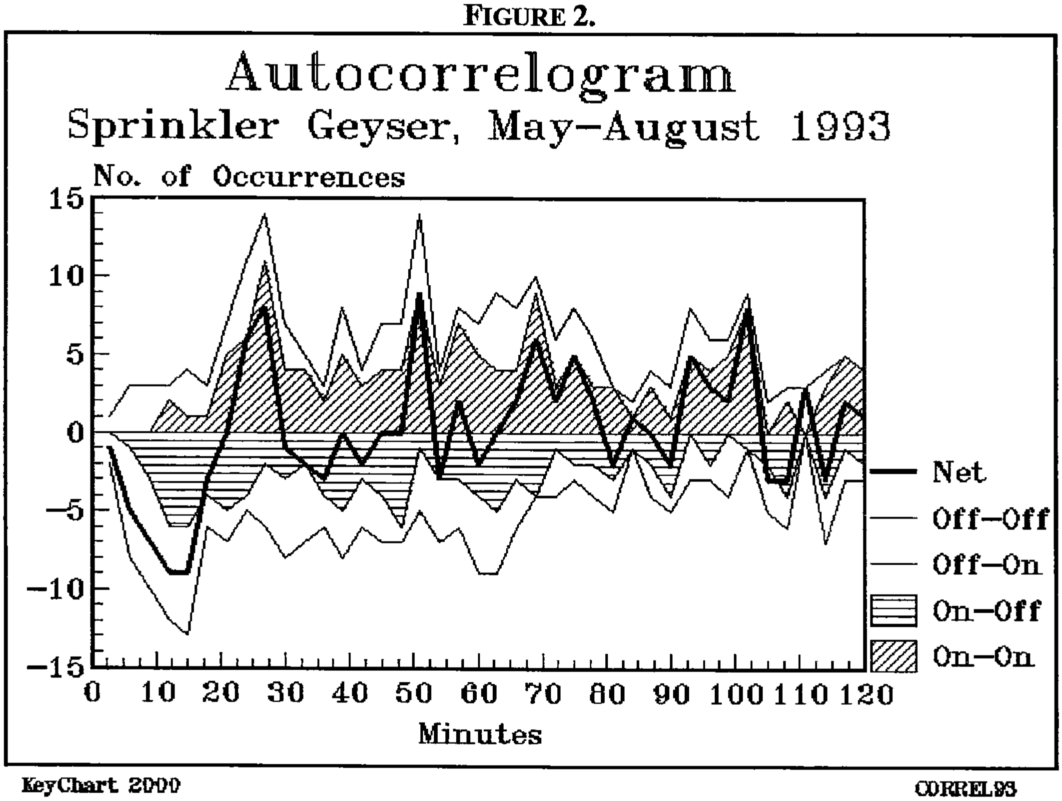


FIGURE 2.



The Rotorua Geothermal Field, New Zealand

Geysers in New Zealand

by

Ashley Cody

Introduction

Prior to the Wairakei geothermal power station and Ohakuri hydroelectric dam constructions in the late 1950s, New Zealand had about 240 geysers. However, by the late 1960s only some 40 of these remained. These losses were directly attributable to human activity, most notable being the building of a geothermal power station at Wairakei 90 kms south of Rotorua (Figure 1), where 70+ geysers disappeared due to severe water level drawdown; and the building of an hydroelectric power dam at Orakeikorako, where ~90 geysers were lost by flooding. In the late 1980s Ohaaki power station was commissioned and one year after, no geysers or flowing alkaline hot springs remained there either.

At Taupo, the Waikato River channel was blasted in the 1950s to facilitate flows, which coincided with the cessation of all geyser activity at Taupo/Spa, along the riverside. At lake Rotomahana, the 1886 AD eruption of Mount Tarawera totally destroyed the Pink and White Terraces, but created the totally new geothermal system of Waimangu Valley; the only geothermal system Worldwide created in historical records?

Today six geysers remain at Waiotapu; several at Waimangu and Rotomahana; a few at Ketetahi (on the northern slopes of Mount Tongariro); at least 26 at Orakeikorako; and 15 at Rotorua.

The Rotorua Geothermal Field

Rotorua city is located on the southern shores of Lake Rotorua, within the Rotorua caldera (Figure 2). This caldera has two active geothermal systems and a now extinct geothermal system once existed beneath the northwestern present day lake. The caldera forming eruption occurred 220,000 years ago and produced the Mamaku Ignimbrite, a weakly welded and gas phase altered deposit of about 200 km^2 volume. Several hills within the Rotorua caldera are rhyolite lava domes, extruded sometime after the last ignimbrite (caldera forming) eruption.

All existing geysers and the greatest number and total outflows of hot springs remaining occur at Whakarewarewa, just inside the southern caldera wall (Figure 3). Today about 65 extinct geyser cones can be seen here, representing prehistorical geysers spanning the past 20,000 years or less.

Whakarewarewa is transected by several identified faultlines which run variously radial and parallel to the caldera wall. Based on geochemistry, downhole geology and pressures, a major fault is recognized and named as the Inner Caldera Boundary Fault. [Wood 1992] This provides some degree of isolation between Whakarewarewa and the main exploited portion of the geothermal system. It is possible that this structure may have saved the geysers of Whakarewarewa from extinction during 1970s-1980s, when the Rotorua geothermal field was at severely depleted water levels and pressures due to excessive and uncontrolled drawoff from numerous hot water wells. In 1986 about 500 wells throughout Rotorua city were producing about 26,500 tonnes per day, rising to 31,500 tonnes per day in winter months. By contrast, total natural spring outflows in Rotorua were estimated at 17,000 tonnes per day in 1985.

Exploitation and Management of the Rotorua Geothermal Field

Before describing Rotorua geysers (see later section), some background on the exploitation and management of the Rotorua Geothermal Field, together with a brief mention of other New Zealand geyser fields, will help outline the situation that lead to the loss of many hot springs and geysers here.

At Yellowstone National Park, Americans have been fortunate in that this was not a prime site for early colonization. By contrast, Whakarewarewa and other thermal areas within the Rotorua Geothermal Field were settled by Maori some time about 1350 years AD or soon after and was a major centre of pre-European settlement. The Maori were quick to

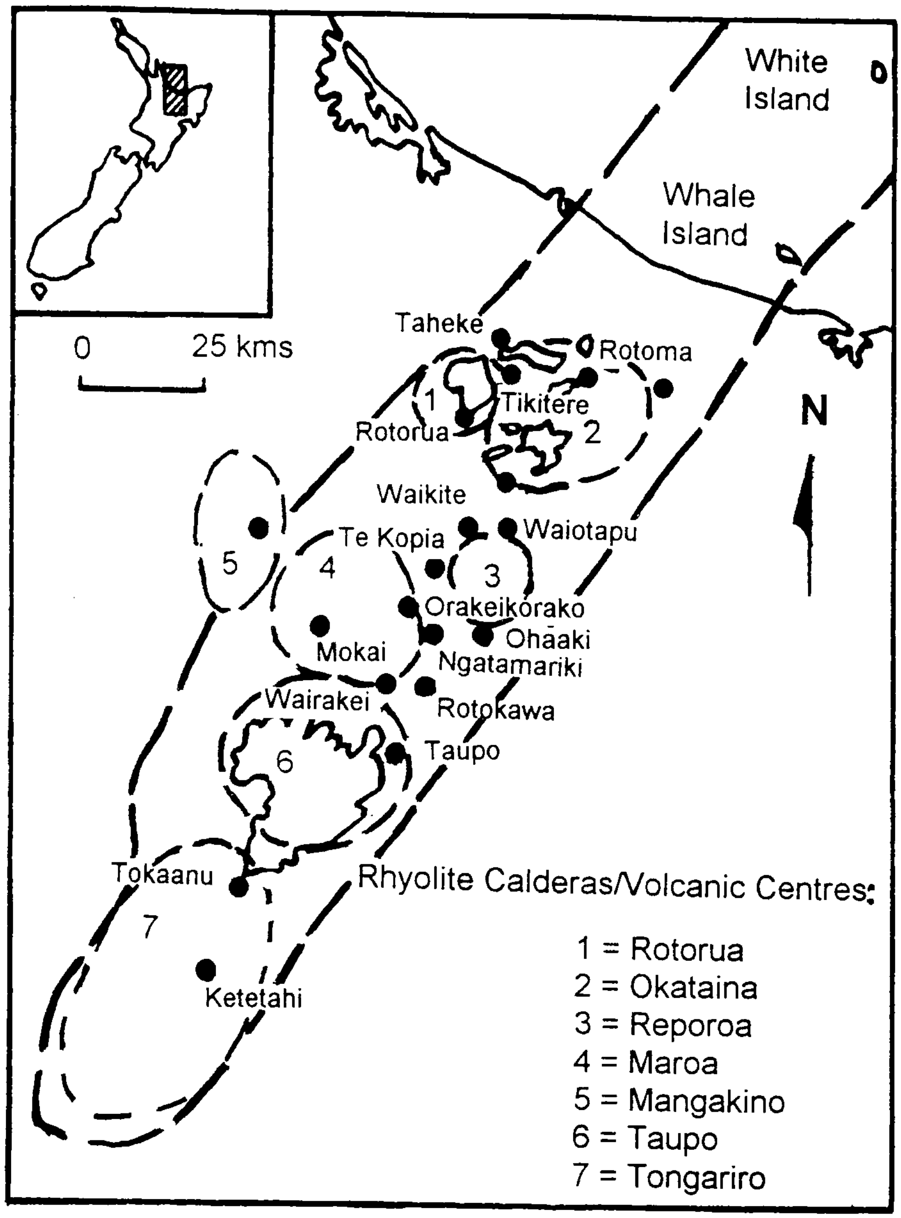


Figure 1: Location of Volcanic Centers and major geothermal fields (>220°C) in the Central Volcanic Zone of New Zealand.

recognize and utilize the hot springs of Rotorua (and other) geothermal areas in New Zealand for bathing, cooking and warmth. However, this invariably entailed using only the outflows of hot springs and not the physical modifications that followed with the European settlers who arrived in the late 19th century.

The establishment of Rotorua as a township resulted from local Maori people readily making land available to the Europeans and by the 1880s the hot springs were being engineered and physically modified to provide hot waters for public bathing pools. By the 1920s drilling for hot water was a common practice and by the 1940s some 45 wells were recorded, collectively producing some 450 tonnes per day of outflows. The competition of hot wells with the natural hot springs and geysers had begun!

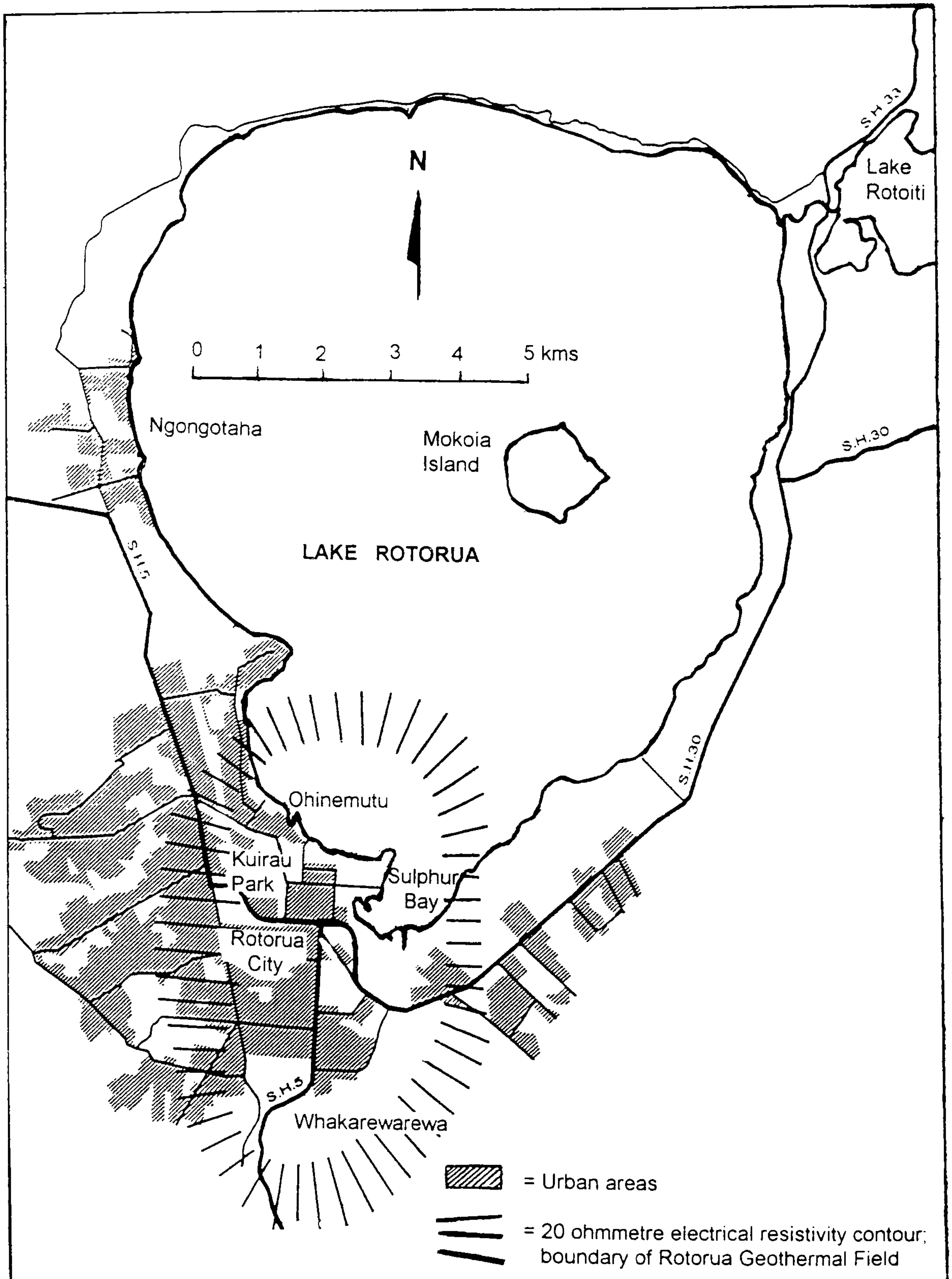


Figure 2: Lake Rotorua and Rotorua city urban areas, with Rotorua Geothermal Field boundaries and areas of surface thermal activity.

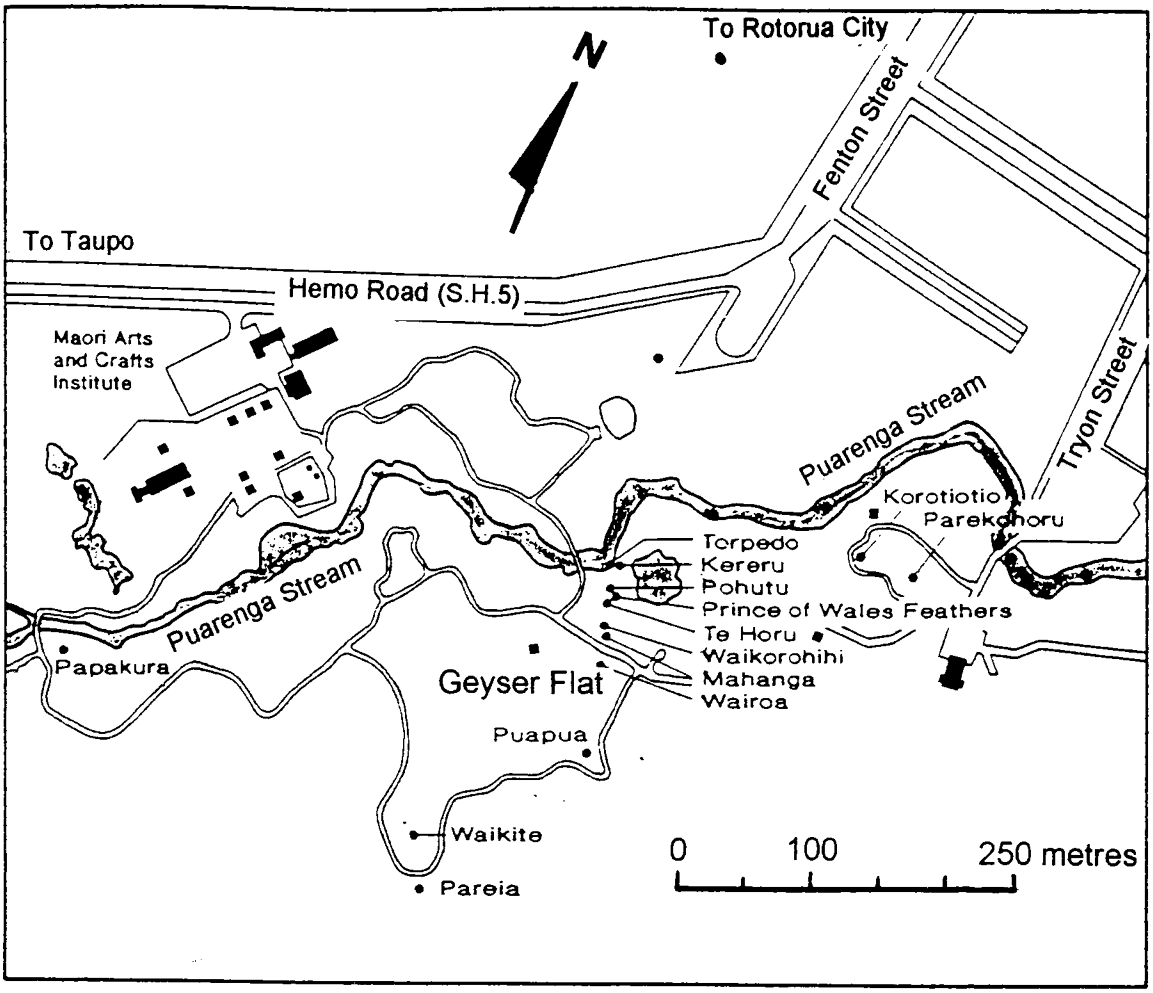


Figure 3: Location of major springs and geysers at Whakarewarewa.

Throughout the 1950s-to early 1980s, steady population growth and increased geothermal exploitation via hot wells lead to progressively declining hot spring flows and loss of geysers. This was a time when there was no management of the Rotorua Geothermal Field whatsoever, yet shortages of electricity in the 1950s encouraged utilization of geothermal heating. In the 1970s, World oil shortages and price rises for oil again resulted in a surge of well drilling in Rotorua. These developments were encouraged by central and local Government of the day.

Concerns and later outright alarm was voiced repeatedly by various scientific researchers, who recognised that failure of flowing springs and cessation of geysers was becoming increasingly commonplace in Rotorua, at rates unprecedented in historical times. Their knowledge and involvement in the exploration and development of the Wairakei geothermal power station, 90 kms (~55 miles) south of Rotorua, in the 1950s, alerted them to similar trends appearing in Rotorua. At Wairakei all (~240) alkaline flowing springs disappeared 2-3 years after power production began and some 70+ geysers were destroyed.

By 1981 Central Government intervened in the "management" (or previous lack of!) at Rotorua and began an intensive monitoring programme.

Findings were so convincing - and alarming - that in 1986 Central Government rescinded the Rotorua Geothermal Empowering Acts of 1957 and 1964, then took direct - and draconian - control; much to the anguish and wailing of well owners! Punitive royalty charges were also imposed, where wells were charged annual royalty fees of up to $NZ15,00 per year. This royalty was also very effective in forcing many more wells to be closed. In addition, an exclusion zone based upon a 1.5 km (about 1 mile) radius of Pohutu geyser meant some 106 wells were forcibly (and with great animosity!) cemented closed. As one may imagine, this period saw considerable civil disobedience and law breaking by irate well losers.

While these Government actions were very controversial at the time, subsequent changes in the Rotorua Geothermal Field has vindicated these draconian measures. Throughout the Rotorua Geothermal Field pressures have risen sharply at first since late 1987, but now with gradual and ongoing recovery totalling ~2.5 metres to January 1997 (Figures 4 & 5). Some geysers have become active once more after many years dormancy and several large hot springs have resumed strong overflows after several decades of being below overflow. More details of spring and geyser changes in the Rotorua Geothermal Field are described in Cody and Lumb [1992].

Post Well Closures in Rotorua

Since 1987, waterlevels and pressures have shown a pronounced and unprecedented recovery in levels, pressures and downhole temperatures. To January 1997 the waterlevels of geothermal monitor wells continue to show an ongoing slow progressive increase, with a total recovery of about 2.5 metres (or about 0.25 bars pressure). Together with this field wide pressure recovery there has been several

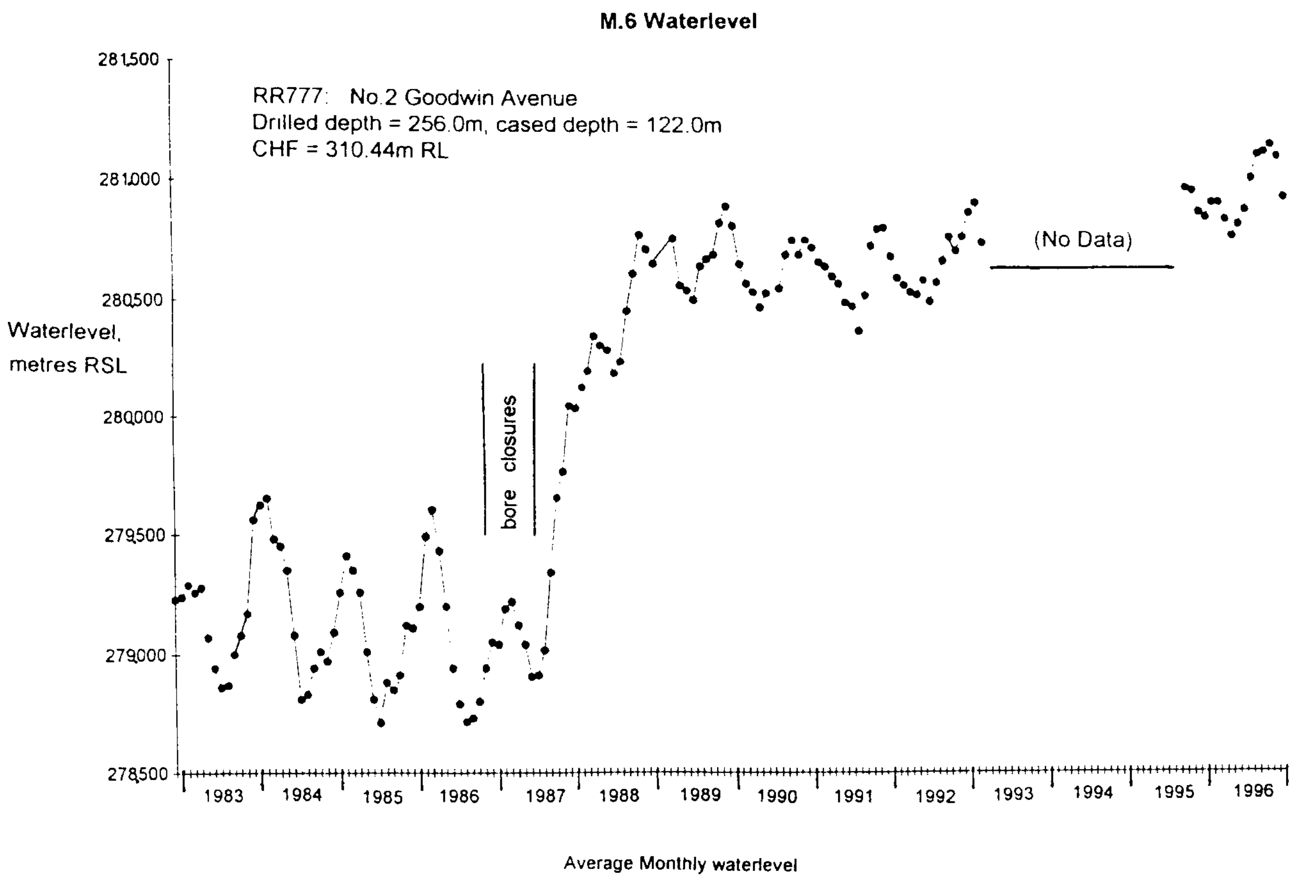


Figure 4: Monthly average waterlevel of M.6 monitor well, typical of rhyolite aquifers in Rotorua geothermal field.

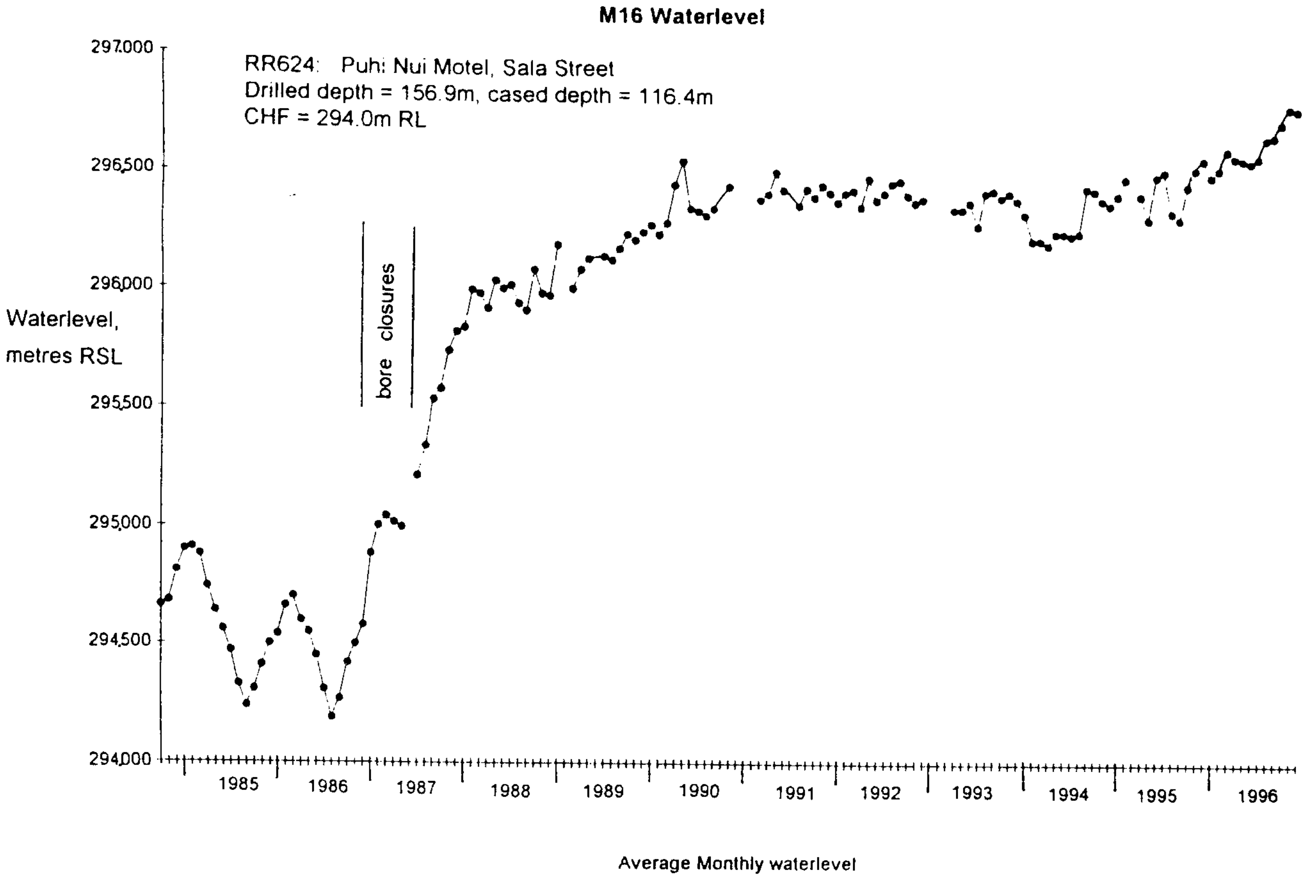


Figure 5: Monthly average waterlevel of M.16 monitor well, typical of ignimbrite aquifers in Rotorua geothermal field.

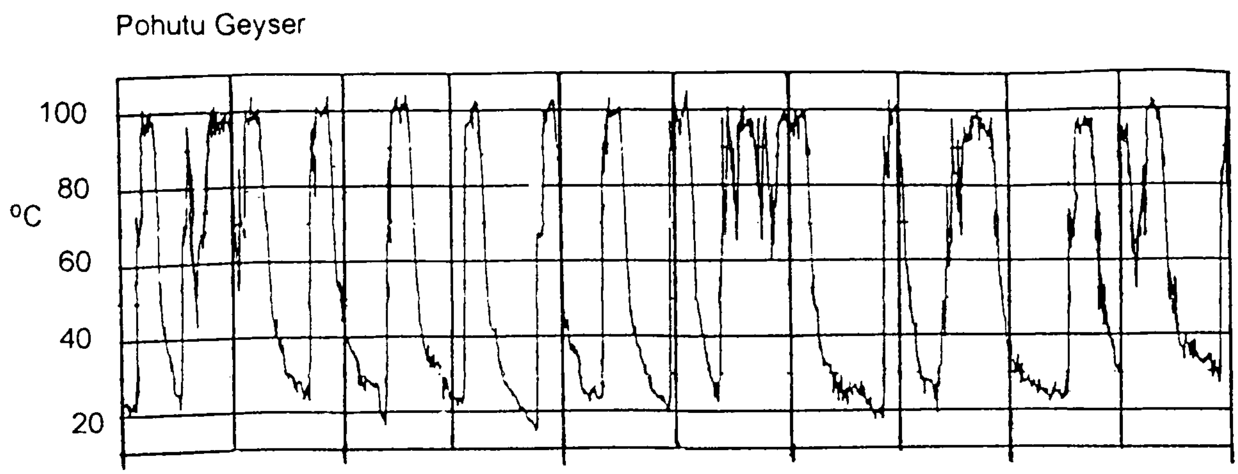
dramatic recoveries of spring and geyser activity, consistent with improving geothermal field pressures. The best illustration of this pronounced pressure recovery are the waterlevel changes shown in all monitor wells (Figures 4 & 5). In addition, people may now see the ongoing strong overflows of Kuirau Lake (~80° C, pH 7.6, ~50-60 litres/second); and Rachel Spring (~95-98° C, ~7-12 litres/second); both phenomena were unprecedented in more than 50 years. During the 1970s-1980s both these springs were typically below overflow, cool and acidic. At Whakarewarewa the most conspicuous recovery of spring activity since well closures is the eruptive activity of Kereru Geyser. Since January 1988 this geyser (last previous natural eruption in early 1972) has been erupting several times weekly and up to seven times daily during daylight hours, to heights of about 10-15 metres.

Whakarewarewa Geysers

In historical times (1900s-1950s) up to sixteen geysers have been active, but during 1995-96 only ten have been playing. Outside of Whakarewarewa elsewhere in the Rotorua geothermal field, no other geysers have been regularly active since 1854. For over 100 years, Whakarewarewa has been the only site of ongoing and reliable geyser activity in the Rotorua Geothermal Field. During historical records (c.150 yrs) there have been at least fifteen other geysers active around Rotorua city. However, all of these have been new outbreaks that geysered regularly, but only persisted for a few days or weeks before ceasing all activity. Apparently they formed in incompetent strata that quickly broke up, thereby destroying their geyser chambers.

The geysers of Whakarewarewa are New Zealand's greatest concentration of large geysers remaining today. Here one can usually see four geysers erupting within every hour and if lucky, up to eight geysers. Being within Rotorua city, they are highly visible and very accessible to locals and visitors alike. In the 1880s when surveying and town planning was undertaken, the main thoroughfare of Fenton Street was deliberately aligned due north and south to give views along it of Lake Rotorua at the northern end and Waikite geyser at its southern end.

Today the main grouping of geysers is at Geyser Flat, a sinter terrace about 7 metres high and of some 2,500 m² area. These geysers are aligned on Te Puia Fault, which provides intimate shallow water connections between all the geyser vents. Most of these geysers have shown changed activity consistent with recovering geothermal pressures following well closures in 1986-1987.



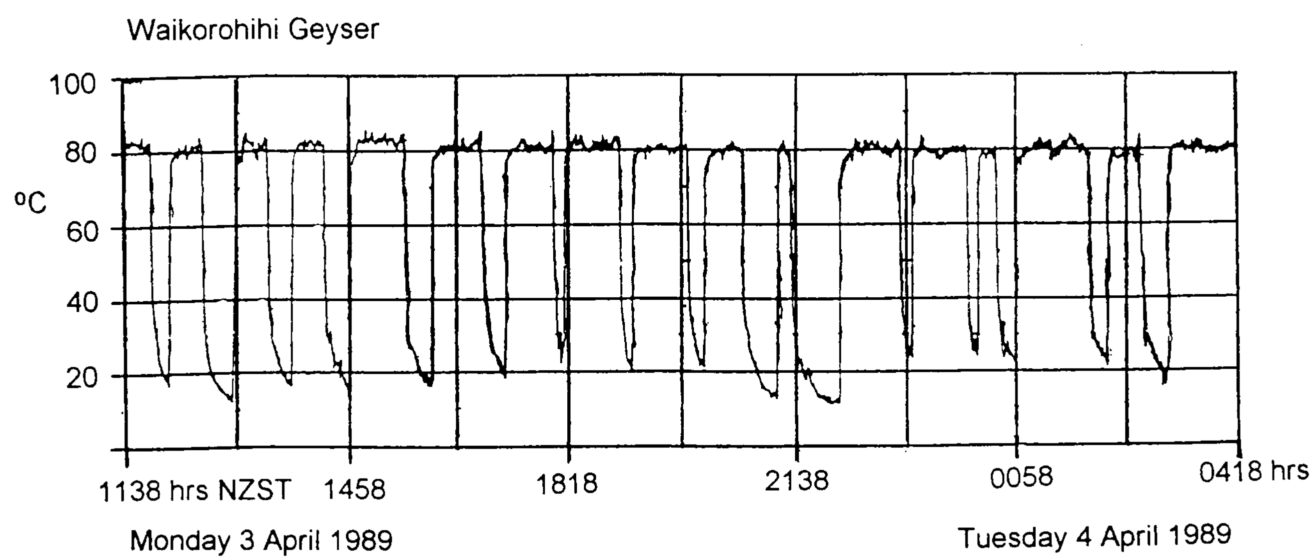
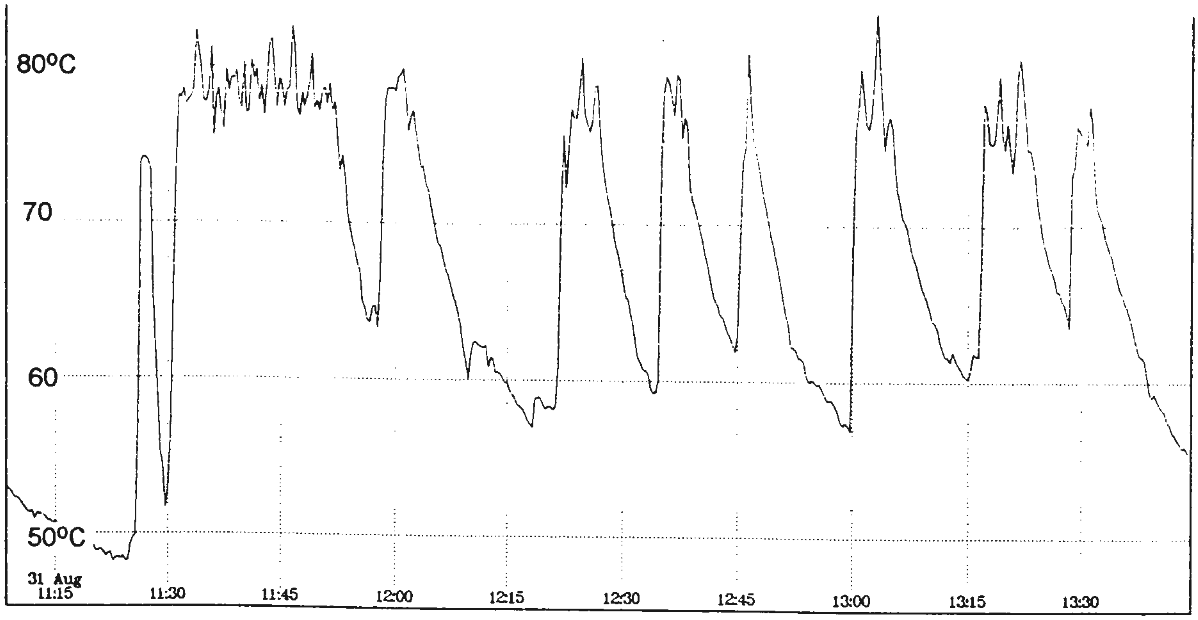


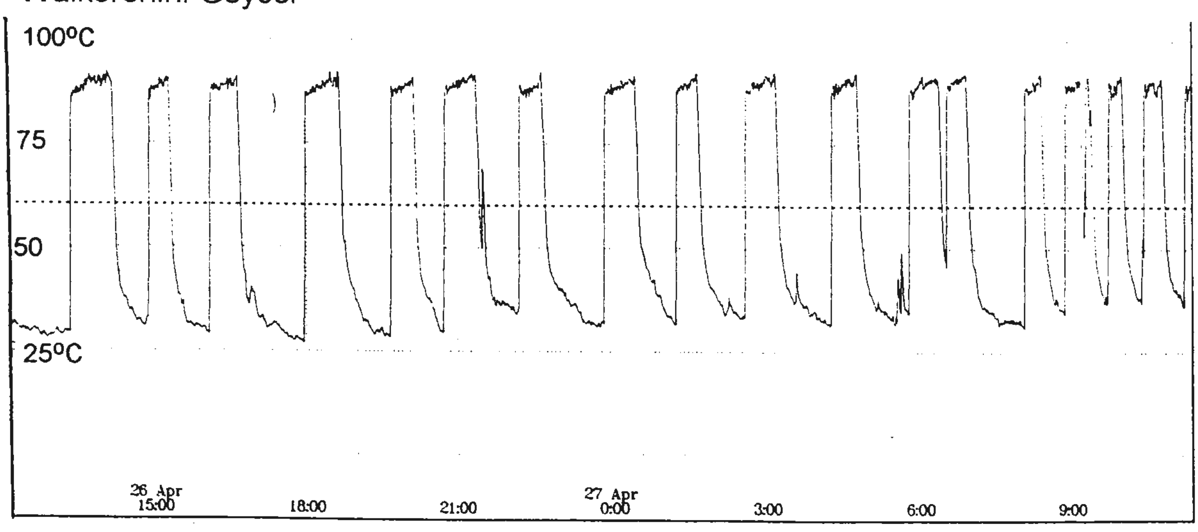
Figure 6: Eruption record for Pohutu and Waikorohihi geysers at Geyser Flat (Whakarewarewa) during c. 1140 hrs NZST Monday 3 April to c. 0420 hrs Tuesday 4 April 1989. Records are of temperastures (centegrade) from sensors alongside geyser vents. Peaks are eruptions (~100°C) and the lows are ambient (air temperature) values when geysers were dormant. Note the interactions of these two geysers.

Pohutu Geyser



31 August 1996 (data recorded at 20 second intervals) hrs NZST

Waikorohihi Geyser



26-27 April 1995 (data recorded at 44 second intervals) hrs NZST

Figure 7: Eruption records for Pohutu and Waikorohihi geysers at Whakarewarewa.

Pohutu Geyser

This is New Zealand's largest existing active geyser. It typically erupts about 21 metres high in a steady vertical column, but it also has a lower energy state of eruption in which large pulsating spurts erupt up to 10-15 m high. Outflows have not been directly measured but are estimated at about 100 litres per second. Pohutu presently erupts about

45% of each 24 hr day, but this play time may be comprised of 30-80 individual eruptions (Figures 6 & 7). An interesting feature of Pohutu eruption behaviour is that winds of more than ~10 knots strongly modify the frequency and duration of eruptions. This is because the erupted waters may variously be swept away from the vent area, or may collect and drain into the neighbouring extinct geyser vent of Te Horu, providing a quenching and regulating action on eruptions.

In the 1890s-1920s, Pohutu erupted infrequently, often being dormant for many days or even weeks at a time. However, during the 1950s-1970s it progressively changed its activity to shorter and more frequent eruptions. This trend continues to the present day and is illustrated by comparing Figures 6 & 7, in which Pohutu eruptions can be seen to have shortened and become even more frequent between 1989 and 1995.

Pohutu geyser erupting ~21 m high
Prince of Wales Feathers erupting ~5 m high
Photo: A.D.Cody, 11 April 1984

Prince of Wales Feathers Geyser

Located 2.5 metres north of Pohutu, with which it is very intimately connected. PWF was created by the 1886 AD eruption of Mount Tarawera, about 20 kms to the east. In the 1890s it was known as The Indicator, as its eruptions always preceded those from Pohutu. PWF erupts at an angle of about 70o above horizontal, with its waters thrown to the north. Of some 180 thermal pools and hot springs in Whakarewarewa with Maori names, this geyser is conspicuous for its lack of any pre-European name or known account of its existence. Newspaper accounts of July 1886 also describe a new geyser that had recently broken out alongside Pohutu.

Throughout the 1980s PWF still acted very much an indicator of eruptions from Pohutu, when both geysers often had dormancies lasting up to a few hours. However, in the early 1990s PWF has changed its behaviour to one of almost continuous eruption. It usually erupts 2-3 m high, then strengthens to a steady column 10-12 m high, soon after which Pohutu may commence eruption. During strong eruption PWF overflows at ~20 lps.

Waikorohihi Geyser

Located ~25 m south of Pohutu, this geyser has been active throughout historical times, although dormancies of several days occurred in the early decades of this century. Typically Waikorohihi erupts 5-8 m high for ~55% of each 24 hr day, usually comprised of 10-15 eruptions per day (Figures 6 & 7). It too is normally preceded by strong eruptions from PWF, at which times competition appears to be occurring until after several minutes, when either Pohutu or Waikorohihi succumbs to the other's demands for water!

Earlier this century Waikorohihi geyser often played many days at a time without cessation, sometimes 15-20 m high. Because it then seemed to prevent Pohutu from erupting, it was called "The Little Nuisance" by the Caretakers. During 1985-1987 Waikorohihi had dormancies or 35-50 hrs, unprecedented in the previous 20 yrs. Comparing 1989 and 1995 eruption records (Figures 6 & 7), it can be seen that within this timespan Waikorohihi has changed to much longer dormancies and with correspondingly less time in eruption.

Mahanga Geyser

This geyser is located ~3 m south of Waikorohihi and is only ~5 m from the tourist pathway. In the 1980s-1990s it has been erupting typically every 1-1.5 minutes for 10-20 seconds, playing 3-5 m high with 2-5 lps overflows (Figure 8). Its name is Maori for "The Twins," but it is uncertain just what that name applied to; did it once play as two distinct jets? or was its close proximity to Waikorohihi why both may have been called the twins? However, the most interesting aspect is that this name was given and used by pre-European Maori, although during historical times (c.1850s-1960) it had never been known to erupt, its vent choked with rubble. That it already had a name suggests that ancient Maori may have seen it geysering?

Abruptly, in October 1961, Mahanga blew out all the accumulated debris and began geysering. For many months it would play 10-20 minutes or so at a time, with dormancies lasting many hours. These eruptions progressively became shorter duration and more frequent, so that today it averages about 20% of each 24 hr day in eruption (Figure 8). A common European name for it is "Boxing Glove," due to the shape of its vent surrounding sinter mounds.

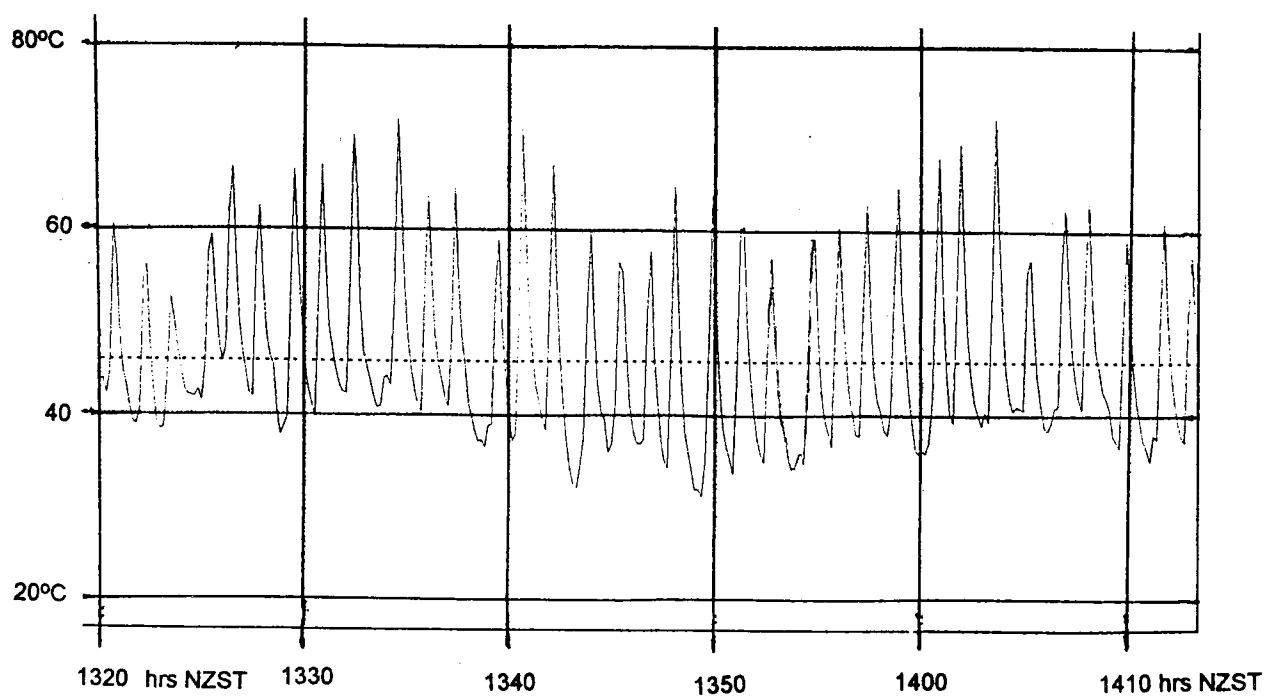
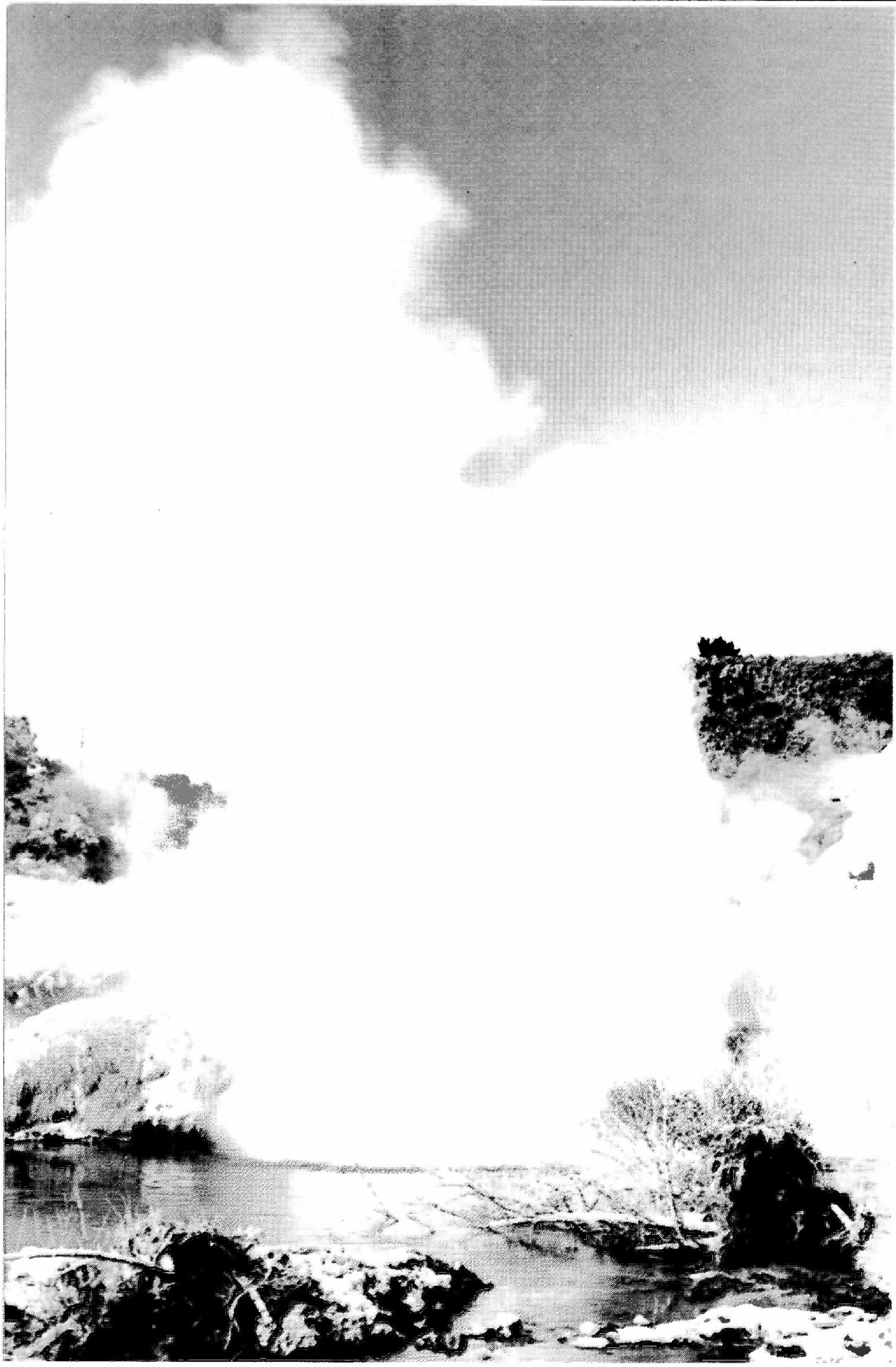


Figure 12: Temperature record of Mahanga Geyser, Whakarewarea, 26 April 1995. Sample rate every 10 seconds. Geyser erupts every ~100 seconds for about 10-20 seconds. Eruptions are 3-5 meters high, with ~3-10 liters per second overflows.



Kereru geyser erupting ~10 m high
Photo: E.F.Lloyd, c. 1972

Its eruptions at this time were also much weaker (~0.5-1.5 m high), and the geyser would often remain dormant for tens of minutes, or abruptly cease erupting whenever another geyser commenced eruptions. Since late 1988, such weak activity has ceased and Mahanga is again vigorously erupting 3-5 m high, with strong outflows and no cessation or faltering when other geysers play.

Kereru Geyser

This geyser is located at the northern base of Geyser Flat, at some 5 m lower elevation than all the above geysers. It is ~15 m north of Prince of Wales Feathers geyser. Kereru is the name of the native New Zealand wood pigeon and its name as used for this geyser is thought to be an allusion to the dark greenish rounded sinter surrounds, which look somewhat like the pigeon's green wings when folded.

Until about1972 Kereru geyser would erupt with intermittent episodes of activity, but was a common and well known geyser. [Lloyd 1975] Since about 1972 until January 1988 no record of any natural eruption is known, although a few soaped eruptions occurred within that time. Since early 1988 until the present day it is now often seen in eruption, up to seven a day during daylight hours in early 1996. However, it still has inactive episodes of many days. Eruptions are always very short lived, typically only 15-20 seconds and may be either as a pulsating series of huge spurts at ~70° above horizontal, or else as a vertical continuous column. Both styles of eruption last similar times and both are 10-20 m high with similar quantities of overflow (~100-200 lps).

Kereru geyser is an enigma because no relationship to any other Geyser Flat geysers has been identified. Its waters are ~20% diluted with respect to the mineral content of all other neighbouring springs and geysers; and together with the greeny black sinter colours (due to iron from freshwater forming black pyrite in its sinters), this seems to infer that nearby Puarenga Stream waters are entering its feeder canals.

Kereru geyser in weak eruption ~5 m high
Photo: A.D.Cody, 11 April 1984

Okianga Geyser

This is rarely seen by anyone, although it reliably erupts every 25-40 minutes and has done so for the past ~8 yrs. It is ~250 m east of Geyser Flat and away from tourist walkways, down in the Puarenga Stream channel and screened from view by a dense bamboo grove. It is thought to have been created sometime prior to 1960 by local people

Okianga geyser erupting ~3 m high
Photo: A.D.Cody, 16 Sept 1995

cutting a channel through its vent wall, to direct its overflows into a pool for washing clothes. [Lloyd 1975] During the 1980s it was rarely active, sometimes a year or so between eruptions. It is therefore a convenient site at which to make geyser study experiments! [Luketina 1996]

Okianga plays 3-5 m high at an angle of ~60° above horizontal; eruptions last only ~10 seconds or so, with overflows of ~5-10 lps during eruptions. Before each eruption its vent begins to overflow weakly, gradually strengthening flow and intensifying its boiling height. When overflowing, it can always(?) be induced to erupt by scooping some 10-20 litres out of its vent; an eruption then occurs a minute or two later.

Waikite Geyser

This geyser is 150 m southwest of Geyser Flat, on top of a huge circular sinter mound some 100 m diameter and 15 m high (Figure 3). When erupting it would play 5-8 m high in splashing pulses. Eruptions typically lasted a few minutes and repeated every hour or less. Its last eruption was in April 1967, since when its vent remained dry and gently steadily steaming; it then became blocked for many years with a great quantity of rubble (thrown in by tourists?). In late 1995 a rockfall opened its vent once more, when it was still dry to 8.5 m depth onto rocks. In June 1996 constantly boiling water suddenly returned up to 2.5-3.5 m depths below overflow and it remains so to date. In January 1997 two attempts to soap an eruption failed; each time it showed no inclination to geyser.

Historically Waikite has only been active as a geyser for short episodes lasting a few weeks or months, with inactive episodes of many years duration. Its eruptive episodes have always occurred during years of prolonged higher than average rainfall.

Its vent is at 315 m above sealevel (m asl), compared to Geyser Flat geysers being 302 m asl and Lake Rotorua at 280 m asl. Waikite geyser is the highest elevation of any spring or geyser in the Rotorua geothermal field that has been active in historical times.

Wairoa Geyser

About 15 m south of Mahanga geyser and also on the Te Puia fault. Last eruptions were soap induced in the late 1950s, when it erupted up to 50 m high for a few minutes together with large outflows. Repeat eruptions could be induced within a few hours. Its last natural eruption was in

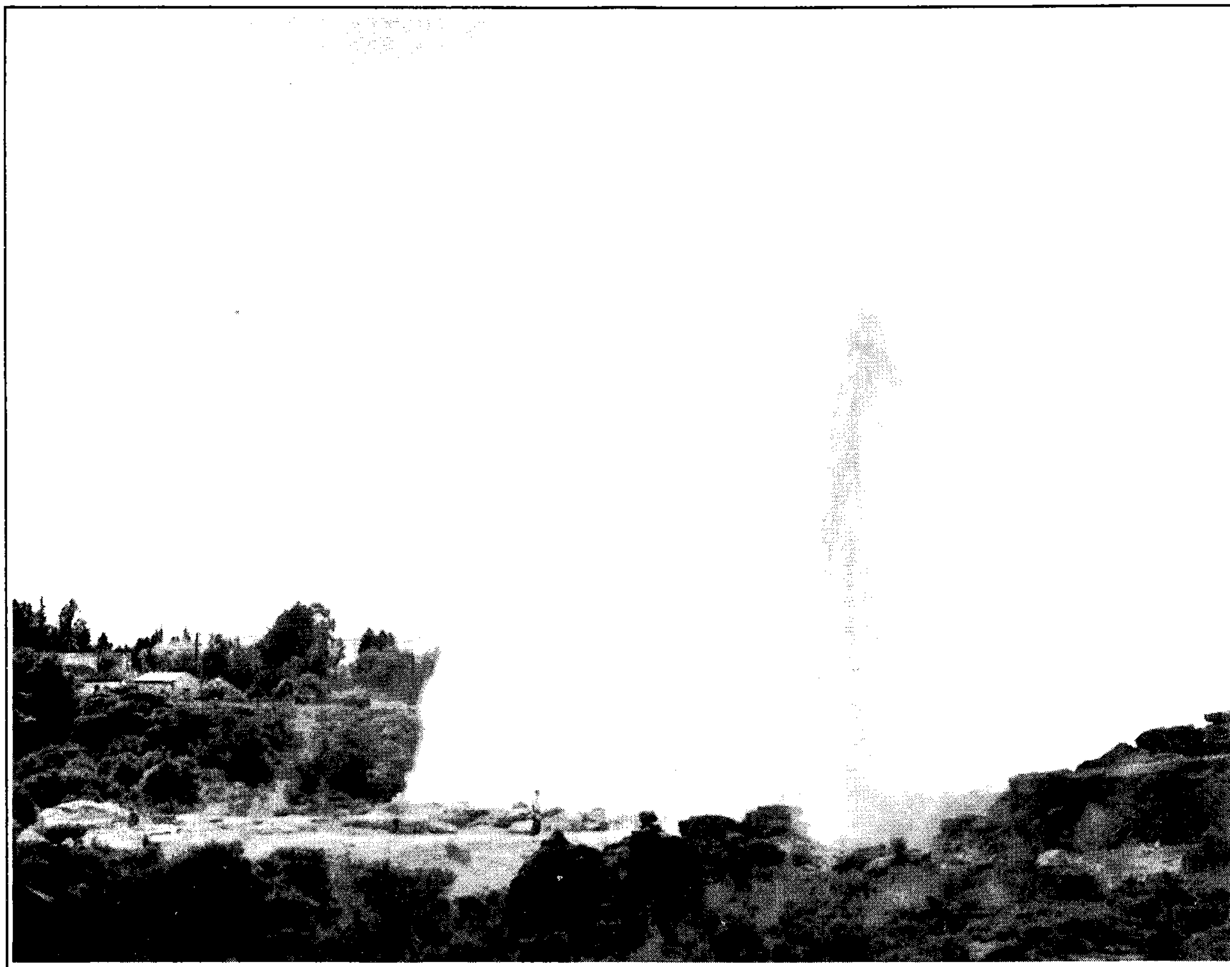
December 1940. Today Wairoa water is constantly boiling, low chloride-high sulphate, inferring steam heating of mixed waters? Waterlevel is 3.5 m below overflow and has remained at this level for several years now. During the 1980s its waterlevel fell to below 4.5 m deep, where a rocky floor was exposed. In the 1900s-1910s Wairoa was frequently soaped into huge eruptions, these events being advertised in advance to locals and tourists. [Lloyd 1975]

Waikite geyser erupting 5-8 m high
Photo: E.F.Lloyd, March 1967

S435, S436 geysers

At Whakarewarewa, about 300 m east of Geyser Flat, the large hot lake of Roto-a-Tamaheke covers about 1.2 hectares. This lake is formed by hot springs building a dam across a broad valley, with groundwater and spring outflows being impounded. Roto-a-Tamaheke has an ongoing history of human disturbances to its outflows and waterlevels. At its eastern end two boiling springs occasionally geyser 2-5 m high. When active, these two geysers erupt for 1-2 minutes, repeating every 5-25 minutes. They usually exhibit a conspicuous exchange of function, with one going dormant while the other erupts. These two geysers have no names and were last active for several weeks in April 1995, prior to which they last geysered during September to November 1984.

Other boiling springs on the northern shore of Roto-a-Tamaheke is the Ororea Group. Through historical times various vents here have geysered, but very infrequently; usually they are constantly boiling.



Wairoa geyser erupting ~40-50 m Pohutu playing behind figure
Photo: E.F.Lloyd, c. May 1959

Earthquake Induced Changes at Geyser Flat, Whakarewarewa

Throughout historical times, various caretakers have described geyser activity changes immediately following local earthquakes. On Thursday 7 December 1989 at 0731 hrs local time, an earthquake of Richter magnitude ML 3.0 occurred, centered only 4 km away at less than 10 km depth. It was strongly felt by Rotorua people. Later that morning I (ADC) inspected many springs and geysers for possible changes.

On Geyser Flat, Prince of Wales Feathers geyser had, since being visited the previous day, ejected an estimated volume of about ten litres of angular gravel and sand sized materials. These were all comprised of crushed pyritised sinter fragments. Within several subsequent days this material was completely washed away.

Although earthquake induced changes to geysers and hot springs in Rotorua requires a separate article, this one event is given here to illustrate that natural changes to these geyser conduits do occur and are likely to occur again. It is likely that such events have, or will in future, cause these geysers to undergo pronounced changes in their eruptive characteristics.

Acknowledgements

I am very grateful to John McIntosh (Manager of Environmental Investigations, Environment Bay of Plenty Regional Council) for his kind permission to use Rotorua monitor well data in this publication; and to my wife Anna who patiently assisted me with many aspects of preparing this material.

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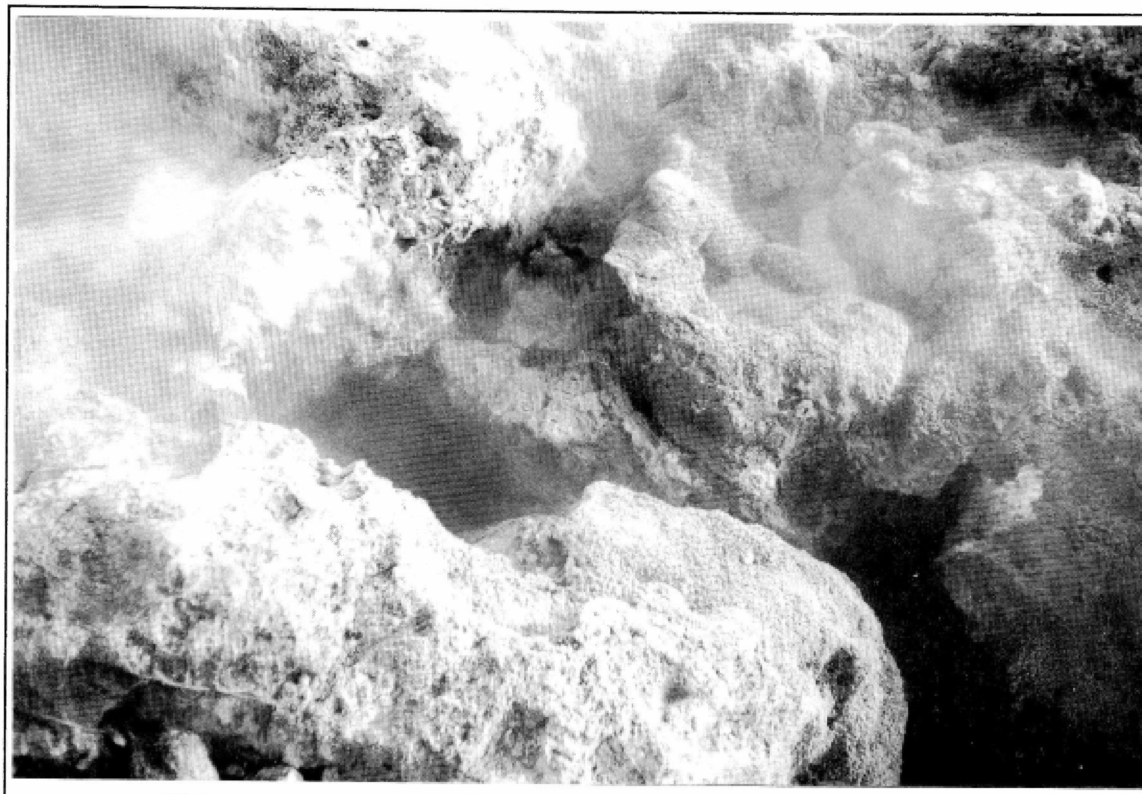

Okianga geyser vent (center left) closeup after eruption end
Field of view ~2 m wide, chopped outlet in right front
Photo: A.D.Cody, 16 September 1995

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Massive Regular Bubble Production by Botryoidal Spring During August, 1996

by

Jack Hobart

ABSTRACT: A series of shallow earthquakes beneath the White Creek area of Lower Geyser Basin energized Botryoidal Spring into a new mode of eruption in which regular eruptions were initiated by spectacular masses of bubbles and textured surface formations in the rising water column. This offered an unprecedented opportunity to observe this rare manifestation of surface tension effects in a geyser eruption. Observed eruptions were extremely regular and much larger than previously noted from this geyser. Many photos were obtained showing a wide variety of eruptive forms even though the observing session was quite brief.

INTRODUCTION

Botryoidal Spring is located 100 meters up the White Creek drainage from Firehole Lake Drive at Great Fountain Geyser in the Lower Geyser Basin. It is 20 meters northeast of the creek on a flat shelf. Its name is derived from the masses of botryoidal (grape-like) sinter beadwork around the pool at and below the flat surface platform. The pool is about 4 to 5 meters across and has no unusual features to draw attention from an observer either on the road or on the path skirting the thermal area about 30 meters away to the northeast.

Its historical activity did little to draw any attention. [Wolf 1986, Bryan 1995, Whittlesey 1988] Eruptions less than 2 meters in height were nearly continual, although a 15 sec pause was observed by Paperiello and Wolf [1986] after which a sudden 2 meter burst filled the crater and washed the adjacent platform with an initial wave of water. That observation gave a hint that unusual, energetic behavior was possible from this geyser.

A number of shallow earthquakes took place in the area some weeks before observations were made on August 12, 1996. These apparently energized the geyser, lowering its water level and changing its eruptive behavior to a significant degree. The changes in eruptive pattern provided the opportunity to observe at first hand one of the rarer forms of geyser activity, the creation of bubble formations at the onset of bursting from a quiet pool. Its regular and frequent eruptions over the course of about 70 minutes of observation allowed precise documentation of behavior using both video and still photography. The initial patterns observed in the rising water column were among the most unusual and bizarre ever observed, approaching those occurring in the mudpots of Yellowstone!

ERUPTIVE BEHAVIOR

The water level in the pool is out of sight when viewed from the nearby trail. That places it at least 20 cm. below the surface of the pool. No splashing is observed during the quiet interval between eruptions. An eruption starts with a sudden upwelling of the water in the pool, usually with a doming of the water toward the northwest side of the pool, the right side when viewed from the trail. This doming is caused by steam bubbles beneath the surface, making the water appear milky-colored. Multiple individual bubbles can be seen. There is never a single large bubble as might be expected. The water mass quickly rises and is broken apart by internal pressure from the steam bubbles. The resulting eruption generally fills the crater to a width of 5 meters and rises to a height of about 4 meters. The initial burst is the largest, lasting only a few seconds. This is closely followed by one or more weaker bursts, lasting for a period of 10 to 16 seconds. The water quickly disappears from view and the pool suddenly becomes very quiet until the process is repeated, less than 2 minutes later.

What sets this geyser apart from all others is the start of the eruption. Imagine a gigantic bubble-blowing machine, dependably churning out bubbles and textured surfaces over the entire eruption surface for the majority of eruptions. What heretofore was a rarely observed event can now be observed many times per hour. These patterns and shapes are often bizarre. Often they have the mottled texture of the human brain. At other times, masses of transparent bubbles are pushed ahead of the water mass. Occasionally, the entire water mass is composed of giant bubbles, reminiscent of transparent bean bag chairs, piled atop one another. These may be up to 2 meters across! The entire pool volume can appear like a giant pile of bubbles. It doesn't seem possible that surface tension could hold the water surface together given the violence of the initial expansion of the water column at the beginning of each eruptive sequence.

I have often seen such effects during my usual activity at Yellowstone; photographing the bizarre forms taken by exploding mudpots. I am accustomed to seeing incredibly complex forms and patterns created by rising steam bubbles within thick pools of mud. However, I was surprised to see similar complex surface patterns in the initial eruptions of this geyser and no soap at all. My son Craig and I were immediately drawn to this activity and recorded it via both video and still photography.

ERUPTION DATA

Thirty-two closed eruptive periods were obtained in an hour of videotaping. The sudden rise of water made determination of the start to start period of the eruption accurate to better than a tenth of a second. The duration of each eruption was less precise. The large initial burst was followed by successively smaller bursts for 10 to 16 seconds. About half the time, a brief pause was followed by 2 to 5 seconds of diminishing bursting. Thus, the duration of the eruption is accurate only to the nearest second. The data derived from the video record are presented in Table 1.

The start to start period was remarkably regular, averaging 114.4 seconds with a standard deviation of only 3.1 seconds and a variance of 9.25 seconds. The eruption duration was 14.6 seconds with a standard deviation of 1.6 seconds and a variance of 2.6 seconds, based upon visible water. The vast majority of the bursts, 80 percent, resulted in formation of an initial bubble or brain-like water surface. The others erupted as splashing water from below the crater rim at the ground surface. Generally these eruptions were less forceful than those which emerged from a tall initial mass of water. When the domes reach 1.5 to 2.5 meters in height, the eruption can extend more than 4 meters tall. Surprisingly little water is ejected from the pool in these eruptions.

Table 1: Botroidal Spring Eruption Data

BURST	START to Start (min)	DURATION (sec)
1		16.00
2	116.21	12.79
3	125.26	10.53
4	114.49	15.04
5	115.51	14.53
6	117.66	11.87
7	116.99	14.88
8	114.55	13.33
9	116.00	16.33
10	113.40	13.93
11	116.95	14.98
12	113.29	12.69
13	110.46	12.23
14	111.13	16.10
15	117.27	13.83
16	113.54	12.29
17	112.90	16.09
18	115.90	16.19
19	117.47	15.72
20	114.93	12.79
21	109.47	14.32
22	111.70	16.32
23	112.74	13.88
24	111.96	14.92
25	113.04	17.88
26	112.76	16.12
27	111.10	14.02
28	113.23	14.79
29	110.91	15.88
30	115.79	17.09
31	113.77	14.32
32	109.67	14.32
33	115.30	16.02
34	118.50	14.52
35	115.90	13.62
Mean	114.40	14.58

PHOTOGRAPHY

The regularity of this geyser makes photography of the initial surface phenomena relatively easy. Unfortunately, the delicate nature of the water surface is difficult to reproduce in low resolution printing devices or in the video imagery, for which my camera didn't have a high-speed shutter. Photos in Figures 2 through 9 show the variety of shapes that are observed early in the eruptive sequence. No rapid sequences of high resolution still photos were obtained.

CONCLUSIONS

The ease at which dramatic bubble photographs can be obtained is only paralleled by eruptions of Strokkur Geyser in Iceland. A series of dramatic "blue bubble" doming eruptions from this geyser can be seen on pp 100-103 of Maurice and Katia Kraft's *Volcano*. Other geysers in Yellowstone have also reported to have bubble-forming eruptions, including "blue bubbles." These include Morning, Fountain, Great Fountain, Cauliflower and Solitary Geysers. On the other hand, these geysers do not produce an initial mass of bubbles most of the time at two minute intervals as did Botryoidal Spring.

Recent earthquake activity has apparently been the source for energizing Botryoidal Spring and several other features in the White Creek area. An extremely regular, energetic geyser has been rejuvenated, creating the ideal attributes for formation of complex surface features at the start of nearly every burst.

The study of liquid surface tension effects is a truly rewarding experience. Using the same high speed photography techniques as employed for freezing the exotic shapes of mudpots, similar exotic patterns have been shown to occur in geyser eruptions as well. All that is needed is a sudden, forceful eruption from a calm water surface. Now, it is hoped that this approach can be applied to other geysers as well.

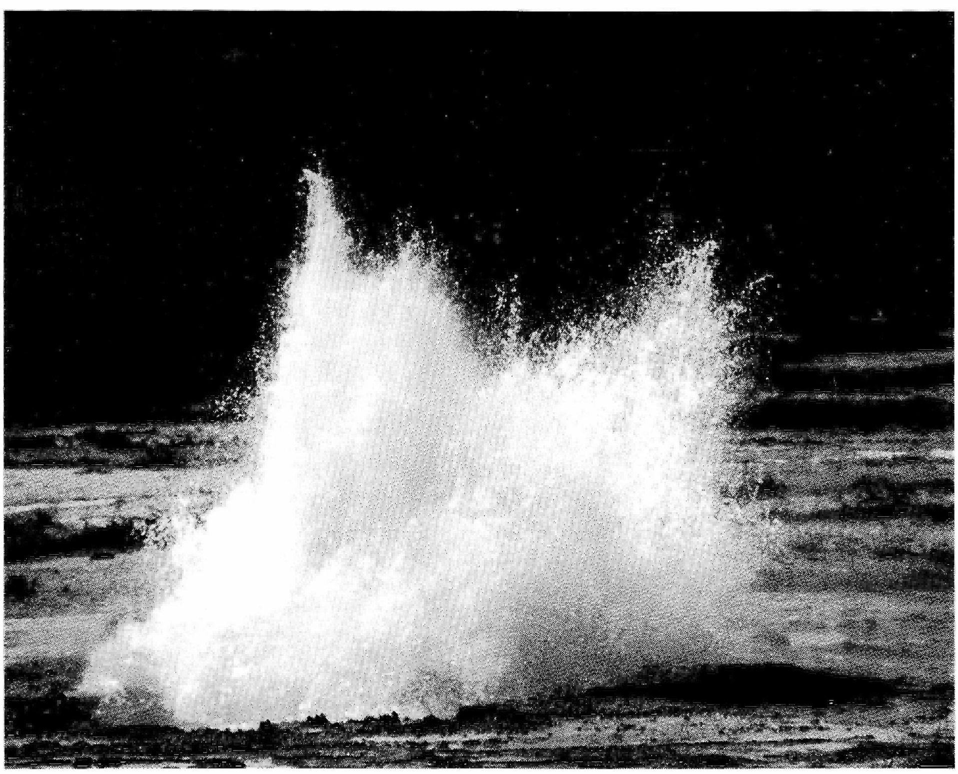


Figure 1 shows a large burst at its maximum extent, filling the crater. Its height is about 4 meters and width about 5 meters. Such bursts occurred more than 10 percent of the time.

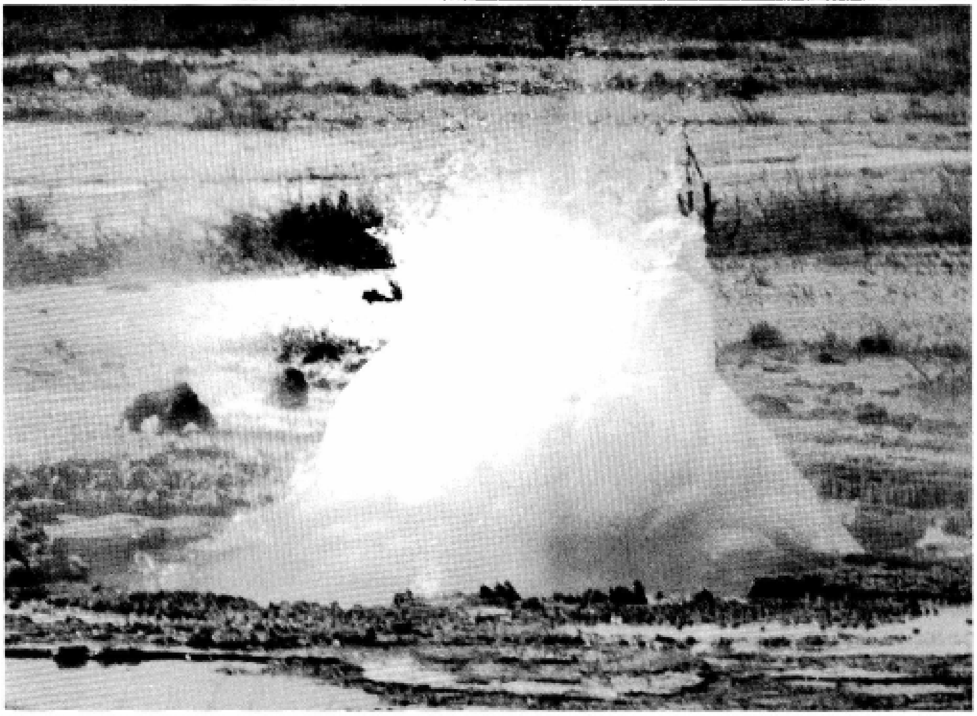
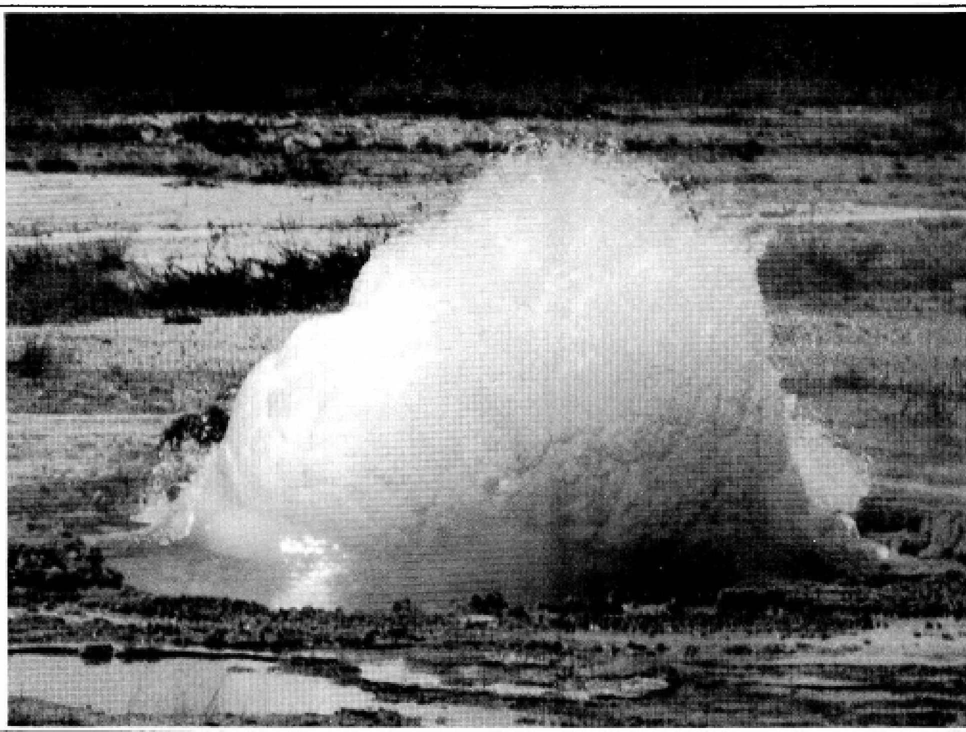
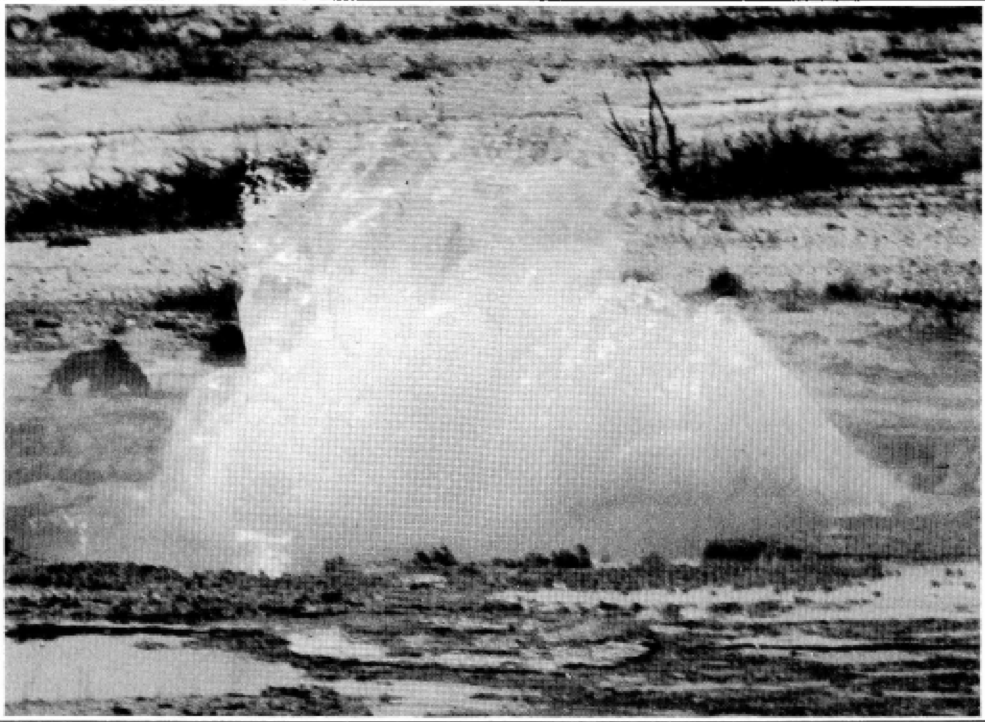


Figure 2 is especially dramatic. An exceptionally tall burst is beginning to burst from a tall cylindrical mass of water, composed of 0.5 meter diameter bubbles. Around the bottom of the cylinder, the pool surface is pulled up as a smooth surface with bubbles visible beneath its surface.



Brain-like surface texture is evident in **Figure 3**. Bursting is just beginning from the top of this large water mass. Large bubbles occur on the right and at the top. The water surface has been pulled upward around the periphery of the water mass.



The next picture, **Figure 4**, shows a complex surface of both large and small bubbles rising from a water surface which is pulled upward around the periphery of the rising water mass. Three regions of bubbles are rising high above the rest of the water mass and appear to be breaking apart at the top. A prehistoric animal seems to appear in the left side of the pictures, behind the geyser. Probably a tree root, but very realistic at that.

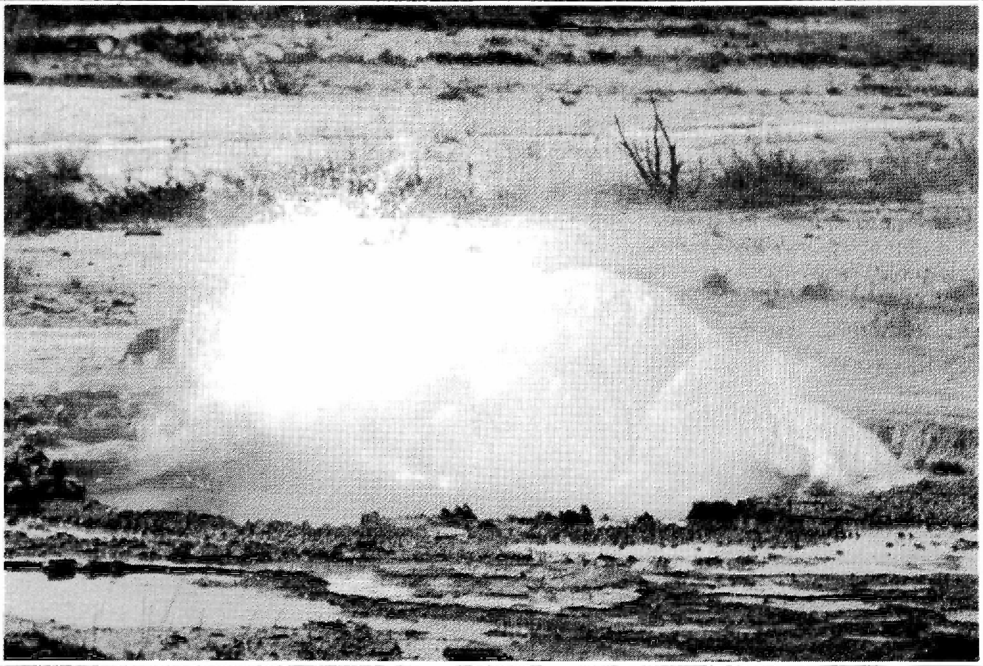


Figure 5 shows a low, wide dome, extending to the pool edges at the right and left, with large, textured bubbles comprising its surface. Water is pulled up from the surface on the left and a spray of water is just beginning to erupt from a small portion of the left surface of the water mass.

An irregular, churning mass of water can be seen in **Figure 6**, about to erupt in an explosive spray. Several masses of transparent bubbles are being pushed ahead of the water mass.

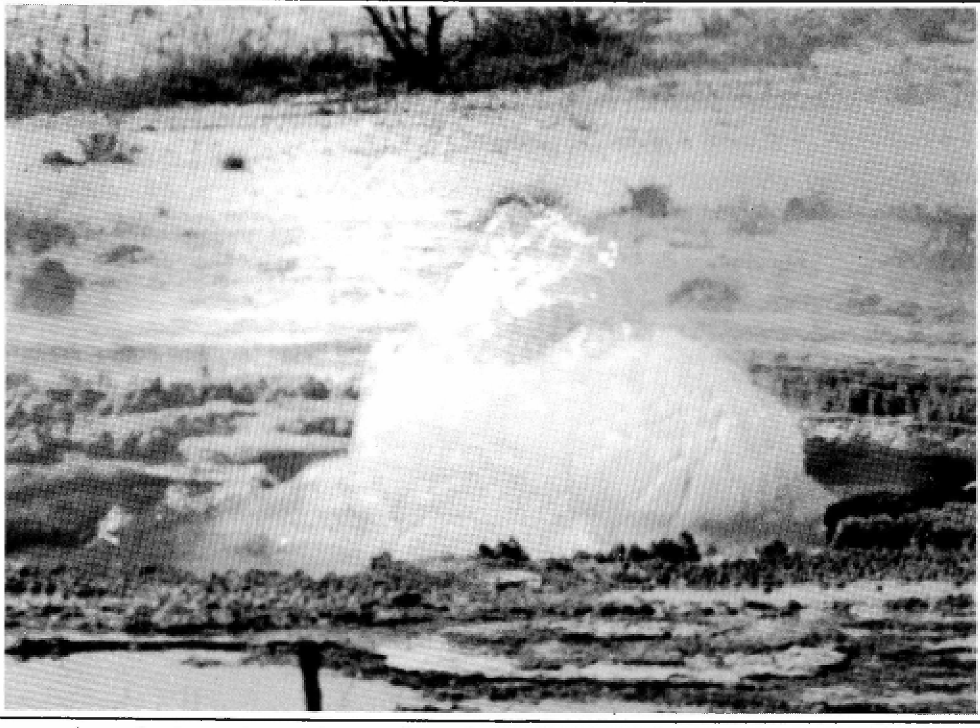


Figure 7 is complex. An irregular water surface is pushing a tall, transparent bubble mass upward. To the right is a large opaque bubble with a brain-like textured surface. To the left, steam bubbles can be seen pushing up a smooth dome of water.

A striking view of a huge bubble is shown as **Figure 8**. It is about 2 meters across, partially transparent and is embedded in a mass of flattened bubbles. All have textured surfaces that reflect sunlight brightly.

Another dramatic and unusual view of giant bubbles appears as **Figure 9**. A 2 meter bean bag-like transparent bubble is perched atop at least seven other large bubbles.

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The Location of Oblique Geyser

H.Koenig

Abstract: Oblique Geyser was located in the Gibbon Canyon, and was named in passing by A.C.Peale in 1878. Since that time, the location of that geyser has been lost. The name itself was then applied to another geyser in the Geyser Creek area, and the name forgotten. Finally, it was resurrected and is now being imposed on the wrong geyser. This report details how this came to happen.

Introduction

There is considerable controversy over the name of the largest geyser in the Geyser Creek Group. Some have claimed that the proper name for this geyser is "Oblique Geyser." This report will show that the name Oblique has been erroneously reapplied to this geyser, and should instead be reserved for the original Oblique Geyser, whose location is still uncertain.

No attempt is made to describe the activity of the Geyser Creek and Gibbon River thermal features. Two recent reports include descriptions and maps of the hot springs and geysers of Geyser Creek, including Oblique/Avalanche Geyser: [Wolf & Paperiello 1985] and [Dunn 1993].

Naming by A. C. Peale

The name Oblique was first used by A.C.Peale in his report on the thermal activity observed as a member of the Hayden Survey [Peale 1883]. This was the first visit to the Norris and Gibbon Geyser Basins by a party with the Hayden Survey, and Peale's visit was little more than a cursory survey of the more accessible areas.

> The spring areas on Gibbon River are some six in number. The three most important of these will be described in detail further on. Near the head of the main spring are some sulphur vents and dead springs, much like those at the head of Obsidian Creek, just across the divide from the head of Gibbon River. They are unimportant and will not be further described. West of these fumaroles and north of the main Gibbon [Norris] Basin is a locality that has never been visited. It is indicated on the map at the head of a small stream that joins the river in the broad open valley north of the monument basin. Great volumes of steam were noticed rising from it, and it is probable that it is the site of an important geyser. The two other localities which will not be described in detail are those of Geyser Creek and the one on the west side of the broad open valley. [Peale 1883], p.124.

All of these unvisited areas are clearly shown on Map 1 and they are, in order, the area north of Norris Geyser Basin that includes Frying Pan Lake; "Sizzling Creek," a rarely visited group northwest of Norris that was the site of explosive mud volcanoes in 1987 [Hobart 1989]; the Geyser Creek Group; and the Sylvan Springs Group. Note that Peale specifically states that he is aware of, but not describing, the features of Geyser Creek.

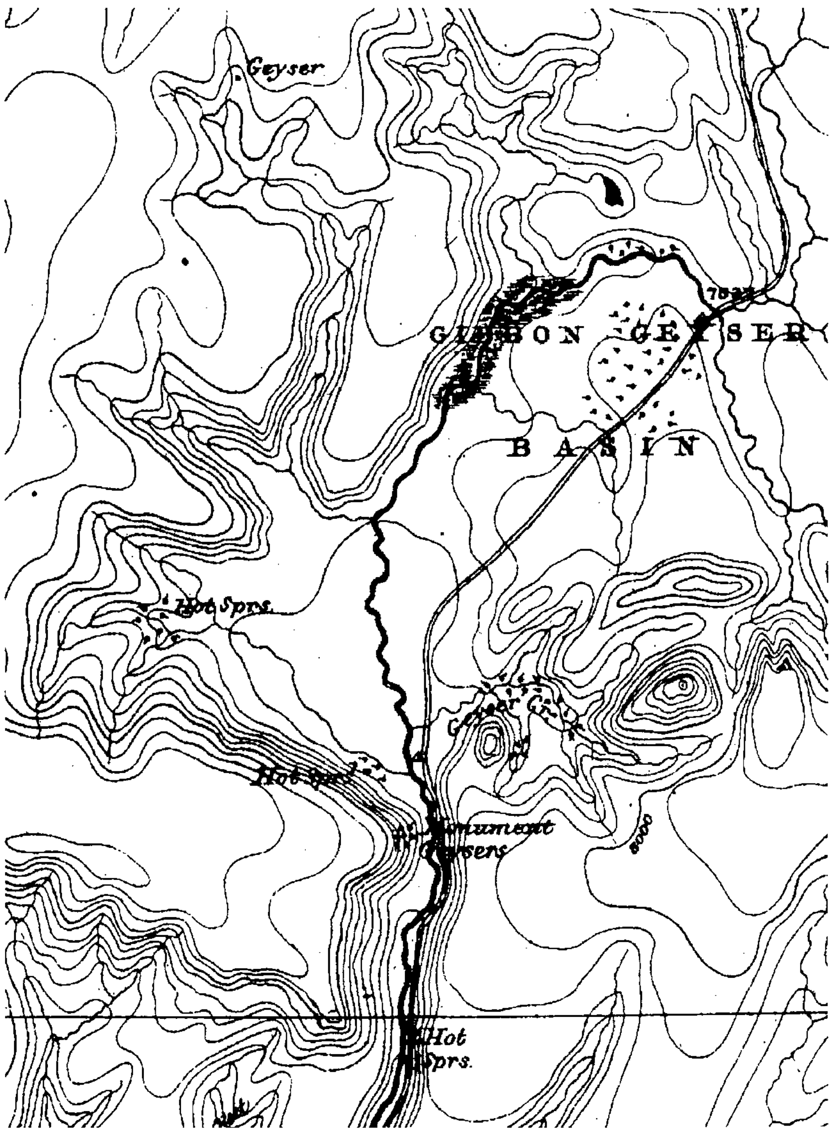
> The Gibbon [Norris] Geyser Basin covers an area of about 6 square miles, and is one of the most interesting within the limits of the Park... [Superintendent] Norris built his wagon road through the basin in 1878, and soon after it was finished we passed over it and visited the springs described in this chapter. [Peale 1883], p.124.

Map 1 clearly shows this road. Once outside the Norris Basin proper, it closely follows the current road alignment, which runs through Elk Park south into the Gibbon Canyon.

After enumerating the springs and geysers of the present-day Norris Geyser Basin, Peale then gives a short description of the Monument Geyser Basin:

> This collection of geysers ... is on a spur of the plateau on the south side of the open valley above the head of the lower cañon of Gibbon River. The group is about 1,000 feet above the level of the river, and the columns of steam can be distinctly seen from the open valley. I was unable to visit them from lack of time...
>
> About 2 miles down the cañon is another small group in which there is a geyser which we call "Oblique," that spouts out obliquely over the road [Peale 1883], p.132-133.

That short comment is the first of Peale's three short references to Oblique Geyser. It is quite obvious that he spent no time investigating any of the small groups of



Map 1
Portion of Map of Yellowstone National Park in [Hayden 1883] (after page 490).

hot springs in the southern end of the Gibbon Basin, including Geyser Creek, but instead proceeded directly south on the road toward the geyser basins of the Firehole River.

A figure of 75 feet as the height of Oblique is given in a table of geysers in the original report [Peale 1883], p.302. This same figure is mentioned in a magazine article which summarizes the information on the geysers of the world [Peale 1884] . No other references are known.

Use by Walter Weed

The year after the publication of Peale's report on the thermal springs, Walter Weed visited the park. He made extensive observations and notes on the geysers and their activity. In the southern end of the Gibbon Basin, Weed knew that there was a large geyser that Peale called "Oblique," but he didn't know the exact location. One field notebook contains a sketch map of the Geyser Creek springs[Weed 1884a]. In this map he placed the name on what was probably then, and is now, the largest geyser active in the area. The description he gives of the geyser closely matches that of the present day activity for this geyser. Yet, in that same notebook he expressed doubt as the whether this was really Peale's "Oblique" [Weed 1884b]. In retrospect, it seems obvious that Weed's doubts were correct, in that his description and location for Oblique Geyser do not match the description or location of Peale's Oblique.

In any case, this is the last documentable case of the use of the name "Oblique" in almost a century.

Falling Out of Use

Following his description of the usage by Weed, Whittlesey gives two further citations that describe the activity of this geyser in the 1920s and 1930s. In both cases, Whittlesey neglects to mention that his sources did not actually use the name "Oblique," even though a careless reader could come to that conclusion.

Phillips described the Geyser Hill geyser [Phillips 1927], p.128, and his description closely fits the present activity of the geyser in the Geyser Creek area.

The 1939 edition of the Haynes Guide describes a geyser in the Geyser Creek area as erupting to 25 feet. [Haynes 1939], p.66. Again, it is not clear from Whittlesey that the original source simply called this one of the two "Unnamed Geyser in Geyser Springs group".

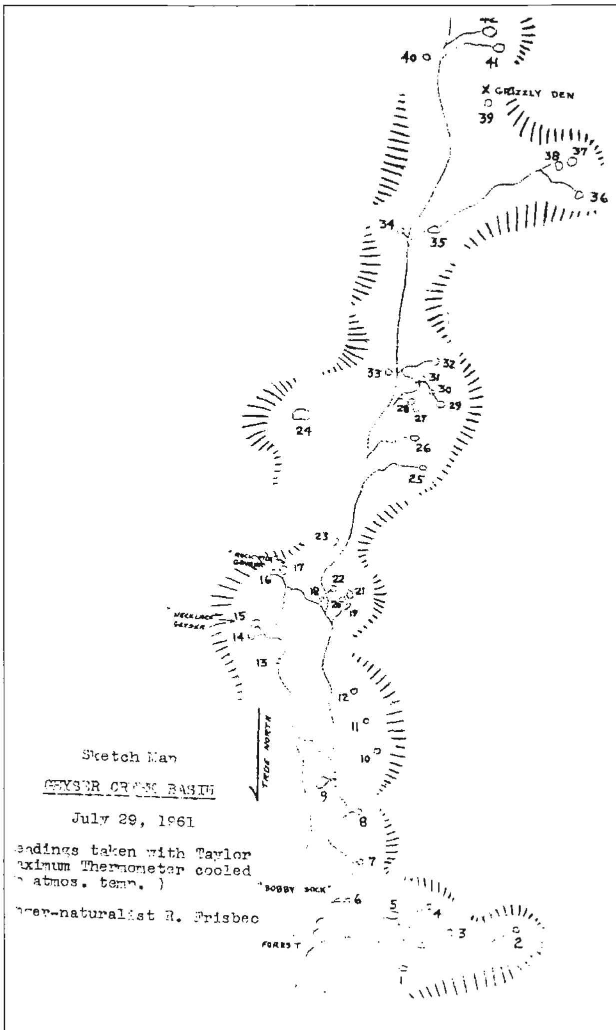
Two books on geysers and their activity published in the 1930s have no mention of Oblique Geyser. While it contains an extensive list of geysers in an appendix, except for Monument and the statement that Geyser Creek contains 5 geysers, *The Story of Yellowstone Geysers* doesn't mention any features in the Gibbon Basin or Geyser Creek Groups [Bauer 1937] ,p45. Allen & Day's *Hot Springs of the Yellowstone National Park* makes no mention of a name for the large geyser in the Geyser Hill group, despite describing its behavior and even providing a photograph [Allen & Day 1935], p.451-453.

An attempt at naming this geyser was made in 1961, when the name "Rock Pile Geyser" appeared in [Frisbee 1961]. This seems to be the first use of an actual name for the geyser since Weed's. By the mid-1970s the geyser in the Geyser Creek Group had acquired at least six names (Avalanche, Rockpile, Talus, Marvelous, Geyser Creek and Spray) [Bryan 1979] p.159.

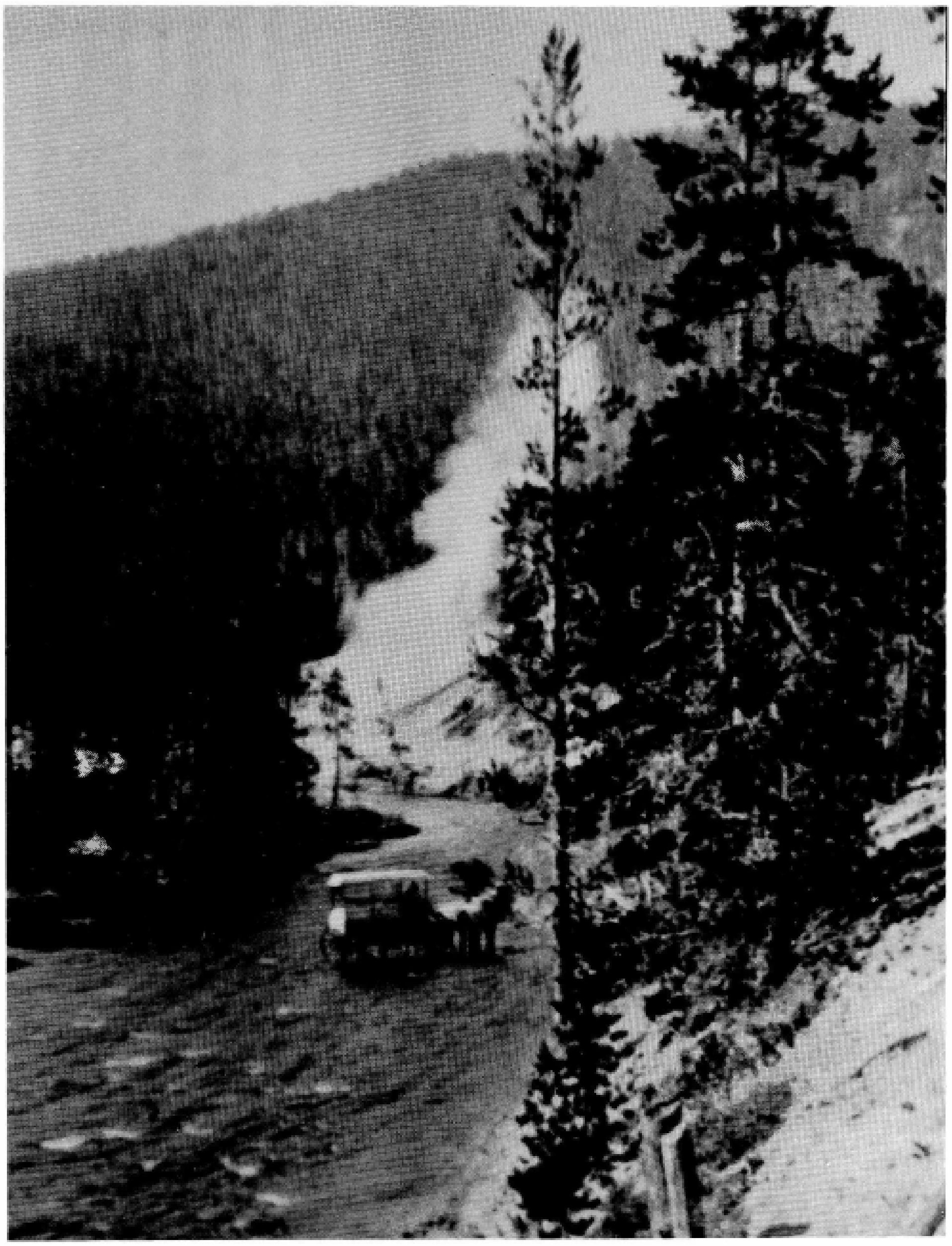
The sources of the names Talus and Spray are currently unknown. The name "Geyser Creek" was simply formalizing a term commonly used to designate that geyser. "Marvelous" was used by Bryan in the early 1970s until he learned that another name was more commonly used [Bryan 1996].

That name was "Avalanche Geyser." By the mid-1970s it was in common use by Norris Geyser Basin naturalists and volunteers [Vachuda 1996] . Through their use in the Norris Logbooks, in their guided walks to the area, and other use, by the mid-1970s, this was the name new gazers were told was the name to use. Photographs taken in 1979, for example, were labeled "Avalanche"[Strasser 1995]. A contingent of gazers who lived at Lake and frequented Norris in the late 1970s and early 1980s all called the geyser "Avalanche" [Schrayer 1996].

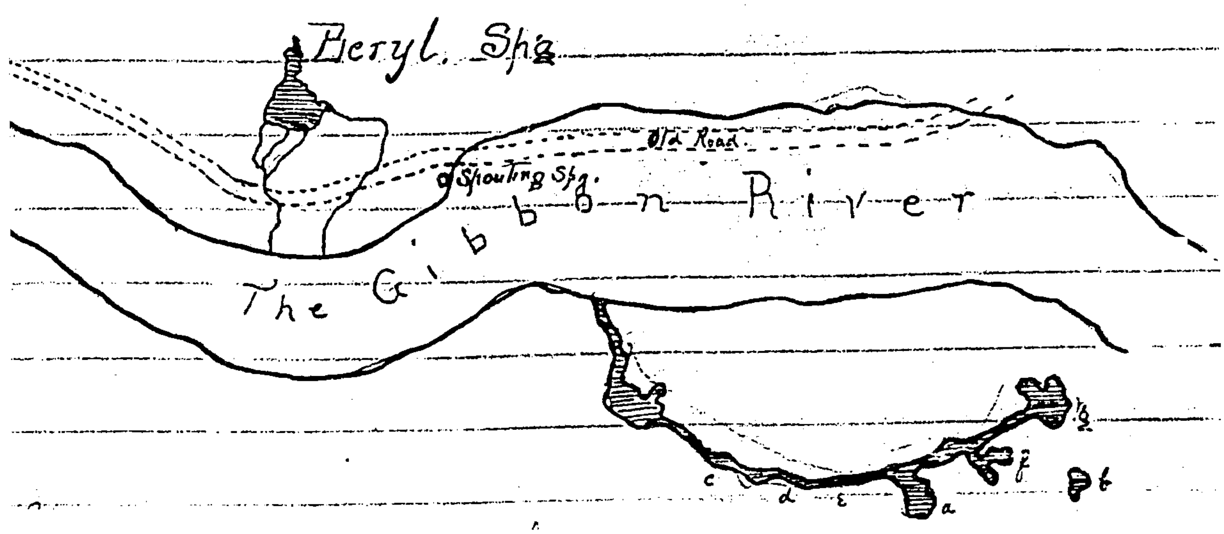
When I first visited Geyser Creek in 1981, "Avalanche" was the name used by the more experienced members of the group I was with. At the same time, the exact location of Oblique was under some speculation. Part of the corduroy road is still visible on the east bank in a thermal area beside the present bridge across the river north of Beryl. Farther south, and prior to the fires of 1988, there was also a noticeable gap in the trees just



Map 2
Geyser Creek Basin [Frisbee 1961]



An 1884 photo showing a wagon fording the Gibbon River on the old wagon road just below Berly Spring. Photo from YNP photo archives.



Map 3
"Springs on the East Bank of Gibbon" River
Walter Weed sketch Map [Weed 1883]

the right width for a wagon road. An examination in 1982 of the east bank of the Gibbon River by several gazers (including myself) showed at least one possible site for Oblique existed, a boiling spring in an alcove opposite Beryl Spring.

The only problem with this location is that it is only about one mile from the entrance to the canyon. But this objection depends on how accurate one believes Peale's use of "about 2 miles" really was, and how much uncertainty is implied by "about." In any case, Map 1 distinctly shows a "small group" at the proper location in the canyon. Weed also describes "the largest cluster of springs [in the Gibbon Canyon are] situated two miles south of the north end of the cañon" [Weed 1883]. So it seems likely, as Paperiello has suggested, that at that time the north end of the canyon was considered to be near the Chocolate Pots.

So a more likely possibility is that Oblique Geyser was located near Beryl Spring. It turns out that Weed also sketched a map of that area, on which he placed a geyser about forty to fifty feet northeast from Beryl. A sketch map (Map 3), shows a "spouting spring" located between Beryl and the Gibbon River. The text itself describes the spring as being "[a]bout 3 feet from the river, and one foot above it[,] an irregular vent which issues a jet of boiling water and steam, the spray forming a column 10 feet high."[Paperiello 1996], [Weed 1883] That area is now buried by the road, a not uncommon practice in Yellowstone's early road-building days. This spring, or a successor, may have been again encountered in the early 1960s, when it was established that it was connected to Beryl:

> "In the course of road construction in the vicinity of Beryl Spring a gushing pool of near boiling water was uncovered beneath the road approximately 45 N.E. of Beryl Spring. Further excavation of old fill material in the area lowered the overflow level of this new spring about 3-1/2 feet. This has led to a corresponding decrease in elevation of the water in Beryl Spring." [Fournier 1962].

The ultimate fate of the spring is not described.

In any case, there are several candidate locations for "Oblique" in the Gibbon Canyon. Also, by 1982 the name "Avalanche" for the Geyser Creek feature had become entrenched, in common usage by those who visited the geyser, used in written records, and used to describe the geyser to newcomers.

Resurrection of "Oblique"

During his research into the history of the place-names of Yellowstone, Whittlesey discovered Weed's field notes in the national archives. [Whittlesey 1988] It was his insistence on the use of this name that led for it to be used on the geyser which by then was being called Avalanche.

Whittlesey's justification for replacing Avalanche rests on two tests. First, that the name Oblique was properly used by Weed, and that no other name was being used for the feature. As the previous section demonstrates, the latter test fails completely, and the first is suspect, because it is based on the assumption that Weed knew what he was doing when placed the name Oblique on the feature in Geyser Creek.

Some of the interpretations of Weed are troubling, because they disregard possible explanations for Weed's error, while at the same time citing them. About Peale's original mention of Oblique, he writes in a footnote: "Peale stated that it spouted 75 feet high. Either this was an error, or Oblique changed 1878-83." [Whittlesey 1988], p.1293. In many places in his *Wonderland Nomenclature*, Whittlesey uncovers situations where names have drifted from one spring to another, especially in the earliest days of the Park. Yet in this particular case he fails to consider that perhaps Weed was wrong in his location of "Oblique," which would explain the apparent change in activity, instead preferring a major change in the geyser's activity. This interpretation that Peale was in error is further supported in a second footnote on that page: "In another notebook, Weed stated that this was 'probably the "oblique geyser"'". [Whittlesey 1988] , p.1293. In other words, Weed himself recognized that he wasn't sure where Oblique was.

Portion of Map of Yellowstone National Park in [Norris 1883], p.234
Map 4

Whittlesey also notes that "Norris's map of 1881 clearly shows a trail he opened *that year* running through the present Geyser Springs area ..., a trail that Peale probably knew about before his 1878 report was published in 1883. [emphasis added]." [Whittlesey 1988], p.1293. (Note: this statement appears as if part of a footnote which otherwise references a description by Phillips of a geyser in the Geyser Creek group. A closer examination show it was added later).

This is wrong for several reasons. The most obvious assumption should be that Peale refers to the road as it existed in 1878, not as it would appear three years in the future. Also, note that the map included in [Hayden 1883] (Map 1 , included in this report) clearly shows the road running near its present location, not through Geyser Creek.

The route taken by this trail is shown in Map 4 . Also, Norris himself wasn't impressed with his trail: "A bridle-path extends from the end of [the road to Geyser Creek] through the earthquake shakes and fallen timber— 11 miles in all—... but it is unsafe to attempt to follow it without a guide."[Norris 1883], p.250. The use of the term "bridle-path," as opposed to "road," is probably a good indication of the quality of the trail. It's also been observed that given the probable location of the bridle-path, that the geyser would have had to erupt at a 45° angle to a height of 100ft. [Paperiello 1996].

It is also claimed that as part of the Survey naming features, Weed had the right to move names around or change them as he saw fit. While this might be true, especially in field notes, it is hard to believe that he would do this for a feature whose name had already appeared in print [Peale 1883], for then the question becomes, does a reference to Oblique mean Peale's "Oblique," or Weed's "Oblique."

Despite these problems, this interpretation of Oblique's location gained immediate currency among geyser observers, deferring to the authority of the source, and despite not having been presented with the facts behind these determinations. The fact that this geyser had been called by so many names helped, in that no one had previously made any attempt to determine what were the proper names for the more obscure features. For example, when he revised his book on the geysers, T.S.Bryan changed the name in the text, but didn't include it in the index [Bryan 1982], p. 159, 223.

Conclusion

The original Oblique Geyser was located in the Gibbon Canyon south of the Monument Geyser Basin, near present day Beryl Spring, probably on the west side of the river. Walter Weed, knowing that a large geyser existed in the area, mistakenly labeled the largest geyser he observed in the Geyser Creek area with the name Oblique. The name Oblique almost immediately fell into disuse. Despite the use of as many as five other names, by the late 1970s, it has been established by entrenched usage that the name of this large geyser was Avalanche. It was around that time that Whittlesey, in his research, re-discovered Weed's passing use of the name Oblique, and proceeded to impose this mistake upon present-day observers.

With the more obscure springs, there has been some effort to restore their original names, especially when their current names are only a few years recent, or haven't become entrenched. And this is the proper thing to do. Yet in this case, despite the entrenched name, we have seen an attempt to impose the wrong name on the wrong geyser, a case where digging through old records had the effect of making matters worse by causing greater confusion.

It is recommended that the name Oblique Geyser be reserved for the original geyser in the Gibbon Canyon, even though the locations is unknown, since it may reactivate some day, and that the entrenched name Avalanche Geyser be restored to the large geyser in the Geyser Creek group.

Finally, thanks go to Rocco Paperiello and Tom & Genean Dunn for providing copies of some of the source material cited in this report.

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Notes on "Pocket Basin Geyser"

by

Mike Keller

ABSTRACT: The following is a report on the extreme variability of "Pocket Basin Geyser," and what one might expect in the attempt to view its eruptions.

Scott Bryan [1995] wrote the following about "Pocket Basin Geyser:"

> [This geyser] as often as not known simply as "Pocket Geyser," lies near the natural drainage exit of the Pocket Basin mud pot area... The nature of its geyserite formations and its very deep runoff channel indicate that it is an old spring that reactivated rather than a new one. It has been known to go as long as several days without erupting, yet at other times the intervals are regular and [are] as short as 14 minutes... ...some jets reaching over 15 feet high. The entire play lasts about 45 seconds.

Pocket Geyser is an excellent example of a cyclic eruptive feature. Located in the River Group of the Lower Geyser Basin, "Pocket Geyser" has been active every year since 1976. All signs about the geyser indicated that the recent activity was new. The area around the basin is still being carved by the eruptions.

I spent about three weeks watching "Pocket Geyser" in the summer of 1989. For the most part, its time of eruption was totally unpredictable. In fact it was easier to tell when it was not going to erupt! Still, there were some fairly consistent patterns within its activity. The water would rise within its vent, and then "Pocket Geyser" would do one of two things -- overflow or erupt. Note that it could even erupt before it had its first overflow. This happened on about 9% of the eruptions witnessed.

The pattern of "Pocket Geyser" was very consistent, except when it erupted before it had its first overflow. Once its water level was about 6 inches from the top of the vent, the pool started to palpitate and bubble. It took from 45 to 90 seconds from this point for Pocket to reach "maximum" overflow. If Pocket was going to erupt, it would be now. The boiling would suddenly become rapid, and the geyser would quickly climb to a height of 8 to 15 feet. Its usual duration was 30 to 60 seconds. If Pocket Geyser did not erupt, the basin would drain quickly. At no time would the basin become completely empty. It would then be from 7 to 18 minutes before the next "maximum" point of overflow. The duration of each overflow was very consistent, but the number of overflows that would occur was unknown. The high degree of variance in Pocket Geyser's interval was a mystery. There was no visible reasons as to why it could have an interval of 20 minutes followed by one of over 100 minutes. Once the fourth or fifth overflow was reached, the water level remained unchanged within the cycles until the next eruption.

TABLE I

ACTIVITY OF POCKET GEYSER: **6/20/89** TO **7/15/89**

Date	**Time**	**# of overflows**	**Duration** (sec)	**Interval** (min)
6/20	10:49	6	43	
	12:01	4	39	72
	12:10	2	42	51

	14:16	3	38	66
6/22	15:34	5	41	
	15:58	0	39	24
	16:51	2	41	53
	18:55	7	52	124
	19:32	1	44	37
6/23	17:53	4	47	
	18:48	2	44	55
	19:50	3	41	62
	20:41	2	43	51
	21:50	3	42	69
6/25	07:21	>2	47	
	07:46	0	39	25
	09:10	5	54	63
	11:52	10	55	162
	12:37	1	40	45
	13:16	1	42	39
	14:12	2	44	56
	15:37	5	53	85
	16:48	4	45	71
	17:06	0	40	18
6/26	13:26	>1	42	
	14:14	2	46	48
	17:03	12	50	169
6/28	05:57	>1	52	
	06:14	0	37	17
	07:36	5	45	82
	09:10	6	48	94
6/30	10:16	>3	42	
	11:28	4	44	72
	13:14	7	43	106
	14:13	3	46	59
	16:20	10	51	127
	17:43	5	32	83
7/2	09:53	>4	42	
	11:25	6	48	92
	12:04	2	45	39
	17:01	23	53	257
	18:21	5	44	80
7/5	08:08	>1	38	
	09:55	3	39	57
	10:52	3	38	57

	11:32	2	44	40
	12:35	6	42	63
	14:02	8	36	87
	15:14	5	45	72
7/6	05:23	>1	43	
	06:29	6	48	66
	07:39	6	43	70
	08:23	4	49	44
	08:54	3	50	31
	10:48	9	50	114
	11:47	5	43	59
	12:03	0	41	16
	13:44	7	50	101
	14:29	8	44	45
	15:12	2	52	43
	17:40	12	62	148
	18:38	5	50	58
	19:37	5	33	59
7/10	12:03	>6	42	
	12:49	3	39	46
	14:01	5	41	72
	15:47	8	50	106
	17:12	6	48	85
	17:44	2	50	32
	19:21	8	43	97
7/12	08:24	>1	51	
	09:55	7	42	91
	11:06	5	50	71
	12:30	8	58	84
	13:00	2	49	30
	13:54	3	47	54
	15:16	9	44	83
	18:27	16	60	191
7/15	04:41	>1	49	
	06:55	11	44	134
	08:44	8	48	109
	10:07	7	57	83
	12:31	15	43	144
	12:56	1	41	25
	13:48	3	44	52
	14:49	6	58	61
	15:59	7	46	70
	17:11	7	42	72
	18:09	6	55	58
	18:35	0	32	26

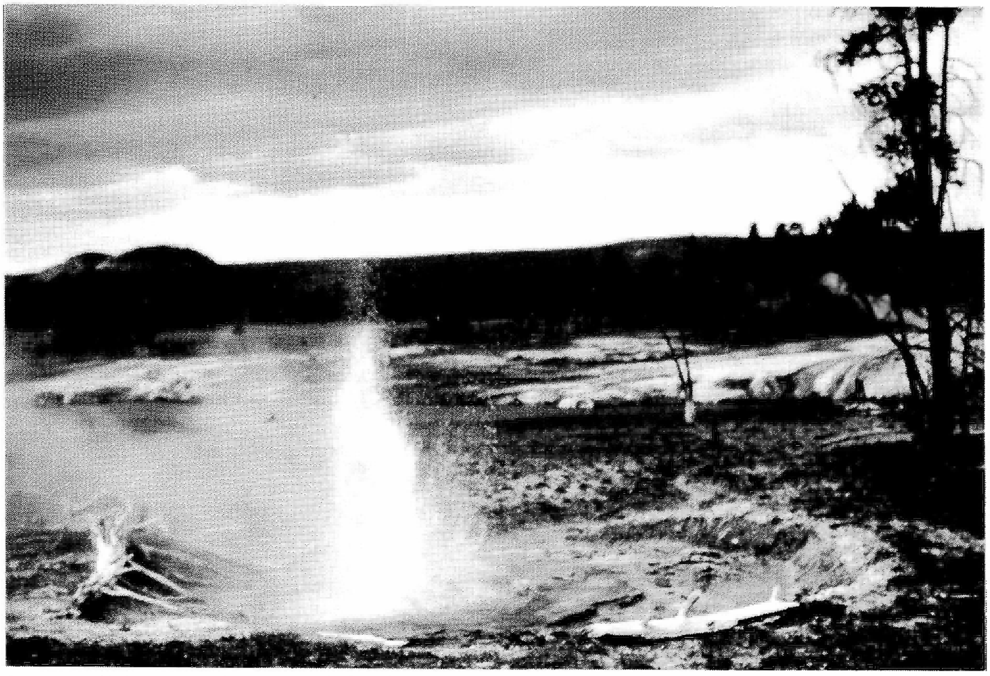
TABLE II

OVERFLOWS TO ERUPTION DATA ON "POCKET BASIN GEYSER"

# of overflows	eruptions	% of eruption total
0	7	9
1	4	5
2	11	14
3	9	11
4	5	7
5	11	14
6	8	10
7	7	9
8	6	8
9	2	3
10	2	3
11	1	1
12	2	3
. . .		
15	1	1
16	1	1
. . .		
23	1	1

Reference:

T. Scott Bryan, *The Geysers of Yellowstone*, University Press of Colorado, 3rd Edition, 1995.



POCKET BASIN GEYSER Paperiello Photo

"A Pronounced Weakness for Geysers": Early Geyser Gazers in Yellowstone

by

Lee Whittlesey

ABSTRACT: The term "geyser gazer" is a more modern invention, but Yellowstone's "geyser gazers" have existed as long as there was a national park, and perhaps even before there was a park. The following paper attempts to highlight a few of the more interesting geyser gazers of earlier times.

"He is said to become at times so excited when present at an eruption of a large geyser, as to burst into tears."
-- 1881 park visitor, describing Dr. F. V. Hayden.[1]

Geysers are rare and strange and wonderful natural treasures that do not exist in many places on the face of the earth. The earliest Yellowstone travelers loved them fervently and ecstatically. "A geyser!" wrote an 1897 traveler, "How shall one describe it or explain it?" And he waxed poetic in trying.[2]

There was an immediate need on the early Yellowstone tours to predict geyser eruptions just as there is today. Visitors and guides alike wanted to know when to expect the great spoutings, especially from the larger and "less regular" geysers such as Beehive, Giantess, Giant, Daisy, and Grand geysers. Accordingly, a network of oral informers developed among those who possessed significant interest. Often those persons were stagecoach drivers or other "park guides."

Whether 1830s fur trapper Warren Ferris can be classed as a "geyser gazer" under today's definition is debatable. Ferris heard accounts of the hot springs and geysers from Manuel Alvarez at the Bear Lake Rendezvous in 1833. The next season, with two Indians, he headed east from Henry's Lake and eventually made it to the area of the Upper Geyser Basin. His visit was purely one of curiosity., and with that in mind one could call him a "gazer." On the other hand he was a short-term visitor and not someone who really spent time in the basins studying geysers in detail simply because he loved them (what geyser gazers do and are today). Regardless of what one calls him, Ferris stayed there overnight and spent the next day watching the geysers, about which he later wrote: "I immediately proceeded to inspect [the springs], and might have exclaimed with the Queen of Sheba, when their full reality of dimensions and novelty burst upon my view, 'the half was not told me'."[3]

The 1870 Washburn party had gasped and effervesced over the geysers. By 1871, the true geyser enthusiasts had arrived in Yellowstone, having heard and read the accounts of the Washburn party. These "geyser gazers," for that is what they are called today, were and are a different breed of person. Other park features such as animals, canyons, mountains, lakes, or waterfalls did and do not matter so much to them; they lived and live only for geysers and hot springs, which they today call "thermals." From earliest Park days, these people generally wanted to tell anyone who would listen about their passion, and that in itself constituted a kind of early interpretation of park features. In using the term "geyser gazer," I differentiate between those with a passion and those who were and are merely passingly interested visitors.

Among Yellowstone Park's earliest "geyser gazers" were Drs. F.V. Hayden and A.C. Peale of the 1871 Hayden survey. Dr. Hayden, as described above, sometimes burst into tears when viewing a geyser. An 1872 visitor added: "It is said of Prof. Hayden -- a man of extremely nervous temperament and with an unbounded enthusiasm for the sciences

[1] Banard Leckler, "A Camping Trip...". *American Field,* 2:237, March 8, 1884.

[2] Wade Warren Thayer, "Camp and Cycle in Yellowstone Park," *Outing,* 32:19, April, 1898.

[3] Warren Angus Ferris, *Life in the Rocky Mountains, 1830-1835*, edited by Leroy Hafen, Denver, Co.: The Old West Publishing Company, 1983, p.326-9, 334.

-- that he cannot compose himself in the presence of a geyser in eruption; but, losing recollection of the material world for the time, rubs his hands, shouts, and dances around the object of his admiration in a paroxysm of gleeful excitement."[4] Dr. Peale was less prone to theatrics, but still had a passion for thermals. He wrote the first treatise on the Park's hot springs and geysers, as well as numerous articles on not only Yellowstone's but also the rest of the world's hot springs. Peale, being a scientific man, was not overly given to writing much about his personal feelings for geysers (or his trips around the basins for purposes of explaining them to others), nor were his successors, geologists Arnold Hague and Walter Weed. But these four men were fascinated by thermals and wrote thousands of pages on them. No doubt all three gave many short "tours" of geyser areas; Hague in particular conducted a great number of his fellow geologists through the thermal basins of Yellowstone during the summer of 1891. But the four men's contributions to Interpretation are easier to evaluate from a purely informational standpoint than they are from a lecture or "program" standpoint.

By 1880, some Yellowstone "guides" had become geyser enthusiasts and were imparting their knowledge to visitors. There are probably many that we will never know about, but Wilbur Edgarton Sanders and George Graham are two about whom we do know.

Sanders first visited Yellowstone as a child with his father during the 1870s. In 1880 and 1881, he also made visits and kept journals of those trips. From those journals it is apparent that Sanders was very interested in the geysers. When one reads his early journals, it is evident that Sanders was a true geyser enthusiast. One reads:

> Gen'l Sheridan is now camped near us and he with the other high officials with him as well all the civilians in the whole Basin went over about 4 PM to see the Grand Geyser spout. We waited until about 5:30 before she began but it proved to be a grand eruption and fully repaid us for all our patience. She played 8 times of which the 5th and 6th proved the best. She at times threw the stream up fully 150 feet. Ladies, Officers, Civilians, and soldiers yelled, talked, screamed, laughed and nearly danced at the sight. After it was over I waited to see the crater and basin refill and this proved quite an interesting sight. Today we have seen the Soda Geyser, the Fan, the Riverside, the Grand, the Sawmill, the Castle, old Faithful and the Splendid Geysers play today.

Sanders apparently was so interested that he asked his father, Wilbur F. Sanders, a very prominent Montana Politician, to write to Arnold Hague asking him to include his son with the park survey that coming summer of 1884. Thus, while on summer vacation from Columbia College of Illinois, he accompanied Arnold Hague, Walter Weed, and the other members of the U. S. Geological Survey on their 1884 trip to Yellowstone. Sanders' thermal notebook of that trip is in the National Archives with others of the survey.[5]

George Graham, a Scotch Canadian around thirty-five years of age, was present in Yellowstone during the season of 1881, where he worked out of the Marshall Hotel. According to a traveler who enlisted his services, Graham had been there for several other seasons as well. He seems to have been quite interested in the geysers, as his employers noted when the subject of seeing Giantess Geyser came up:

> George said that probably not a hundred persons had ever seen it in action, although many people, when they get out of the Park, claim that they have. He was one of the oldest guides in the place, and had never seen it otherwise than as still as a pond, and rather doubted the great stories told about it.

But the party did see Giantess erupt along with numerous other geysers in the Upper Geyser Basin, and their early "geyser gazer" guide commented on their luck:

> George was dumbfounded at our good fortune, and said we were the luckiest party

[4] Harry J. Norton, *Wonderland Illustrated...*, 1873, p. 30.

[5] W. E. Sanders, [Trip to Yellowstone Nat. Park], 1880; [Journal of Wilbur Edgarton Sanders Aug 19 - Sept 8. 1881]; both at the Montana Historical Society. Wilbur Fisk Sanders, Letter to Arnold Hague, dated May 31, 1884, NA, RG 57, E - 90, Box 1, Entry 67.

> that had ever been in the Basin; no other, so far as he knew or had heard, had ever been able to witness the eruptions of all the larger geysers, although many had remained a week or two in the Basin.[6]

No doubt many of the park guides and stagecoach drivers of that era were also "geyser gazers." Geologist Arnold Hague, in discussing Giant Geyser's tendency in 1883 to erupt every two weeks, gave that strong impression: "The average interval was 13 days, 14 hours, and 45 minutes, which was at that time in accord with the popular opinion of the guides that it was, as they termed it, a fortnightly geyser.[7]

Hague's mention of "the guides" for geysers who were in place in 1883 is confirmed by a diary excerpt of Henry and Frances Reynolds. They traveled to Yellowstone that summer by wagon and spent three days in the Upper Basin where they saw the Giantess, Splendid, Grand, and other geysers in eruption. They mentioned that "the shouting of the park guides" attracted them to Grand Geyser and that "the guides gave out . . . timely information" so that a good crowd could be on hand for an eruption of Beehive Geyser. We do not know who these 1883 "geyser gazers" were, but two of them personally escorted the party around Geyser Hill.[8]

These early geyser enthusiasts imparted much information to visitors and to park employees, such as stagecoach drivers or park guides, who in turn passed it on to their visitors. In fact, some of these people were themselves stagecoach drivers or guides, such as the driver who chauffeured Edmund Muskpratt to the geyser basins in 1884:

> We were lucky in seeing seven or eight [geysers] play, as our driver knew the signs and drove furiously to reach the springs in time for the display.[9]

There were others. G.L. Henderson, was himself a geyser gazer, as was George Marshall, another early park guide, and "Geyser Bob" Edgar, a stagecoach driver. A stagedriver named James O'Neill, who was driving in 1885, was apparently a geyser aficionado, for a passenger noted that "he knows, apparently, each one of the 600 odd holes in the ground in the National Park from which hot water flows or is projected to greater or less heights, together with their varying characteristics." At Old Faithful, this traveler reported that O'Neill came running to announce, "the Castle is going off!"

One early "geyser gazer," J. C. Callahan, is a mystery. We know of him only because Leslie Quinn, an eighteen-year Yellowstone employee, recently purchased Callahan's 1887 geyser-eruption card in a second hand store. A copy is now available in the Yellowstone Research Library, but no known library possesses an original. The card reads:

> A Record of the Eruptions of the Largest Active Geysers in the World; the Upper Geyser Basin, Yellowstone National Park. Compiled from official reports, personal experience and observations, by Mr. J. C. Callahan, during the season of 1887.

Geyser eruption statistics are then listed for twenty-eight geysers, as well as distances and altitudes in the park. Apparently Mr. Callahan spent much of the summer of 1887 observing geysers and writing down his observations. But his notes, if they still exist, have not surfaced, and nothing else is known of him. He and his geyser card are one of those many Yellowstone enigmas which simultaneously intrigue and torment us.

George Anderson, who was superintendent of Yellowstone 1891-97, was also very interested in geysers. He ordered his soldiers stationed in geyser areas to keep records on geyser eruptions during the seasons of 1893-1897. And with one of his

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[6] Banard H. Leckler, "A Camping Trip...", *American Field,* 2:236, March 8, 1884. It seems possible, if not likely, that this George Graham was the same man as George Graham Henderson, a blacksmith in the park during the 1880s, who later was a partner in the Marshall's (or Firehole) Hotel with Henry Klamer. Both men were at Marshall's in 1881, both men were Scottish, both were in the blacksmith trade, and both had the first two names George Graham. G.L. Henderson, a friend of this man who had business ties to him through a son-in-law, referred to him as "George Graham" in his 1883 letter to P.W. Norris and stated that Graham was a devotee of Mr. Norris.

[7] Arnold Hague, unpublished ms, "The Geyser Basins," p. 35, in NA, RG 57, Arnold Hague papers, Box 11.

[8] "An Excerpt from the Journal of Dr. Henry Sheldon Reynolds incorporating data from the Journal of Frances Reynolds (his wife), Aug 22 to Sept 15, 1883, typescript, n.d., pp. 3-4, YNP Library.

[9] Edmond K. Muskpratt., *My Life and Work,* 1917, p 223.

compatriots, Anderson constantly looked at and studied geysers:

> Both Captains Anderson and Scott have a pronounced weakness for geysers, and were always stopping at every little steam-jet to examine it.[10]

An 1895 traveler, going between the Fountain Hotel and Upper Geyser Basin, mentioned the way the park guides and drivers traded information among themselves, especially with regard to geysers:

> It is common to hear the guides say to each other: 'They say that Old Buster went off last night,' or 'Is there any indication of The Grotto [Geyser] doing anything?'[11]

This is the same thing that park naturalists, tour guides, and geyser gazers do today in Yellowstone. Park administrators had noticed by 1898 that the trading of such geyser information might be useful in the aiding of visitors. The superintendent noted that year that eruptions might be predicted from the temperature of the water, and that if so the park would start making geyser predictions to "thus afford tourists the opportunity of seeing them."[12]

F.E. Corey and Roland Grant were two other early "geyser gazers." Corey, a medical doctor from Alhambra, California, got interested in Yellowstone geysers about 1900. In 1903, he wrote to the park:

> For several years I have been giving talks and showing views of the National Park to entertain my friends and so have become much interested in geysers and have formed in my mind a theory of their cause; whether new or not I do not know. I have engaged to give an exhibition soon and would like very much to get some more information . . .[13]

Nothing else is known of Corey. Dr. Roland Grant seems to have been a very interested "geyser gazer." An article of his, published in a scientific journal in 1908, discussed visits he made to the Park once "before the railroads," and then again in 1891, 1899, and 1900. The article hints that there were other visits made for the purpose of examining thermal features.[14] Grant apparently studied geysers for a very long time. If more of his notes or articles could be found, they might shed important new light on the thermal history of his period. Like other enthusiasts, Grant no doubt gave impromptu "tours" of geyser areas, and I earnestly wish we knew more about both him and Corey.

A number of hotel porters became geyser and hot spring enthusiasts around the Park, at Old Faithful, Fountain Hotel, Norris Hotel, and Mammoth Hot Springs Hotel. There is evidence from hotel company records that they were hired not only for their hotel duties, but also to conduct walking tours for visitors through park thermal areas. I will have more to say about these persons in the chapter on early park tour guides, but for now a single example will suffice. "Joe", last name unknown, was a hotel porter at Old Faithful Inn during the first ten years of the twentieth century. In an era when there were no National Park Service ranger walks or talks, Joe, by virtue of his intense interest in and knowledge of the geysers, filled the void. Joe was apparently there for the seasons of 1903-1908, and probably for a number of others as well. His interpretive geyser walks became well enough known to merit these lines in a guidebook, under the heading "The Walk With Joe":

> "The Walk With Joe" over the Geyser Basin will prove a most interesting one. Incidentally, "Joe" is the head porter of the

10 "In the Yellowstone Park. A Horseback Ride to the Great Geysers", newspaper clipping attributed to *Evening Post*, n.d. [trip in June, 1885], in NA, RG 48, no. 62, roll 3 (hardcopy at YNP Library); Frederic Remington, *Pony Tracks* (New York: Harper and Brothers), 1894, p. 177.

11 "Yellowstone Park Brief Notes of a Trip...", 1895, in Scrapbook 4209, p. 60, YNP Library.

12 Letter from Superintendent, September 30, 1898, in Army Letters Sent, vol. VIII, p. 48, YNP Archives.

13 F.E. Corey to Superintendent, February 15, 1903, Archive Document #6087, YNP Archives. The return letter to Corey from the Park encloses a copy of the superintendent's annual report and gives Corey the address of Frank Haynes in order for him to obtain copies of the *Haynes Guide*. Army Records, Letters Sent, vol. XII, p. 416, February 23, 1903, YNP Archives.

14 Dr. Roland Dwight Grant, "Changes in the Yellowstone Park," *American Geographical Society*, Bulletin 1908:277-283.

> Inn, was there before it was built [1904], and I may add, he knows more about geysers as they play or don't play, than anybody. He tells his story well, in a style peculiarly his own, composed of facts as to geysers' habits and reliable statistics. Joe gets his information first hand; he arrives in the Park early and stays late, and being a close observer as to geysers (his stock in trade) he is able to tell you when the Giant played last and when due again; with the others just the same, and his calculations are accurate. "Joe says" is to be relied upon. Joe's hour for starting is usually after luncheon; he will make it known when he is ready. Joe's excursion over the formation commences at Old Faithful and extends north to the Riverside, taking in all the geysers of importance.[15]

Interestingly, these lines were included in the 1914, 1916, and 1923 editions of the same guidebook, giving us the impression that either Joe was still there or else interpretive walks with other guides had simply become homogenized into "The Walk With Joe."

All of the park stagecoach companies hired "walking guides" to give tours to their patrons of park thermal areas, but the Shaw and Powell Company actually kept a person at their Old Faithful camp (present Old Faithful Lodge) who kept track of the geysers so that their predicted times of eruption could be given to visitors. This person, depending upon the intensity of his interest, could be considered an early "geyser gazer."[16]

So few instances of past "geyser gazers" are known to us (it is certain that there were more than I have chronicled here) that I have elected to mention two others from a later period. One is a mysterious "Dr. Van Pelt" who studied geysers from about 1918 until 1926 or so, and the other, Thomas J. "Geyser Bill" Ankrom of the 1930s. Dr. Van Pelt arrived in Yellowstone sometime just after the National Park Service was formed (1916) and appears to have been present most if not all summers through around 1926. He became quite interested in the geysers and reached the point where park personnel routinely consulted him for geyser information. No less of a person than Ansel F. Hall, chief naturalist for the NPS, seems to have consulted Van Pelt regularly, but little else is known about him, and his geyser reports, if they exist, have not surfaced.[17]

Considerably more is known about "Geyser Bill", who seems to have arrived in Yellowstone in 1929. His "biography," published in a newspaper in 1932, reads as if he could have been one of today's "geyser gazers", i.e. a person truly possessed by thermal phenomena, and willing to share his knowledge with any visitor who happened by. I present it here in its entirety because it so typifies the modern "geyser gazer":

> The only name by which he is known in Yellowstone National park is "Geyser Bill." To him geysers are pets, hobbies, school, work, and play. He considers a geyser like others might look upon a favorite dog or a book. He cultivates them like one would a friend. He pampers, pets and protects them as one would a child. He studies them as one might a favorite book.
>
> "Geyser Bill" eats, sleeps, and plays with the geysers in the park. He knows their every mood, records their every impulse. A tall, gaunt, weather-beaten man of sixty or more, he can be seen from early morning until late at night on geyser hill near Old Faithful or at any other geyser basin in the park. Unobtrusive, he is rarely singled out by park visitors, for his garb is simple -- an old army shirt, khaki trousers and sneakers.
>
> But let anyone lay a hand on a geyser cone or on any of the sinter deposited about the geyser for centuries and old "Geyser Bill" goes into eruption. He simply will not tolerate any tampering with or chipping off any formation. To those who are really eager to learn about the geysers, Bill will unfold a wealth of information gathered

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[15] Reau Campbell, *Campbell's New Revised Complete Guide and Descriptive Book of the Yellowstone Park* (Chicago: Roger and Smith Company), 1909, p. 112.

[16] Shaw and Powell, "Yellowstone Park by Camp," 1915 brochure in Army Records, Item 52, File 130, "Financial Reports: Advertisements of Concessioners, 1914 and 1915," YNP Archives.

[17] A.F. Hall, 1926 educational report in box K-10, YNP Archives. See also Dorr Yeager, "Memorandum to Mr. Albright", August 19, 1928, (one page on geysers), vertical files, YNP Library.

from his four years as a geyser observer. He probably knows more about the habits and whims of Yellowstone geysers than any man alive. He comes in long before the season opens and stays long after it is officially closed. This spring he came on May 20, and he declares that he will stay until the heavy snows drive him out.

An old army sergeant, retired from active duty in 1918, this man, who admits to the name of T.J. Ankrom, calls his little car his home. It is equipped with a cot and paraffined canvas, and many a night he sleeps beside a geyser which premonition and close study tells him is about to erupt.

Geyser Bill awakes each morning to the reveille of the Daisy geyser and his lullaby is the sizzling spout of Old Faithful or the Riverside geyser, two reliable and regular vents.

On a day when a number of prominent but irregular geysers choose to play, "Geyser Bill" is a harassed and busy individual indeed. Such an occurrence brought him near a nervous breakdown recently when the Giant geyser, Yellowstone's greatest spout[er], had hardly ceased playing before the Giantess, consort of the big one, began an unexpected and mysterious show of her own. She plays for nearly 36 hours, and it nearly broke "Geyser Bill" up in business when the Beehive, the Grotto and several others began their show while the Giantess was still in play.

To understand his difficulty, it must be explained that Bill keeps voluminous notes. With camera on one side of him, stop-watch on his lap or in hand, and a typewriter placed on his knees or on a log used as a temporary desk, he sits beside the geyser cone and waits. Meanwhile he pecks away at his typewriter, recording every indicator offered by bubbling water, steam, or overflow. His notes read like a statistician's diary, with minutes and heights and distances packed together in a volume understandable only to him.

Like a mother with a restive child, "Geyser Bill" spends many a night watching over his words. When a geyser is overdue there is no sleep for Bill. He wonders what is the trouble and will not rest until the spout has resumed its regular breathing.

As an army sergeant Bill saw two years service in Alaska, more than two years in Porto [sic] Rico, two and a half years in the Phillippines, several months in Cuba in 1898 with Shafter's expedition and later service in the World war. His only known relative is a brother at Cedarvale, Kansas.[18]

"Geyser Bill" Ankrom left detailed notes on his observations of geysers for the years 1931-33, many of which repose in the Yellowstone Archives.

Today's "geyser gazers" are organized and continue to aid Interpretation in Yellowstone. Most of them are members of an organization known as the Geyser Observation and Study Association (GOSA),and they continually aid Interpretation in Yellowstone by gathering and reporting information on the constantly-changing geyser scene in a newsletter and in an annual publication. Some of Yellowstone's best thermal experts are members of this organization, and they often give the same kinds of impromptu talks and walks through thermal basins that their less organized forebears did. A number of National Park Service personnel in Yellowstone are members of this organization. Most NPS persons think the organization provides a valuable, free service to the Park and to visitors, in an endeavor (geyser monitoring) in which the Park Service has never had the money or the manpower to adequately carry out.

[This article is excerpted from Lee Whittlesey's upcoming book: *Yellowstone's Horse-and-Buggy Tour Guides: Interpreting the Grand Old Park, 1872 - 1920,* slated for publication in 1998]

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18 " 'Geyser Bill' Keeps Close Tabs on Spouts in Yellowstone Park," *Livingston Enterprise,* July 30, 1932.

The View from Fountain Overlook
July and August 1994

by

David Starck

ABSTRACT: A number of theories concerning the inter-relationships among the geysers of the Fountain Group have been proposed over the years. This is an attempt to find which relationships were dependable -- at least during a few weeks in the summer of 1994.

INTRODUCTION

For two weeks in 1993, my attempts to see Fountain Geyser in eruption were unsuccessful. Not enough information concerning its current activity was available. In 1994 I was determined to see Fountain erupt.

After only a short wait standing on the overlook, I got hooked by the many other nearby geysers and all the activity that takes place in that area -- from both geysers and visitors.

"Oh, this is a dead-end," was the most often heard phrase from visitors while standing on the overlook boardwalk above Fountain and Morning Geysers. "No it's not," I'd say to myself, "this is the beginning of a geyser-gazer's dream!" There are so many geysers in sight that it's hard to keep track of them all! My main focus was on the activity of Clepsydra, Spasm, Jet, "Sizzler"(or UNNG-FTN-2 or "Super Frying Pan"), Twig, and of course, Fountain and Morning. Some data on other geysers was also recorded. During 4 days in July and 5 in August, I saw Fountain erupt 13 times (10 times from the start). It erupted from various pool depths with intervals as short as 3 hours 56 minutes. I saw Twig attempt over and over again to get started only to drain again. I timed the durations of Jet and found that they were incredibly constant. I saw my first superburst from Fountain, pauses of Clepsydra both between and even during Fountain eruptions, and my first eruption of Jelly Geyser. And off in the distant Kaleidoscope Group, I witnessed several large eruptions including those of Drain, Honeycomb, and Deep Blue Geysers.

From previous years of watching Fountain and Clepsydra (and from reading *GOSA Transaction* articles), I had a few preconceptions and misconceptions: Fountain only erupts when Spasm is erupting. Fountain erupts from a full pool. Jet erupting every 7 to 10 minutes is a good sign that Fountain is ready to erupt. Clepsydra only stops erupting when Fountain finishes its eruption. Jet usually doesn't erupt when "Sizzler" is erupting and Fountain is quiet. And Twig's starts are related to Fountain's stops. While some of these maxims were still valid in 1994, others were not. Here is what I learned from several days of observations from the overlook.

FOUNTAIN GEYSER

Located in the Lower Geyser Basin west of the Fountain Paint Pot, Fountain is one of the major geysers in Yellowstone. Its oval crater has a channel whose outflow is directed toward Morning's basin. Its eruptions are characterized by large bursts of water reaching 30 to 50 feet and lasting for about 30 minutes. (The entire show reminded me of a continuous fireworks demonstration).

Fountain's pool level at eruption varied by about a foot over the course of a few days, so the phrase "erupts from a full pool" had little meaning. At the start of the first two witnessed eruptions (see graphs of July 9 and 10 following), the pool was within 2 to 3 inches of the top of the crater, and overflowing the back channel into Morning's basin. In all the eruptions seen, the pool level surges 4 to 6 inches about one to two minutes before the eruption begins. In the first two eruptions on July 9 and 10, this surge resulted in overflow from the top of the crater, and large waves of water cascaded down the sinter before two spots on the side of the rim nearest the boardwalk began to boil vigorously. This boiling initiated the eruption.

In July, successive eruptions generally began with water levels lower than those of the previous eruption. The August eruptions also seemed to come at lower levels. At the start of the last witnessed July eruption (see graph of July 12), the pool level was down about 12 inches, and water was

Fountain Geyser Oct, 1981

barely coming out the back channel. The 4 to 6 inch surge sent waves out the back channel, and the same two spots near the rim began to boil vigorously, initiating the eruption. This eruption included a superburst that was at least twice as high as the normal bursts. Three other bursts spaced throughout the eruption were also noteworthy for their height.

The variation of Fountain's pool level at eruption made it a difficult geyser to predict. It also tended to sit at its eruption level for several hours before erupting. (See footnote #7 to graph of August 19). Spasm Geyser being in eruption was usually a good sign, but note the graph of the same August 19th eruption when Spasm died 1 hour and 17 minutes <u>before</u> Fountain erupted. Spasm was completely drained for over an hour before Fountain began. Eruptions of Jet Geyser recurring regularly at 7 to 10 minute intervals was also a good indicator, but this could occur for hours. (See graphs of July 9, 11, and August 19, 24, & 25). The best way to predict Fountain's eruption was by knowing some recent prior intervals and the time of the last eruption. I also believe that the drain of Fountain's pool after an eruption can be important to its next interval. From a very few observations, it seemed that if the pool was drained out of sight 10 to 15 minutes after the conclusion of an eruption, the next interval would be similar to the last one. However, if the pool did not drain out of sight, a short interval could be expected. It also appeared from the three times I saw Fountain erupt from a very high pool level (see graphs of July 9, 10, and August 27), that the pool did not drain out of sight when the pool level at eruption was high (within 4 or 5 inches below the top of the crater). This is a conjecture that I would like to follow up on in the future.

Another possible significance of the high pool eruptions on July 10 and August 27could be the fact that Clepsydra quit during the Fountain eruptions. This, however, was not the case with the July 9 eruption, when Fountain's starting at a very high level did not correspond to a pause in Clepsydra's eruption. But, I feel this is still worthy of future study.

Can Fountain's eruptions be predicted more accurately? I do not think so from this data. I do know, for what it's worth, that eating lunch or breakfast in the Fountain parking lot will almost always cause Fountain to erupt.

SPASM GEYSER

Located 5 feet or so off the boardwalk and directly in front of Clepsydra Geyser, Spasm's crater fills rapidly with the onset of an eruption. It boils and spits for several hours at a time. It is sometimes overshadowed by Clepsydra, a more powerful neighbor.

The old adage about Spasm being in eruption before Fountain would go off proved usually true. (See exception on graph of August 19). The shortest period from Spasm's start to a Fountain eruption was 1 hour 41 minutes. (See graph of July 10). Sometimes Spasm played for over 5 hours before Fountain erupted. (See graph of August 25). Thus, while Spasm is a likely indicator for Fountain, you can't hold your breath!

I watched the start of Spasm's eruption only once. On August 19th, I happened to be standing next to Spasm when it began to erupt. The pool filled slightly with cloudy, murky water. The first few boils were quite large and came from a low pool level. After about 10 minutes, the water had cleared up and the pool was full and overflowing.

TWIG GEYSER

Twig Geyser is located about 20 feet east of the boardwalk at the foot of the stairs descending from the overlook to Fountain Geyser. It erupts from a shallow funnel-shaped hole in the sinter after the vent fills with water. This filling can take a minute or less and the eruption consists of a series of small blips of water like the top of a percolator coffee pot. Major splashes may reach 6 feet, but normally the height is 3 or 4 feet.

Twig's recorded durations ranged between 37 minutes and about 3 hours. The only closed interval was 1 hour 25 minutes recorded on July 10. Several times it seemed to have a difficult time getting started. (See graphs of July 11 and August 25). Water would partially fill Twig's crater, splash once or twice and then drain. It did this 7 to 10 times over an hour and a half before it finally filled and erupted. According to Lynn Stephens' article on Twig in *GOSA Transactions*, VOL. V, this was pretty normal behavior in 1991. However, Twig's eruption times did not seem to correspond at all to Fountain's eruptions as she had noted in her 1991 observations of Twig and Fountain.

I also noticed Twig erupting powerfully and in concert with Fountain several times. That is, Twig would burst simultaneously with Fountain and would be more powerful than usual. The two geysers may be somehow be related. Perhaps vibrations of the sinter caused by Fountain's underground plumbing system could shake Twig's plumbing system and cause these simultaneous bursts.

One powerful eruption of "Sizzler" coincided with a powerful Twig eruption. (See footnote #3 on August 26th graph).

On August 24 and 25 Twig showed a "pulsing mode" to its eruption. Its pool would slowly fill, with pulsing water creating small waves or undulations. It would then burst once or twice and then drain about 6 inches. This cycle would then repeat itself. This activity lasted for 52 minutes the first time I saw it, and for over 3 hours the next day.

UNNG-FTN-2: "SIZZLER" OR "SUPER FRYING PAN"

Located in a sinter crack between Jet and Spasm Geysers, and "inside" the loop of the boardwalk, this small geyser erupts from a series of cracks and holes near the boardwalk. The steam emitted from the eruptions can be quite warm when the wind is blowing it toward the boardwalk. It seems to have an excess of energy and a lack of water.

This summer seemed to be a growing season for "Sizzler." It seemed to get more powerful as the summer commenced and at least one of its occasional sputter vents grew from a small hole in the sinter to an 8 to 10 inch crack. I first noticed the enlargement of this vent on August 26th. It is in the loose sinter about 10 feet to the right of the main vent. Hot water from the main vent is now being occasionally splattered over the boardwalk with the help of the wind.

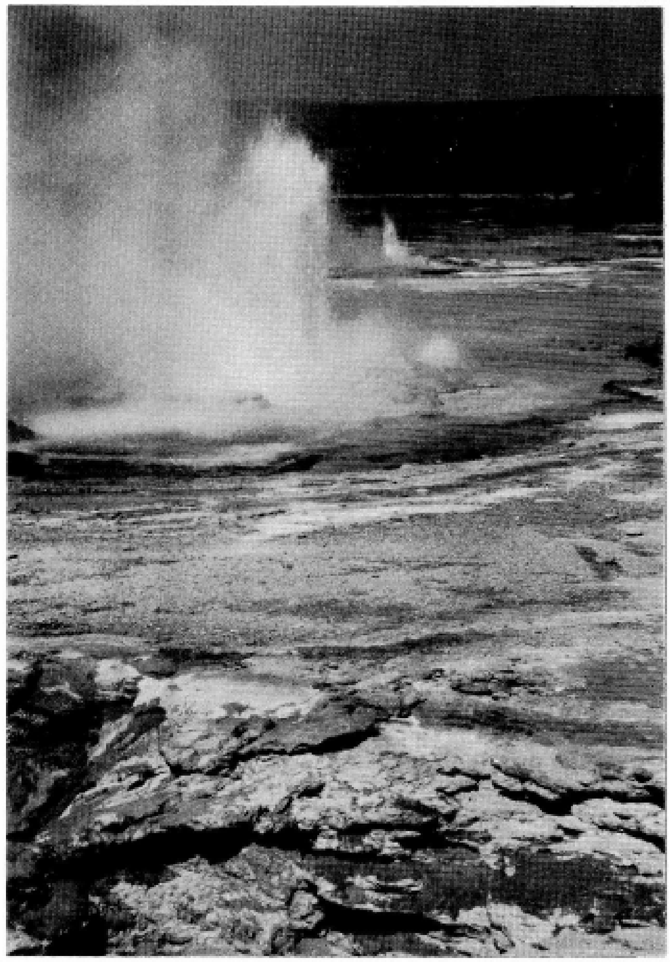
Durations of "Sizzler" were quite similar varying from 14 to 21minutes and with intervals ranging from 1 hour 51 minutes to 2 hours 45 minutes. On the evening that Fountain had its superbursts, "Sizzler" erupted just prior to Fountain and was very powerful with water spitting as high as 6 feet. (See graph of July 10). On August 25, it erupted just as Fountain did, but generally, the times of "Sizzler's" eruptions did not seem to be related to Fountain.

Gordon R. Bower [*GOSA Transactions*, Vol. III], noted an interesting relationship between "Sizzler," Jet, and Fountain in his 1990 observations. He noted that Jet would stop its eruption series when "Sizzler" erupted during Fountain's quiet period. But if "Sizzler" was erupting when Fountain was erupting, Jet would continue its series of eruptions. This was verified by almost all of my observations (See note #3 of August 19th graph for the two exceptions). An iunusual pattern occurred on July 11th. (See graph and data of same date). Jet was erupting on its pre-Fountain interval of about 7 to 9 minutes with "Sizzler" quiet. As Fountain erupted at 15:55, Jet switched into its quick mode, erupting every 2 to 4 minutes. At 16:17 "Sizzler" erupted with Fountain still playing and Jet continued to erupt on the quick mode until Fountain stopped. With "Sizzler" still playing, Jet erupted once briefly after Fountain died, but then quit erupting for 32 minutes. On August 19th, Jet did erupt twice as "Sizzler" was erupting without Fountain. This was a break in the pattern which was otherwise unblemished in my observations. "Sizzler" still appeared almost always to control Jet during my 1994 observations.

JET GEYSER

Jet's complicated cone structure lies close to the overlook boardwalk and begins the seemingly straight line that goes through "Sizzler," Spasm, Clepsydra, and New Bellefontaine. Its roughly 4 foot high cone has several vents from which water is jetted out during its frequent eruptions. It's eruptions begin with a growling noise followed by jetting streams of water and steam that last for about a minute or less.

Jet appeared to have at least two different kinds of eruptions, majors and minors, with different durations and intervals. Minors (durations within about 10 seconds of ½ minute) seemed to occur when Fountain was playing and would recur about every 2 to 3 minutes. Majors (durations within a few seconds of one minute) occurred much of the rest of the time and had intervals of about 7 to 10 minutes. Jet seemed to have major eruptions for hours before Fountain erupts. Then as Fountain erupted, Jet switched into its "minor mode." It quit erupting when Fountain finished and remained quiet for about half of Fountain's interval. (See graph of August 19).



Clepsydra Geyser, Aug, 1994 Starck Photo

Jet, Clepsydra, and New Bellefontaine have the only three cones that rise above the sinter plane in this area. All the other vents are craters in the sinter platform. Why the deposition of minerals in some geysers seems to be different than in others is an interesting question.

I was amazed at Jet's constant duration and tried to measure durations one day with a stop watch. (See data for July 11 and all of the August dates). I could almost set my watch by the length of its eruptions. (See footnote #2 on graph of July 11). I also noticed several powerful eruptions of Jet just prior to, and shortly after, Fountain's eruption. One such eruption threw a couple of small rocks into the air. Other times it erupted very weakly, sometimes building up to better eruptions in the next couple of cycles. At least one time (July 10 from 15:40 to 16:00) it had several weak eruptions in a row. On August 25, it had several weak eruptions as it tried to restart its series after being interrupted by "Sizzler's" eruptions.

Jet is the geyser that makes the overlook a great place to record data. It won't let you lose your attention or talk to someone for very long. It just keeps going off much like a clock keeps ticking. And it's fun to watch and listen to as it growls shortly before each eruption.

CLEPSYDRA GEYSER

Located about 30 feet north of the boardwalk behind Spasm Geyser, Clepsydra is in almost constant eruption. Through clouds of steam, the yellowish sinter cone is quite beautiful. It is indeed unusual to see Clepsydra when it is not erupting and until this trip, I had always thought that it quit only after Fountain's eruption was finished. This notion, however, was refuted the day Fountain had two eruptions within 4 hours of each other. (See graph of July 10).

Bellefontaine Geyser July, 1982

When I first arrived at the overlook that day, Clepsydra was looking very weak and stopped at least 10 times during the 2 hours before Fountain's next eruption. These pauses lasted anywhere from 1 second to 2 minutes. (See data for July 10). During this time Jet was totally quiet. Whether this was due to Clepsydra's behavior or to the proximity of Fountain's prior eruption could not be determined from the data. Spasm began to erupt in the middle of this weak period. About 10 minutes into Fountain's eruption, Clepsydra stopped again, for about 10 minutes. After 5 minutes of weak blurps, it paused again for 21 minutes, starting during the final 12 minutes of Fountain's eruption and continuing past its end for 9 more minutes. During this time period, Jet and "Sizzler" were both erupting with Fountain. (See graph of July 10). It should be noted also that Spasm, which had been erupting for close to 2 hours prior to Fountain's start, shut down only briefly as Fountain drained into its pool. It then began erupting again through its flooded pool before Fountain had finished. Spasm continued to erupt after Fountain had quit and was in eruption when I arrived back on the scene an hour and a half later. Spasm possibly had about a six hour duration and might have been the reason Clepsydra was so weak during part of this time. Clepsydra's energy may have been shifted to Spasm and even to Fountain, and this shift could have been at least part of the cause of Fountain's short interval.

During Fountain's second eruption on July 10, Clepsydra stopped for 28 minutes and came back to life about 8 minutes after the eruption ceased. All in all, it was an interesting day as viewed from the Fountain overlook!

Later, when I returned in August, I saw one more very long shutdown of Clepsydra. On August 27, Fountain erupted from a very high pool. Without warning, Clepsydra paused 11 minutes into Fountain's eruption. It remained quiet for 40 minutes -- the longest pause I had seen. Except for the high pool level from which Fountain erupted, no unusual circumstances were noted.

JELLY GEYSER

Jelly Geyser is located a few feet from the boardwalk, and about 20 feet southwest of Spasm. Through its pool would flow the runoff from Spasm and Fountain. I have never previously witnessed any activity from it. But it erupted one day while I was standing on the overlook boardwalk. (See footnote #10 on graph of July 10). I saw the steam cloud and rushed down to see it close up, but its "eruption" was over. According to a visitor who was sitting on the benches across the boardwalk from Jelly, its pool belched up in a single thrust about 3 to 4 feet high, sending a large amount of runoff down the back, or west side of the pool. This burst also coincided with a shut down of Jet for 19 minutes. Jet was having a series of erratic, weak eruptions that day prior to Jelly's eruption. After the period of quiet, Jet erupted twice on its short interval mode, and then Fountain erupted. So Jelly also contributed to the orchestration of these six geysers.

"FROLIC GEYSER"

"Frolic Geyser," while probably not associated with the other six geysers, was quite active this summer. Its 20 foot high bursts of water and steam were just barely evident through the trees from the overlook. It is located in the flats south and west of Clepsydra and erupts from a small hole in a brown sinter sheet just visible from the boardwalk when standing at Jelly Geyser. Its eruptions are brief, but impressive. Its recorded intervals ranged from 19 to 50 minutes. (See August 25th data).

NEW BELLEFONTAINE & FITFUL GEYSERS

New Bellefontaine Geyser is located directly behind Clepsydra when viewed from the boardwalk at Spasm. Fitful Geyser is located slightly to the south of New Bellefontaine. Both are very active. New Bellefontaine is in almost constant eruption. It was difficult to keep track of both of these geysers from the overlook because of the steam cloud from Clepsydra. Fitful Geyser, a member of the Gore Springs (see Rocco Paperiello's map of this area in "A New Look at the Fountain Group" in *GOSA Transactions*, Volume IV, p. 148), played quite often.

OTHER FEATURES OF INTEREST

Two UNNG's over the sinter ledge behind and to the left of Clepsydra were active in August, occasionally bursting up over the top of the sinter ledge. (From Rocco's map they would appear to be in the Fissure Springs group -- possibly #32 and #33 on that map).

It should also be noted that from the overlook, one could be kept busy forever trying to keep track of eruptions of various distant geysers in the area of the Kaleidoscope Group and sweeping across to the east and the road. This region is full of small geysers which seemed very active. Slightly to the west of "The Firehose," which was an almost constant spouter that looked just like its name, I witnessed several huge eruptions. Three eruptions, spaced about 5 minutes apart and tripling the height of "The Firehose," came from Drain Geyser. (See data of July 12th). In August, I again witnessed some major activity in that area. From maps in T. Scott Bryan's *The Geysers of Yellowstone*, and Mike Keller's article on this group in Volume V of the *GOSA Transactions*, and also from his more recent article in the *Sput* (Volume 8, Number 4), I ascertained that Deep Blue (see August 19 data), Drain (see same data), and Honeycomb Geyser (see data for August 26th) were all seen in eruption. These determinations were difficult, with the geysers several hundred yards away. The activity down there was awesome at times.

The keen observer can spend hours here at the overlook recording data without ever getting bored,listening to people talk and talking to people. One young couple from the Netherlands, on their first visit to the USA, thought that our weather in the U. S. was HOT! It seems that they had flown into Phoenix, rented a car and headed for Death Valley. The next day where it was 129 degrees! I hope that their travel agent doesn't recommend that route to a lot of people.

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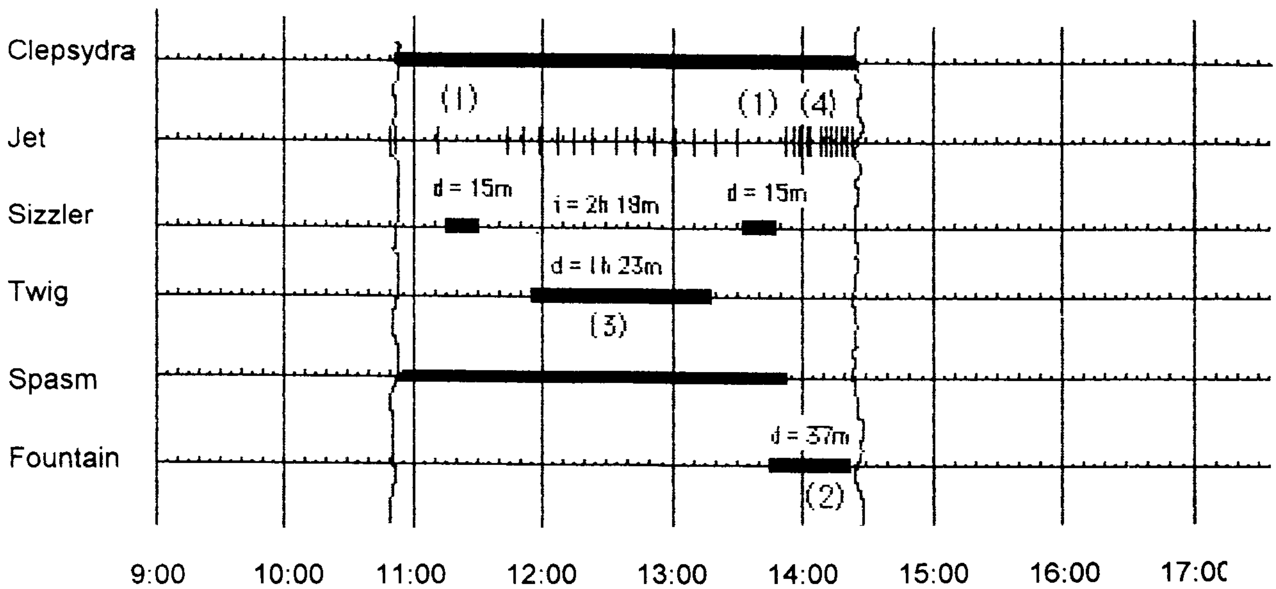
JULY 9, 1994



(1) Note that in two instances Jet Stopped erupting while "Sizzler" erupted and Fountain was not erupting. (See Gordon R. Bower's "Activity of the Fountain Group Complex," *GOSA Transactions*, Vol III, p.55).

(2) Fountain erupted from a pool that was as full as I had ever seen it. I would estimate that it was 2 to 3 inches below the top of the crater and overflowing into Morning's crater. The surge, a minute or so before Fountain's eruption caried the water in the pool over the top of the crater and the entire Fountain-Morning crater was awash. The eruption began with boils from two points on the crater rim nearest the boardwalk (the south side of the crater). The pool remained at this level for the entire 3h of observation prior to the eruption.

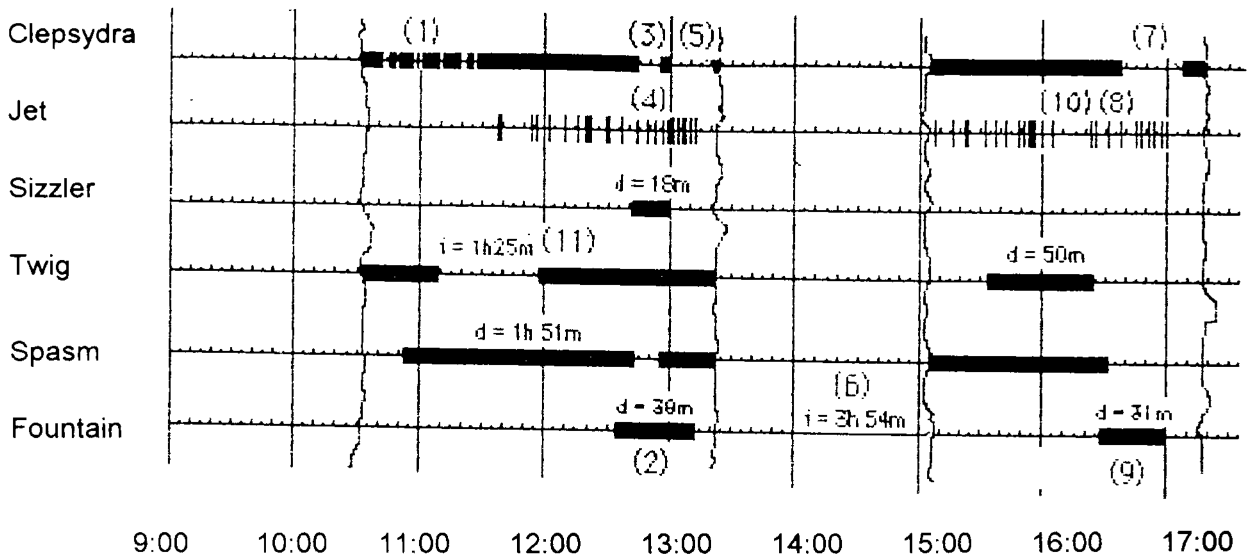
(3) Note here that Twig's eruption seemed to be independent of Fountain's eruption. (See lynn Stephen's "Activity in the Fountain Complex, Lower Geyser Basin, During 1991 -- A Series" under Twig Geyser, *GOSA Transactions*, Vol. V, p. 120).

(4) Note that Jet shortened its interval while Fountain was erupting.

JULY 9, 1994 DATA

10:52	Jet erupted
10:52	Spasm (IE)
11:00	Both Ft'n and Morning pools were as full as I had ever seen them
11:01	Jet
11:12	Jet
11:13	Morning boiled from a point in the back, left side of its pool during occasional hot periods
11:15	Sizzler erupted.
11:30	Sizzler off (d=15m)
11:44	Jet (weak)
11:51	Jet
11:55	Twig erupted
11:59	Jet
12:07	Jet
12:15	Jet
12:24	Jet
12:34	Jet
12:43	Jet
12:52	Jet
13:02	Jet
13:11	Jet
13:18	Twig off (d=1h 23m)
13:20	Jet (strong)
13:30	Jet
13:33	Sizzler erupted (i=2h 18m)
13:45	Fountain erupted
13:48	Sizzler off (d=15m)
13:52	Jet
13:56	Jet
13:56	Clepsydra began pounding in steam phase
13:59	Jet
14:02	Jet
14:04	Jet
14:08	Jet
14:11	Jet
14:13	Jet
14:16	Jet
14:18	Jet
14:21	Jet
14:22	Fountain off (d=37m)
14:24	Jet

JULY 10, 1994



(1) Clepsydra was weak and acting strangely as I entered the area. It would die for a few seconds to a few minutes before weakly blurping a few times.

(2) Fountain erupted from a very full pool that was flowing into Morning's pool. It had stayed this way for about an hour and a half before the big surge that set off the eruption. The surge added 4-6" of water to the pool in one or two minutes before the eruption began.

(3) Clepsydra paused for about 10m during Fountain's eruption.

(4) Note here that Jet continued to erupt while Sizzler and Fountain erupted.

(5) 12m before the end of Fountain's eruption, Clepsydra paused for 21m. The cone was dry for 10m.

(6) Note the extremely short interval for Fountain.

(7) Clepsydra paused for 28m during Fountain's second eruption.

(8) Jet had some very powerful eruptions just as Fountain began erupting, including one where some small rocks were thrown out.

(9) This time Fountain erupted from a pool that was 6-8" below the top of the crater. The pool was filling the back channel, but was not spreading out across the sinter toward Morning's pool. Again, there was a surge a minute or two prior to Fountain's eruption.

(10) At 16:06 Jelly erupted with a single belch of water and steam. From the overlook, I saw the large steam cloud and ran down to Jelly hopeful that there would be more. Jelly's pool was overflowing from Spasm's runoff an hour before and was now down about 5" below its rim. According to a visitor who was sitting on the bench across the boardwalk from Jelly, the entire pool boiled up to a height of 1 meter(3-4') emptying the pool in a few seconds. The runoff went mostly out the back(west side) of the crater. Note that this eruption seemed to turn off Jet for 19m. This could indicate an underground connection between Jelly and Jet (and therefore Sizzler and Fountain).

(11) Twig's stops and starts did not seem to be related to Fountain's eruptions. (See Lynn Stephen's article "Twig Geyser, Activity During 1991" in GOSA Transactions, Vol V p.120)

JULY 10, 1994 DATA

10:32	Twig erupted
10:43	Clepsydra was very weak and then quit
10:46	Clepsydra resumed
10:50	Clepsydra still acted strangely - it quit for a few seconds - Twig burst when it did
10:52	Clepsydra died again
10:52	Spasm erupted
10:58	Clepsydra died for 9s (twice)
11:00	Clepsydra died for a second or two
11:02	Clepsydra died for 1s
11:09	Twig off (d=37m)
11:10	Clepsydra died

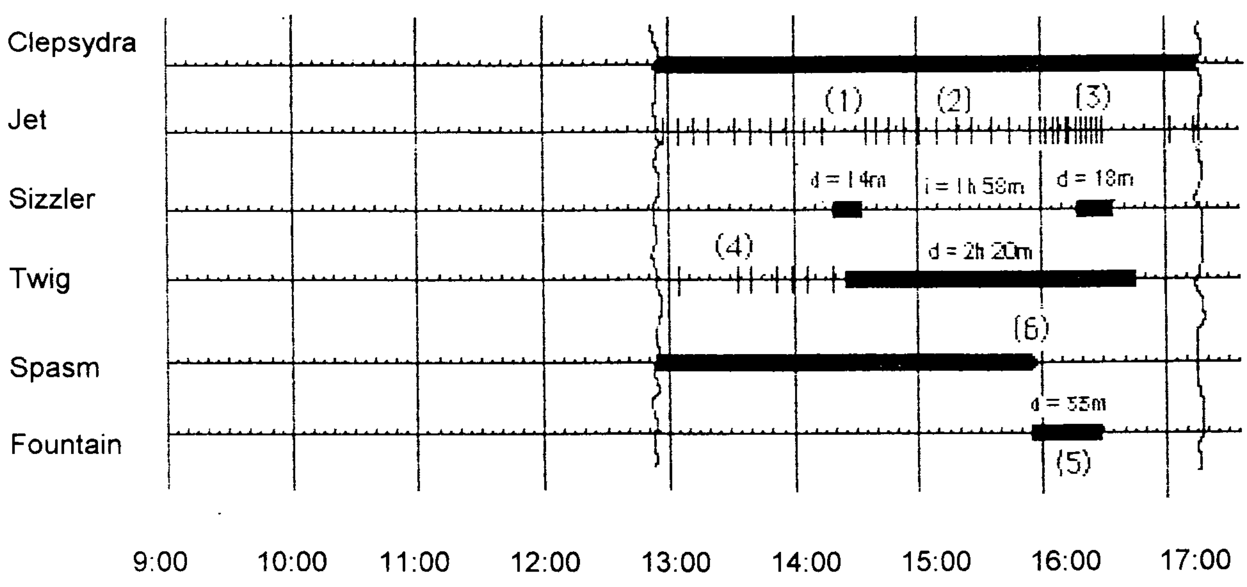
11:20 Clepsydra died
11:21 Clepsydra died for 20s
11:26 Clepsydra died for 2m
11:37 Jet (one burst)
11:37 Ft'n pool very full
11:39 Jet
11:54 Jet
11:56 Jet
11:57 Twig erupted (I=1h25m)
12:02 Jet
12:09 Jet
12:16 Jet
12:19 Jet
12:20 Ft'n pool overflowing almost into Morning's
12:21 Jet (small blurp)
12:22 Jet (better eruption)
12:29 Jet (small blurp)
12:30 Jet (better eruption)
12:34 Fountain eruption
12:37 Jet
12:42 Sizzler erupted
12:43 Spasm flooded and off (d=1h 51m)
12:44 Jet
12:45 Clepsydra off
12:49 Jet
12:53 Jet
12:55 Clepsydra blurped - so did Spasm
12:56 Jet
12:57 Clepsydra weakly burped
12:57 Spasm erupted again
12:59 Jet
13:00 Sizzler off (d=18m)
13:00 Clepsydra died
13:00 Jet
13:02 Jet
13:04 Jet
13:06 Jet
13:08 Jet
13:10 Jet
13:11 Clepsydra cone was dry
13:12 Fountain off (d=38m)
13:13 Jet
13:21 Clepsydra began weak burps

. . . .

15:05 Spasm (IE)
15:05 Clepsydra (IE)
15:05 Ft'n pool was quite full no overflow into Morning
15:08 Jet
15:16 Jet

15:23 Jet (just 2 bursts)
15:24 Jet
15:32 Jet
15:34 Twig erupted
15:37 Jet
15:42 Jet (weak)
15:48 Jet (weak)
15:51 Jet (weak)
15:53 Jet (weak)
15:55 Jet (weak)
15:56 Jet (weak)
16:00 Jet
16:04 Jet
16:06 Jelly erupted in large steam cloud
16:23 Jet
16:24 Twig off (d=50m)
16:25 Jet
16:28 Fountain erupted
16:32 Jet (super eruption w/ rocks flying out)
16:33 Spasm flooded and off (d>1h28m)
16:38 Jet (powerful)
16:39 Clepsydra died
16:45 Jet (good one)
16:48 Jet (good one)
16:51 Jet (medium power)
16:54 Jet (medium)
16:57 Jet (medium)
16:59 Fountain off (d=31m)
17:00 Jet (short)
17:07 Clepsydra erupted (pause=28m)
17:13 Ft'n pool down 18"
17:13 Spasm drained

JULY 11, 1994



(1) Note that Jet did not erupt while Sizzler was erupting and Fountain was not. (Again, see Gordon R. Bowers "Activity of the Fountain Geyser Complex," *GOSA Transactions*, Vol III p.55)

(2) Jet had an incredibly constant set of durations measured from 13:20 until Fountain erupted at 15:55. Recorded durations were 60s, 60s, 60s, 45s, 63s, 59s,59s, 60s, 60s, 63s, 61s,66s, and 62s. After Fountain erupted, Jet's durations dropped to 33s, 35s, 30s, 40s, 30s, 30s, 21s, 17s, unrecorded, 31s, 32s, and 20s. After Fountain stopped, Jet's durations went back to 65s and 57s.

(3) Note here that Jet continued to erupt during "Sizzler"'s eruption while Fountain was also erupting.

(4) Twig had several false starts during this time period where water began to rise in the crater and would burst once or twice and then drain.

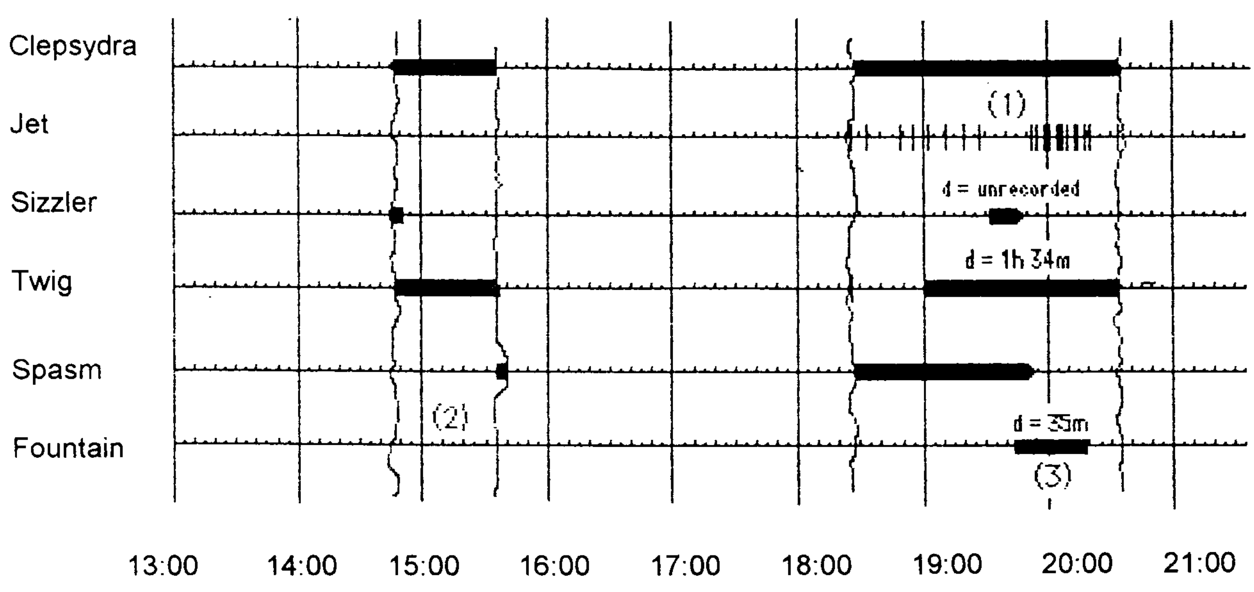
(5) Fountain erupted from a pool that was 12-14" below the top of the crater. Water was just barely out the back channel. The pool remained at this level from the time that I arrived on the scene until Fountain erupted about 3h later. It again began its eruption with a 4-6" surge of water minutes before the two spots on the rim of the crater nearest the boardwalk began to boil vigorously.

(6) Spasm's stop time was unrecorded, but it did get flooded out by Fountain in its usual manner.

JULY 11, 1994 DATA

12:52	Spasm (IE)
12:52	Ft'n pool was low - about 12-14" below rim
12:58	Jet (long, but not powerful
13:05	Jet
13:05	Twig started to fill, then disappeared
13:13	Jet (short)
13:20	Jet (60s)
13:32	Jet (60s)
13:34	Twig tried again, then disappeared
13:40	Jet (60s)
13:40	Twig tried again
13:48	Jet (60s)
13:52	Twig tried again
13:56	Jet (~45s)
13:59	Twig tried again
14:05	Jet (63s)
14:07	Twig tried harder - but without success
14:13	Jet (57s)
14:19	Twig tried again
14:19	Sizzler erupted
14:25	Twig erupted finally
14:33	Sizzler off (d=14m)
14:35	Jet (60s)
14:39	Jet (63s)
14:46	Jet (59s)
14:53	Jet (59s)
15:00	Jet (60s)
15:09	Jet (60s)
15:18	Jet (63s)
15:26	Jet (61s)
15:35	Jet (66s)
15:44	Jet (62s)
15:54	Jet (?)
15:55	Fountain erupted
15:59	Jet (33s)
16:03	Jet (35s)
16:06	Jet (30s)
16:09	Jet (40s)
16:11	Jet (30s)
16:14	Jet (30s)
16:17	Jet (21s)
16:17	Sizzler erupted (i=1h 58m)
16:19	Jet (17s)
16:22	Jet (?)
16:24	Jet (31s)
16:27	Jet (32s)
16:28	Fountain off (d=33m)
16:30	Jet (20s)
16:35	Sizzler off (d=18m)
16:45	Twig off (d=2h 20m)
17:02	Jet (65s)
17:14	Jet (57s)
17:20	Left the area to watch Giantess

JULY 12, 1994



(1) Here again, Jet stopped erupting when Sizzler erupted without Fountain. But note also that as soon as Fountain erupted, Jet starting erupting with Sizzler.

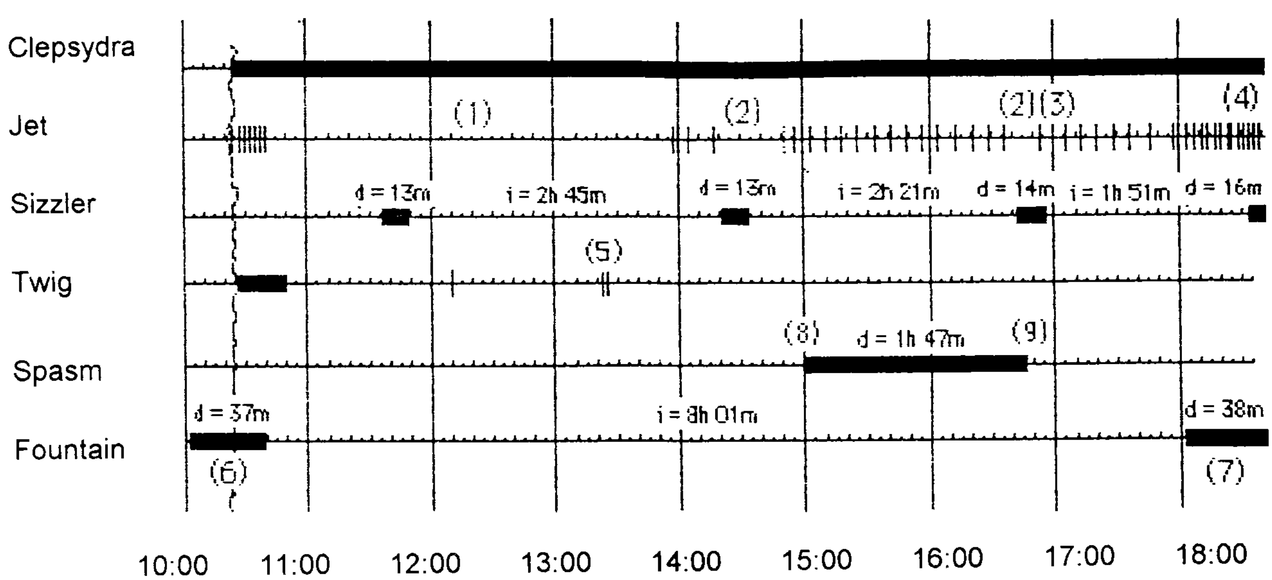
(2) Fountain"s pool was just barely visible from the boardwalk - about 18" below the top of the crater.

(3) Fountain erupted from a low pool about 12 -14" below the top of the crater. 7m into this eruption, there was a large burst that went up an estimated 30-35 meters (80-100') high. There followed three additional large bursts during the course of the eruption that were in the 20-25 meter (60-75') high range.

JULY 12, 1994 DATA

14:45	Sizzler (IE)
14:45	Twig (IE)
14:45	Spasm was dry
14:45	Ft'n pool out of sight
14:49	Ft'n pool just visible from boardwalk
14:51	Sizzler off (d>9m)
15:36	Spasm erupted. At this there were 3 tremendous explosive bursts from the Kaleidoscope area spaced about 5m apart. They were from Drain Geyser.
18:26	Jet (IE)
18:26	Twig tried to erupt
18:26	Clepsydra (IE)
18:26	Spasm (IE)
18:26	Ft'n pool was at 12" from top - small waves coming out back channel
18:33	Jet (68s)
18:49	Jet (60s)
18:56	Jet (64s)
19:00	Twig erupted
19:03	Jet (63s)
19:11	Jet (67s)
19:20	Jet (62s)
19:28	Jet (56s) good eruption
19:32	Sizzler erupted - going up 1.5 meter (5') in powerful bursts
19:43	Fountain erupted
19:50	Fountain large burst - estimated at 30-35 meters (80-100')
19:50	Jet (?)
19:52	Jet (?)
19:52	Morning's Thief (or West Satellite) boiled up 1 meter (2-3') high while Fountain erupted
19:55	Jet (?)
19:58	Jet (?)
20:01	Jet (?)
20:04	Jet (?)
20:06	Jet (?)
20:09	Jet (?)
20:10	Jet (?)
20:13	Jet (?)
20:14	Jet (?)
20:15	Jet (?)
20:18	Fountain off (d=35m)
20:18	Jet (?)
20:20	Jet (?)
20:34	Twig off (d=1h 34m)
20:34	Jet (?)

AUGUST 19, 1994



(1) Jet was off for 3h 18m of Fountain's 8h 01m interval. Also, Jet began erupting again 4h 05m before Fountain's second eruption. (Not a very good indicator for Fountain's eruption)

(2) Here Jet stopped erupting when "Sizzler" erupted without Fountain erupting (the usual pattern).

(3) Jet erupted here at 16:53:30 breaking the usual pattern since "Sizzler" was still erupting without Fountain in eruption.

(4) Here Jet continued to erupt through "Sizzler's" eruption while Fountain was also erupting (again, the usual pattern).

(5) Twig tried to fill its pool a couple of times but never did and remained off the rest of the observed time. (almost 8h)

(6) Fountain was in eruption when I arrived, so I did not see the pool height before the eruption. I got the start time from another observer.

(7) I estimated Fountain's pool level to be 10-11" below the top of the crater prior to the eruption. During the 8 hour interval, Fountain's pool level looked like this:

Time after AM eruption	Time before PM eruption	Pool level below top of crater
10m	7h 50m	out of sight from boardwalk
1h 45m	6h 15m	barely visible from boardwalk
3h 30m	4h 30m	estimated 15"
4h 40m	3h 20m	estimated 12"
6h	2h	estimated 10-11" (the eruption level)

(8) Spasm began its eruption with cloudy, murky water for the first 10m.

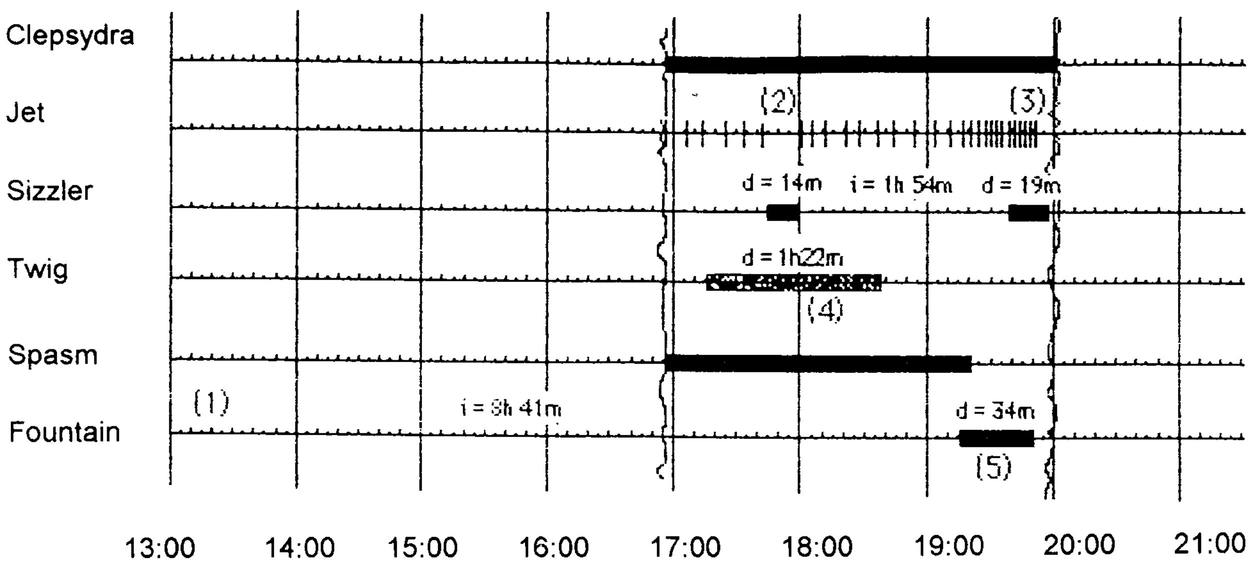
(9) Spasm drained 1h 17m before Fountain erupted and did not erupt again. This was the first time that I had observed Fountain erupt without Spasm in eruption.

AUGUST 19, 1994 DATA

10:02	Fountain erupted (from Lynn Stephens)
10:23	Twig (IE)
10:23	Clepsydra (IE)
10:24	Jet (?)
10:26	Spasm flooded & off
10:26:45	Jet (28s)
10:29:31	Jet (32s)
10:32:03	Jet (31s)
10:34:40	Jet (31s)
10:37:13	Jet (29s)
10:39	FOUNTAIN off (d=37m)
10:39:52	Jet (33s)
10:43	Sub steamed
10:48	Bear Claw
10:50	Twig drained and off
10:50	Ft'n drained out of sight
10:50	Spasm almost drained
10:50	Jelly pool 1 ½" below top
10:50	Morning pool low, but visible from boardwalk
11:16	Morning pool dropped almost out of sight
11:36	Sizzler erupted
11:49	Sizzler off (d=13m)
11:49	Ft'n pool visible from boardwalk
12:10	Twig sputtered for 1m
12:19	Deep Blue erupted with 5 large, wide bursts 15-17 meters high.
12:19	Firehose dropped in height
12:57	Deep Blue
13:00	Ft'n pool up to ~18" below top - Spasm remained empty. Jelly pool was 12" below top. Small waves evident in Ft'n pool
13:23	Twig tried to start for 20s.
13:25	Twig sputtered
13:27	Clepsydra weakened
	-Morning"s pool filled to ~12" from top
13:34	Ft'n pool ~15" below top-waves evident in pool - Jelly pool 10" below top
13:42	Water evident in Spasm
13:48	Ft'n pool up an inch
13:58	Jet (~90s)
14:05	Jet (~60s)
14:17:15	Jet (67s)
14:21	Sizzler erupted
14:05	Jet (~60s)
14:17:15	Jet (67s)
14:21	Sizzler erupted
14:34	Sizzler off (d=13m)
14:40	Ft'n pool up to 12"
14:40	Jelly pool up to 6"
14:40	Spasm pool empty
14:45	Spasm pool coming up fast
14:49	Spasm pool drains
14:51:04	Jet (a single burst)
14:55:54	Jet (82s) good eruption
14:57	Spasm erupted from a low pool with cloudy water
14:59	Spasm large burst 2 meters above pool level
15:03:18	Jet (58s) large 4-5 meter burst from main vent
15:08	Spasm water cleared up
15:09	Spasm pool began overflow
15:10:24	Jet (59s)
15:11	Frolic erupted
15:12	Ft'n pool holding at 12"
15:18:29	Jet (70s)
15:26:15	Jet (61s)
15:34:02	Jet (63s)
15:41:48	Jet (68s)
15:45	Sub (single burst)
15:46	Deep Blue erupted
15:49:23	Jet (55s)
15:56:30	Jet (67s)
15:59	Sub over rim
16:01	Jelly pool is full
16:01	Morning pool was boiling
16:04:09	Jet (62s)
16:07	Ft'n pool up to 10-11"
16:12:56	Jet (62s)
16:21:18	Jet (66s)
16:28:37	Jet (?)
16:36:01	Jet (69s)
16:42	Sizzler erupted (i=2h 21m)
16:46	Spasm off (d=1h 49m)
16:53:30	Jet (?) w/Sizzler
16:55	Kaleidoscope
16:56	Sizzler off (d=14m)
16:58:48	Jet (62s)
17:01	Kaleidoscope
17:05:56	Jet (60s)
17:13	Jet (?)
17:21:11	Jet (55s)
17:29:23	Jet (68s)
17:37:25	Jet (74s)
17:45	Frolic erupted
17:47:22	Jet (68s)
17:56:46	Jet (63s)
18:01	Ft'n pool began surge
18:03	Fountain erupted
18:04	Jet(?)
18:08	Jet (?)
18:11	Jet (?)
18:14	Jet (?)
18:17	Jet (?)
18:20	Jet (?)
18:23	Jet (?)
18:24	Jet (?)
18:25	Jet (?)
18:28	Jet (?)
18:31	Jet (?)
18:33	Jet (?)
18:33	Sizzler erupted

18:36	Jet (?)	18:52	Ft'n pool is empty	19:38	Sub over rim
18:39	Jet (?)	18:56:53	Jet (54s)	19:40	Left the area
18:41	Fountain off(d=38m)	19:20	Sub over rim		
18:49	Sizzler off (d=16m)	19:29	Sub steamed		

AUGUST 24, 1994



(1) Fountain's previous eruption was at 10:35 (NS).

(2) Here Jet stopped as Sizzler erupted without Fountain erupting.

(3) Here Jet continued to erupt through Sizzler's eruption until Fountain completed its eruption at which time Jet stopped while Sizzler continued.

(4) During this very short eruption (for Twig), Twig remained in a "pulsing" mode that I had never seen before. Its pool would fill, then pulse up and down about an inch until a small series of bursts would break the surface. Then the pool would drop a few inches and the pulsing would begin again until a small series of bursts would break the surface. The height of the bursts seem to be normal or a little less than normal, but the number of bursts/minute was very low. Each cycle took approximately 30s.

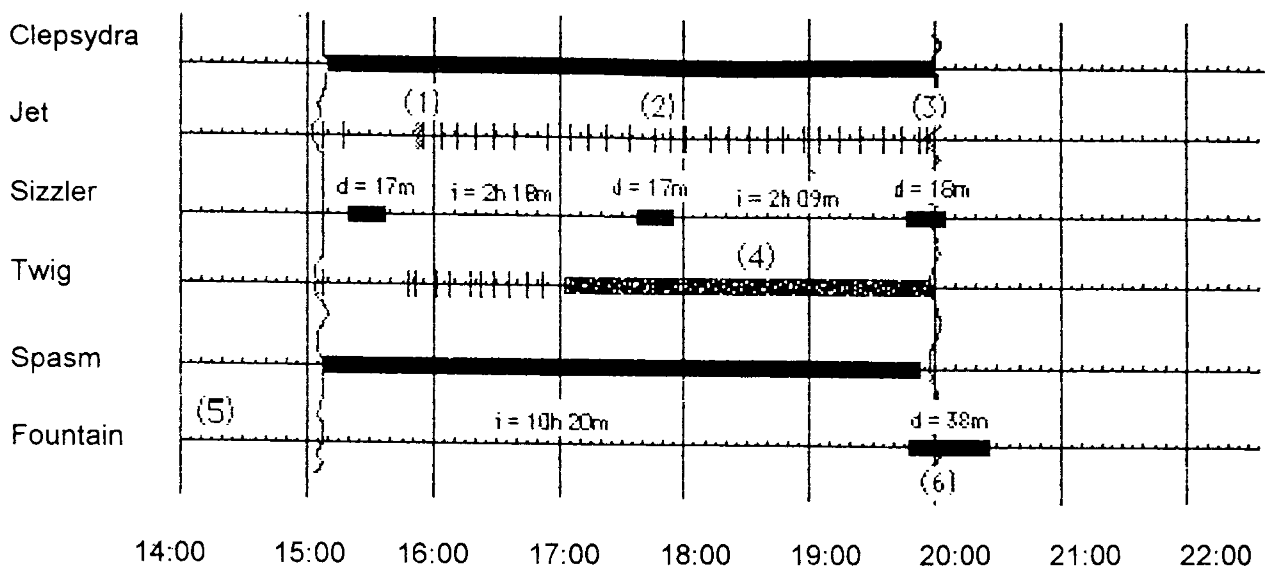
(5) Fountain's pool level remained at about 10" below the top of the crater during this entire observation and the eruption occurred from this same level.

AUGUST 24, 1994 DATA

16:55	Spasm (IE)	17:32:56	Jet (55s)	18:53:17	Jet (70s)
16:55	Jelly pool full	17:42:00	Jet (66s)	19:02:48	Jet (61s)
16:55	Ft'n pool was 10" below top	17:45	Sizzler erupted	19:11:06	Jet (58s)
				19:16	Fountain erupted **
16:55	Clepsydra (IE)	17:59	Sizzler off (d=14m)	19:17:21	Jet (38s)
16:57:22	Jet (60s)	18:01:0	Jet (54s)	19:19	Spasm still going
17:01	Frolic	18:05:46	Jet (54s)	19:21:11	Jet (31s)
17:06:09	Jet (53s)	18:12:15	Jet (58s)	19:21	Spasm flooded and off (d>2h 26m)
17:14:14	Jet (61s)	18:20:34	Jet (63s)		
17:15:50	Twig erupted-quite powerful start, then died for about 10s, then bursts again.	18:28:22	Jet (63s)	19:23	Clepsydra pounded
		18:35:58	Jet (57s)	19:24:31	Jet (30s)
		18:38	Twig drained and off (d=1h 22m)	19:27:35	Jet (27s)
				19:30:23	Jet (30s)
17:24:51	Jet (60s)	18:43	Frolic	19:33:12	Jet (25s)
17:30	Frolic	18:44:22	Jet (63s)	19:34:58	Jet (one burst)

19:36:09 Jet (23s)
19:38:55 Jet (25s)
19:39 Sizzler erupted
19:41:37 Jet (20s)
19:44:00 Jet (28s)
19:46:40 Jet (?)
19:49:12 Jet (?)
19:50 Fountain off (d=34m)
19:51:44 Jet (?)
19:55 Ft'n pool out of sight from boardwalk
19:58 Sizzler off (d=19m)

AUGUST 25, 1994



(1) Jet had erupted prior to Sizzler's eruption, shut down during Sizzler's eruption and then seemed to have trouble starting up again after Sizzler stopped. The first three eruptions consisted of one or two weak splashes. The next eruption lasted only 10s and the next lasted 61s, but was weaker than normal. The 6th eruption was a powerful one and thereafter, Jet got into its groove again.

(2) Jet broke its pattern here as it erupted twice during Sizzler's eruption without Fountain erupting. The first eruption was a powerful one with Sizzler in full eruption. The second one was a normal energy Jet eruption with Sizzler in its last dying steam phase.

(3) Jet continued to erupt as Sizzler erupted since Fountain was also erupting.

(4) Twig continued its "pulsing mode" as it did yesterday. (See footnotes below AUGUST 24, 1994 graph)

(5) Fountain had erupted at 09:28 (NS) according to the Old Faithful Visitor's Center logbook.

(6) Fountain's pool level remained at about 12" below the top of the crater for the entire time of observation (4h 40m). It surged up and down about an inch every 10m or so. Almost 2m prior to the eruption I noticed small waves on the surface of the pool. These led to larger waves and water eventually flooded out the back channel before the same two vents nearest the boardwalk began the eruption.

AUGUST 25, 1994 DATA

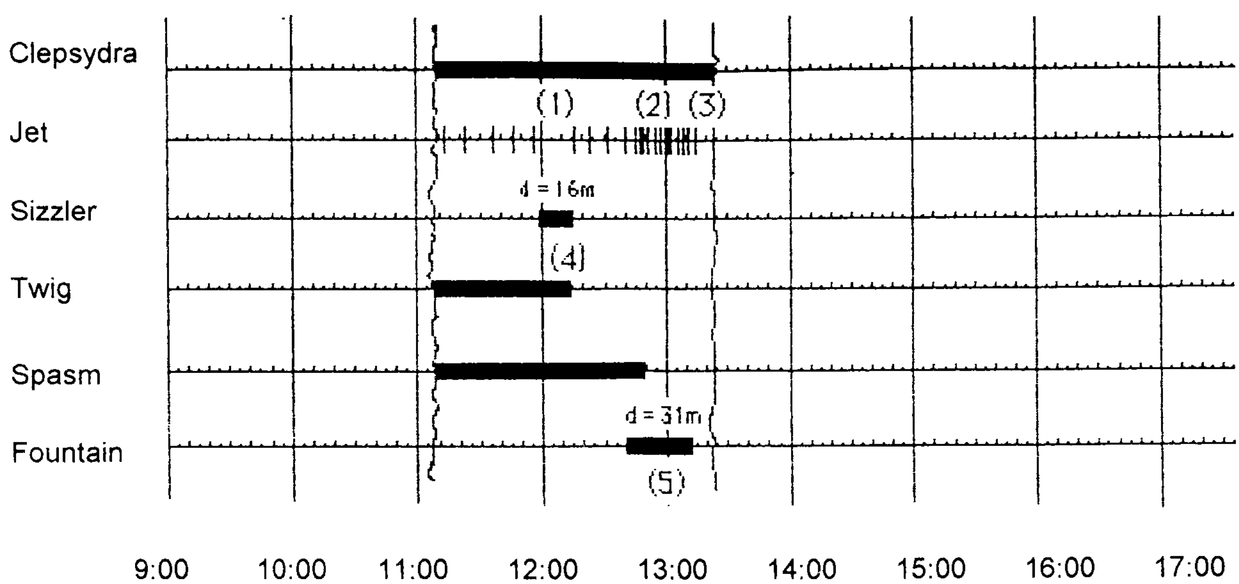
09:28 Fountain erupted (ns) from OFVC logbook
15:07 Twig sputtered
15:07 Spasm (IE)
15:07 Clepsydra (IE)
15:07 Ft'n pool about 12" below top
15:07 Jelly pool was full
15:07:42 Jet (54s)
15:17:22 Jet (62s)
15:19 Frolic erupted
15:20 Sizzler erupted
15:37 Sizzler off (d=17m)
15:48 Twig sputtered
15:50 Sub over the rim
15:52:10 Jet (sputtered)
15:52:20 Twig sputtered
15:53:06 Jet (sputtered)
15:54:26 Jet (sputtered)
15:55:14 Jet (sputtered for 10s)
15:56:18 Jet (61s) weak eruption-no energy
16:02 Twig sputtered
16:03:31 Jet (69s) strong eruption
16:08 Twig sputtered
16:12:13 Jet (64s) good eruption
16:18 Twig sputtered
16:20:13 Jet (68s) good eruption
16:23 Twig sputtered

16:28:24 Jet (62s)
16:29 Twig pool visible and sputtered
16:36 Twig sputtered
16:37:56 Jet (56s)
16:45 Twig pool back up and sputtered
16:52 Twig sputtered
16:55:08 Jet (?)
17:00 Ft'n pool still at 12"
17:02 Twig pool began to rise
17:03 Twig erupted - pulsing mode like yesterday
17:04:41 Jet (64s)
17:14:00 Jet (55s)
17:18 I first noticed Twig's Satellite spouting 18" from right edge (SE) of Twig's pool
17:23:10 Jet (65s)

17:34:04 Jet (63s)
17:38 Sizzler erupted (i=2h 18m)
17:39 Frolic erupted
17:46 Jet (?) powerful with Sizzler
17:53:10 Jet (59s) Sizzler still in steam phase at the time
17:55 Sizzler off (d=17m)
17:58:59 Jet (sputtered)
17:59:38 Jet (sputtered)
18:01:16 Jet (58s)
18:12:37 Jet (69s)
18:17 Frolic erupted (i=38m)
18:18 Twig still pulsing
18:21:32 Jet (58s)
18:30:45 Jet (59s)
18:40:28 Jet (63s)
18:48:29 Jet (60s)
18:56:36 Jet (63s)

19:05:06 Jet (54s)
19:07 Frolic erupted (i=50m)
19:14:00 Jet (62s)
19:23:55 Jet (65s)
19:34:52 Jet (?)
19:41 Frolic erupted (i=34m)
19:43:37 Jet (?)
19:46:48 Fountain pool began to surge
19:47 Sizzler erupted (i=2h 09m)
19:47:40 Fountain erupted
19:51:36 Jet (~30s)
19:52 Spasm off (d>4h 45m)
19:55 Clepsydra steam vent pounded
19:56:03 Jet (32s)
20:00 Frolic erupted (i=19m)
20:05 Sizzler off (d=18m)
20:26 Fountain off (d=38m)

AUGUST 26, 1994



(1) Jet stopped erupting as Sizzler erupted without Fountain erupting.

(2) Jet erupted on its short interval mode (and short duration) as Fountain erupted.

(3) Jet stopped at the end of Fountain's eruption.

(4) Twig seemed to respond to Sizzler's eruption. Both were very powerful eruptions and seemed to expend energy together.

(5) Fountain's pool level remained at about 10" below the top of the crater during this entire observation and the eruption occurred from this same depth. The 1-2 minute surge in the pool level was evident just prior to the eruption.

AUGUST 26, 1994 DATA

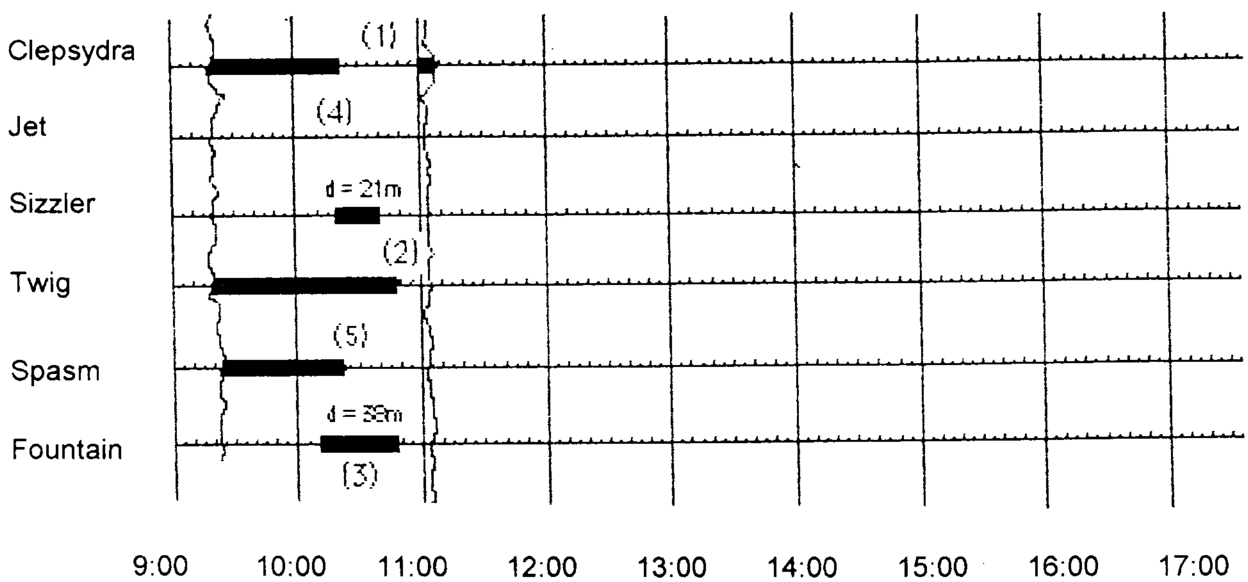
11:06 Twig (IE)

11:06 Spasm (IE)

11:06 Clepsydra (IE)

11:06 Ft'n pool level at 10"
11:06 Jelly pool was flooded
11:12:51 Jet (60s)
11:23:34 Jet (62s)
11:23 Frolic erupted
11:35:59 Jet (59s)
11:45:55 Jet (65s)
11:55:59 Jet (64s)
11:59 Sizzler erupted
12:11 Clepsydra pounded before Fountain erupted
12:13 Twig off
12:15 Sizzler off (d=16m)
12:15:55 Jet (92s) weak start
12:22:55 Jet (59s)
12:24 Clepsydra continued to pound in steam phase
12:31:52 Jet (68s)
12:40 Jet (?)
12:40 Ft'n pool began to surge
12:41 Fountain erupted
12:45:20 Jet (?)
12:47:32 Jet (~30s)
12:49:09 Jet (?)
12:49 Spasm pool flooded and off (d>1h 43m)
12:52:09 Jet (31s)
12:55:00 Jet (27s)
12:57:46 Jet (27s)
13:00:35 Jet (27s)
13:02 Spasm bubbled up through flooded pool
13:03:18 Jet (24s)
13:05 Clepsydra mostly in steam phase
13:06:09 Jet (?)
13:08:38 Jet (26s)
13:11:16 Jet (?)
13:12 Fountain off (d=31m)
13:14:51 Jet (29s)
13:20 Honeycomb erupted. It had13 meter high wide bursts which lasted over 9m. It looked like a slower Fountain eruption with 5-60s pauses between bursts.
13:29 Left the area to see Great Fountain.

AUGUST 27, 1994



(1) Clepsydra paused 11m into Fountain's eruption and stayed completely dead for 40m. At one point after Fountain stopped erupting, the entire area was quiet. Even New Bellefontaine seemed to go dead for a minute or two. It was erie !

(2) Twig and Fountain ended at the same time.

(3) Fountain's pool was very high - about 4-5" below the top of the crater. It erupted from that same level. After the end of the eruption, the pool did not empty as it normally does. The pool dropped about 18" below the top and stayed there.

(4) Jet was doing its normal eruptions during this time, but I did not record them.

(5) Spasm flooded and shut down shortly after Fountain began to erupt.

AUGUST 27, 1994 DATA

09:10 Clepsydra (IE)
09:10 Twig (IE)
09:20 Frolic erupted
10:02 Frolic erupted (d=52m)
10:10 Fountain erupted
10:19 Sizzler erupted
10:21 Clepsydra paused
10:40 Sizzler off (d=21m)
10:48 Fountain off (d=38m)
10:48 Twig off
11:01 Clepsydra resumed
11:05 left the area

Beehive's Indicator Geyser
The "False Indicator" Series of Early July 1994

T. Scott Bryan

Abstract
Beehive's Indicator underwent its second known episode of frequent and regular eruptions without consequent play by Beehive Geyser. the start of this series and its relationship to eruptions by Dome Geyser and Giantess Geyser is briefly described.

Introduction

Beehive's Indicator (Geyser) was named because of the way it sometimes erupts as a precursor to much larger and spectacular Beehive Geyser. Modern observers (those since about 1970) have been somewhat spoiled by its almost infallible action. Historically, however, both Beehive and the Indicator have been erratic performers. Nevertheless, the great majority of Indicator eruptions have preceeded Beehive by a few minutes. Play by the Indicator in which Beehive did not follow, termed a "False Indicator," has been taken as uncommon bad luck.

On August 1, 1992, the Indicator started an episode of frequent and regular eruptions without a consequent Beehive. This observationally unique manner of action was repeated in July 1994. The two episodes were similar in most respects, but eruptions by both Dome Geyser and Giantess Geyser during the 1994 series of "False Indicators" revealed some basic facts about subsurface connections and relationships within Geyser Hill.

History and Terminology

Beehive Geyser, which is a relatively minor part of this report, was first seen and named by the Washburn-Langford-Doane party on September 19, 1870. At the time, Beehive was probably a rather frequent performer. Visits to the Upper Geyser Basin by reporting observers were sparse during the 1870s, yet 24 individual eruptions were logged. During much of the 124 years since it was first seen, though, Beehive has been highly erratic. Most often it would play a few times only in the few hours following (sometimes also just before) eruptions by Giantess Geyser [Whittlesey, 1988]. Times when Beehive has been so frequent and regular as to be nearly predictable, as has been the case much of the time since the early 1970s, have been rare.

Beehive's Indictor was apparently first seen in action as a precursory indicator to Beehive by Ludlow in 1875. It was also described as an indicator by Peale in 1878 and Wylie in 1882, and the name "Beehive's Indicator" was probably first applied by Weed in 1884 [Whittlesey, 1988]. Even when Beehive played only in conjunction with Giantess Geyser, the Indicator worked well, preceeding the larger show by a few (about 5 to 20) minutes. It fell entirely dormant around 1920, and was not seen again until Marler watched it act in 1951. Note that while Beehive was active on occasion during those intervening years, the Indicator was not. Since 1951, the Indicator has continued to be a fairly reliable performer, regardless of the frequency of Beehive itself. As a precursor to Beehive, the Indicator's play usually lasts between 12 and 25 minutes. The steady jetting varies in force but commonly reaches between 6 and 10 feet high.

Just when anything akin to the modern "False Indicator" and "Mid-cycle Indicator" eruptions were first witnessed is unknown. A "False Indicator" takes place at about the time an eruption by Beehive might normally be anticipated. The Indicator's play tends to be extraordinarily long in duration (sometimes greater than 60 minutes) and does not result in play by Beehive. Over the last 20 years, "False Indicator" play was commonly followed by another Indicator eruption *with* Beehive within a few hours. For the Indicator to erupt frequently, regularly, and repeatedly for days on end without a Beehive was unprecedented until August 1, 1992; a similar episode began on July 2, 1994 and is the main focus of this article.

A "Mid-cycle Indicator" is probably of no account. In fact, it might be a relatively common occurrence. This play takes place at about the mid point of Beehive's interval (recently, roughly 5 to 12 hours following the previous full Beehive eruption). It almost always has a duration of less than 1 minute (up to 2 minutes is known, but so too is only 12 seconds) and splashes only 2 to 4 feet high.

The "False Indicator" Series of 1992

I personally know little about the activity of 1992. I had, unfortunately, finished my month-long observation of Geyser Hill activity [Bryan, 1993] and left the park only days before it began. Via miscellaneous reports from other observers, however, it can be said that on August 1, 1992, the Indicator had an eruption with a duration of about 50 minutes. Such eruptions continued every 3 to 5 hours. Beehive responded only on August 3 and August 7, and then entered a dormancy that lasted until September 1. During the following 25 days of complete dormancy in Beehive, the Indicator continued to play with nearly predictable frequency. The durations varied between about 30 and 55 minutes. There was apparently no sign of either the beginning or end of this episode.

This period of "False Indicator" eruptions was entirely without recorded precedent.

The "False Indicator" Series of 1994

On the evening of June 28, 1994, Beehive's Indicator had a "False Indicator" eruption. Beehive then played, with the Indicator, a bit more than 6 hours later. The interval following that eruption again included a "False Indicator," this time followed by a normal Beehive a bit less than 6 hours later. Two of the following three (and probably all three) Beehive intervals also included both "False Indictor" and "Mid-cycle Indicator" eruptions. Despite this abnormal play by the Indicator, Beehive's intervals seemed normal. They ranged between 14h 07m and 21h 40m.

The eruption by Beehive at 00:57 on July 2, 1994 was the last, however. Two "Mid-cycle Indicators" led to a series of "False Indicators" that continued, for the purposes of this report, through July 12, 1994. Differences between this series and that of 1992 were relatively slight. The intervals, rather than being 3 to 5 hours, were generally closer to 1 1/2 to 4 hours; and the durations, unlike the 30 to 50 minutes of 1992, were mostly between 21 and 31 minutes.

This series, and how it was affected by eruptions by Dome Geyser and Giantess Geyser, was observed me. This entire data series is reproduced as Table I. The basic graphical relationships are shown in Figure 1.

The "False Indicator" Eruptions

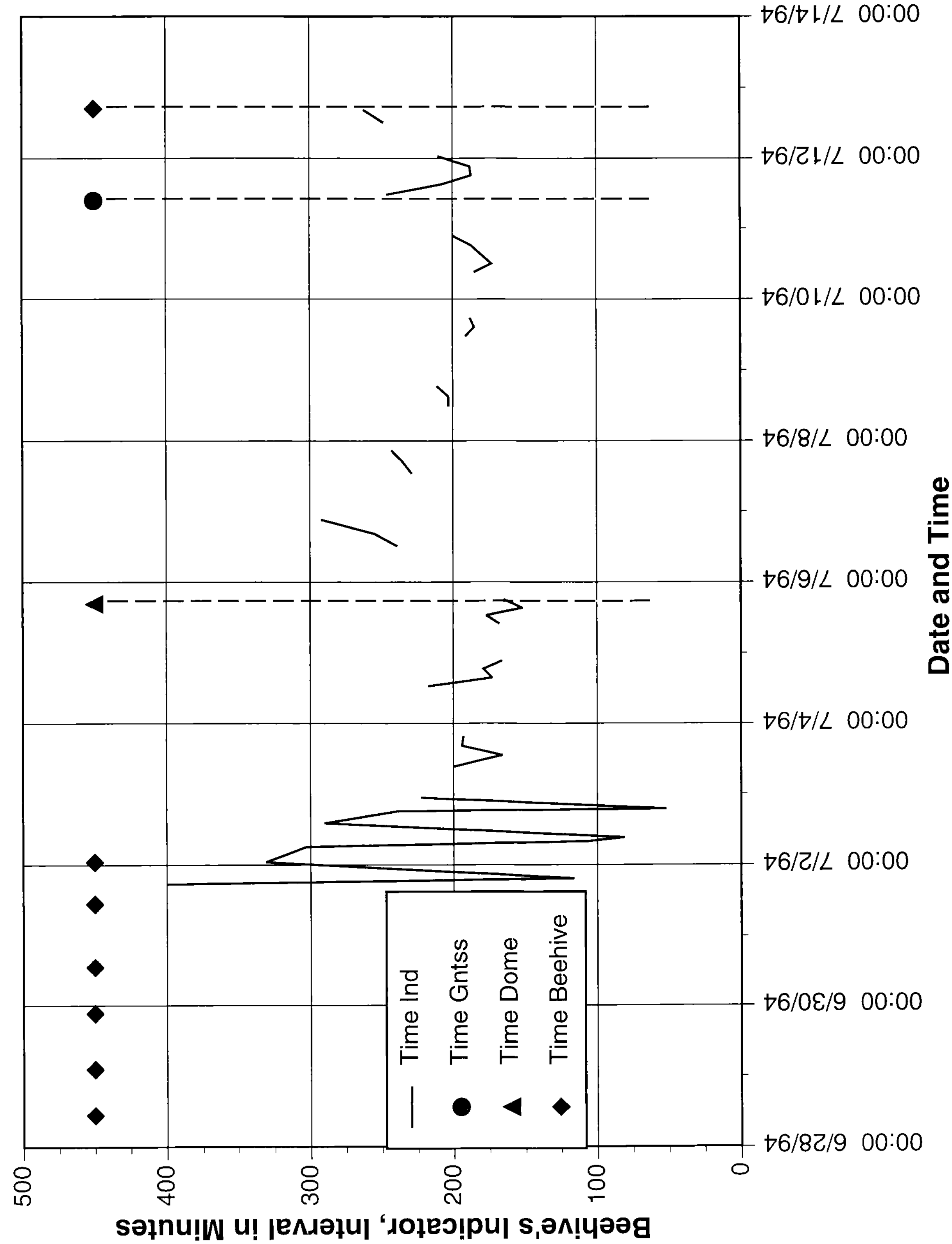
The majority of the "False Indicator" eruptions of 1994 were viewed from a distance, and some of the recorded start times are in error by perhaps as much as 2 minutes. This conclusion is based on a few eruptions whose starts were viewed on-site. They uniformly began with weak and somewhat intermittent bubbling, generally taking longer to produce strong jetting than do normal, pre-Beehive Indicators. Also, on one occasion water was visible standing within the vent a full 36 minutes before the eruption began.

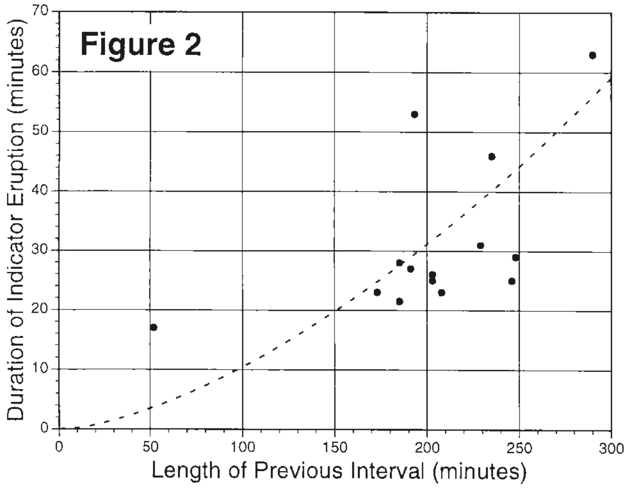
Once started, however, the Indicator's play was "normal" in most respects. With some waxing and waning in their force, these eruptions jetted water steadily to heights of between 4 and 10 feet. The end of the play was foretold by brief pauses in the action, and more than once it was clear that the eruption continued at depth for some minutes after the last surface discharge. The recorded durations, which were most commonly in the 20-minute range, include only the observed period of surface discharge.

Duration versus Interval

My primary initial reason for recording the "False Indicator" eruptions was to check the possibility of a relationship between the durations and the intervals. Only a relatively small number of "False Indicator" durations were accurately recorded, but these 14 data points indicate that they were weakly controlled by the length of the interval leading up to the eruption. This relationship is shown by Figure 2. The dashed line

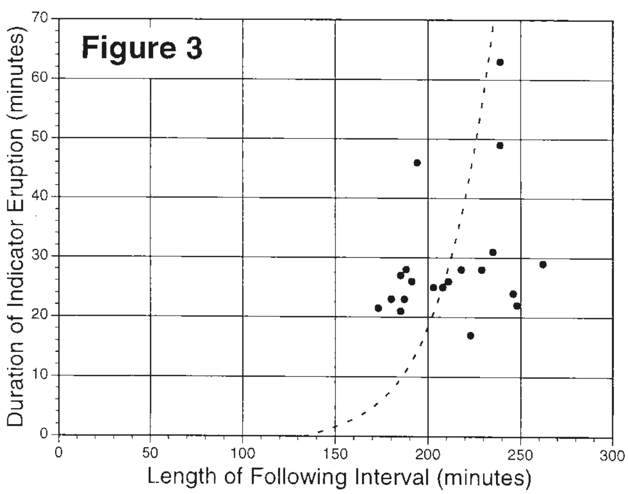
Figure 1


Beehive's Indicator, Interval in Minutes
0
100
200
300
400
500
Date and Time
00:00 6/28/94
00:00 6/30/94
00:00 7/2/94
00:00 7/4/94
00:00 7/6/94
00:00 7/8/94
00:00 7/10/94
00:00 7/12/94
00:00 7/14/94
Time Ind
Time Gntss
Time Dome
Time Beehive



is a first-iteration power curve. The correlation between the two factors is only 33%.

On the other hand, the correlation between the duration and the following interval is far



weaker. Shown in Figure 3, these 20 data points give a correlation of only 9%.

Taken on summary, it is likely that there was no provable relationship between the duration and either set of interval data.

The Effect of Dome and Giantess Geyser Eruptions

As shown in Figure 1, the intervals between "False Indicator" eruptions gradually grew shorter between the last eruption of Beehive Geyser at 00:57 on July 2 and the eruptive sequence of Dome Geyser that began at 16:36 on July 5. The shortest two intervals of this entire sequence, about 152 minutes and 165 minutes, were the last before and the first after the start of Dome. The alternating long–short interval oscillations of July 1–2 have no known explanation, but even they fit the overall pattern of decreasing interval lengths.

There were no overnight observations, but the intervals on the day following Dome's start were significantly longer, peaking at about 290 minutes. From that level, the intervals gradually dropped again, following a curve quite similar to that seen between the last Beehive and Dome; the primary difference is the apparent lack of the long–short interval oscillations. When these intervals had dropped to the same order of magnitude (173 minutes), the eruptive sequence by Giantess Geyser began less than a day later. That eruption was followed by another sharp rise in "False Indicator" intervals and, in this case, subdued long–short oscillations may have evident.

Clearly, there are some differences here, but in an overview it appears that the eruptions by Dome and Giantess had strongly similar effects on the activity of Beehive's Indicator. On February 16, 1994, Mike Keller [1994] observed a similar (though inverse) relationship between these two geysers and Plate Geyser. Plate, long known to be beneficially affected by Giantess, decreased its average interval from 103.9 minutes to 71.8 minutes immediately upon the start of Dome. In both situations, although their manner of play is very different, Dome and Giantess again seemed to play similar roles in Geyser Hill activity, just as has been contended by many previous observers.

It should be noted that the eruptions by both Dome and Giantess caused observable changes in Beehive, but only Giantess and not Dome produced a series of relatively frequent and regular eruptions in Plume Geyser. The eruption of Dome had no observable effect whatsoever on Plume. Ralph Taylor [pers. comm.,1995] has data from 1992, 1993, and 1994 in support of this observation.

Prior to final editing, this article was refereed by Lynn Stephens and Ralph Taylor.

Table I

Beehive's Indicator Geyser, June 28 – July 12, 1994

Date	Time	Duration (minutes)	Interval (minutes)	Comments
6/28/94	**1044**			**Beehive Geyser eruption**
	2006	>53	[9h 22m]	Full "False Indicator" eruption
6/29/94	**0221**			**Beehive eruption**, I = 15h 37m
	1544		[13h 23m]	Full "False Indicator" eruption
	2119	>22		**Beehive eruption**, I = 18h 58m
6/30/94	0909	<1	[11h 50m]	"Mid-cycle Indicator" eruption
	1310			**Beehive eruption**, I = 15h 51m
	no additional data this day			
7/1/94	**1050**			**Beehive Geyser**, I = 21h 40m
	1730	<1	[6h 40m]	"Mid-cycle Indicator" eruption
	1926		[8h 36m]	Full "False Indicator" eruption
7/2/94	**0057**	unknown	331	**Beehive Geyser**, I = 14h 07m
	≈0600	"seconds"	≈300	"Mid-cycle Indicator" eruption
	0747	"1-2 min"	≈107	"Mid-cycle Indicator" eruption
	0908	53	81	Full "False Indicator" eruption, as are all of the following to the end of this table
	1358	63	290	
	1757	48	239	
	1849	17	52	
	2232 i.e.		≈223	
7/3/94	0554 i.e.		[221 X 2]	Inferred double interval
	0914 n.s.	>33	200	
	1309	46	235	
	1623	>50	194	
	1936	53	193	
7/4/94	0908	>28		
	1246 i.e.		≈218	
	1539		≈173	
	1838 i.e.		≈175	
	2124 i.e.		≈166	
7/5/94	0703			
	0951		168	
	1248		177	
	1520 n.s.		≈152	
	1636			**Dome Geyser eruption start**
	1805		165	
7/6/94	0805	49		
	1204		239	
	1619 n.s.		≈255	
	2111 i.e.		≈290	Believed to be single interval
7/7/94	0857	28		
	1246	31	229	
	1640	25	235	
	2043 n.s.	>20	≈240	
7/8/94	0813	25		
	1136	25	203	
	1459 n.s.	26	≈203	
	1830 n.s.		≈211	
7/9/94	0813	26		
	1124	27	191	
	1429	28	185	
	1737	>30	188	
7/10/94	0607 n.s.			
	0910	21	≈185	
	1203	21	173	
	1503	23	180	
	1810		187	
	2130 i.e.		≈200	

7/11/94	0724	24		
	0925			**Giantess Geyser eruption start**
	1130	25	246	
	1458	23	208	
	1805 n.s.		187	
	2113 i.e.		≈180	
7/12/94	0042 i.e.		≈210	
	0753 n.s.	>22	[215 X 2]	Inferred double interval
	1201	29	≈248	
	1623	24	262	Ended during Beehive eruption
	1647			**Beehive Geyser eruption start**
	end of data			

i.e — in eruption; start time not reasonably known
n.s. — near start; start time probably within 5 minutes of time when first seen in eruption
≈ — approximate value

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Bryan, T.S., 1993, Cyclic hot spring activity of Geyser Hill. . .: The Geyser Observation and Study Association, *GOSA Transactions*, v. IV.

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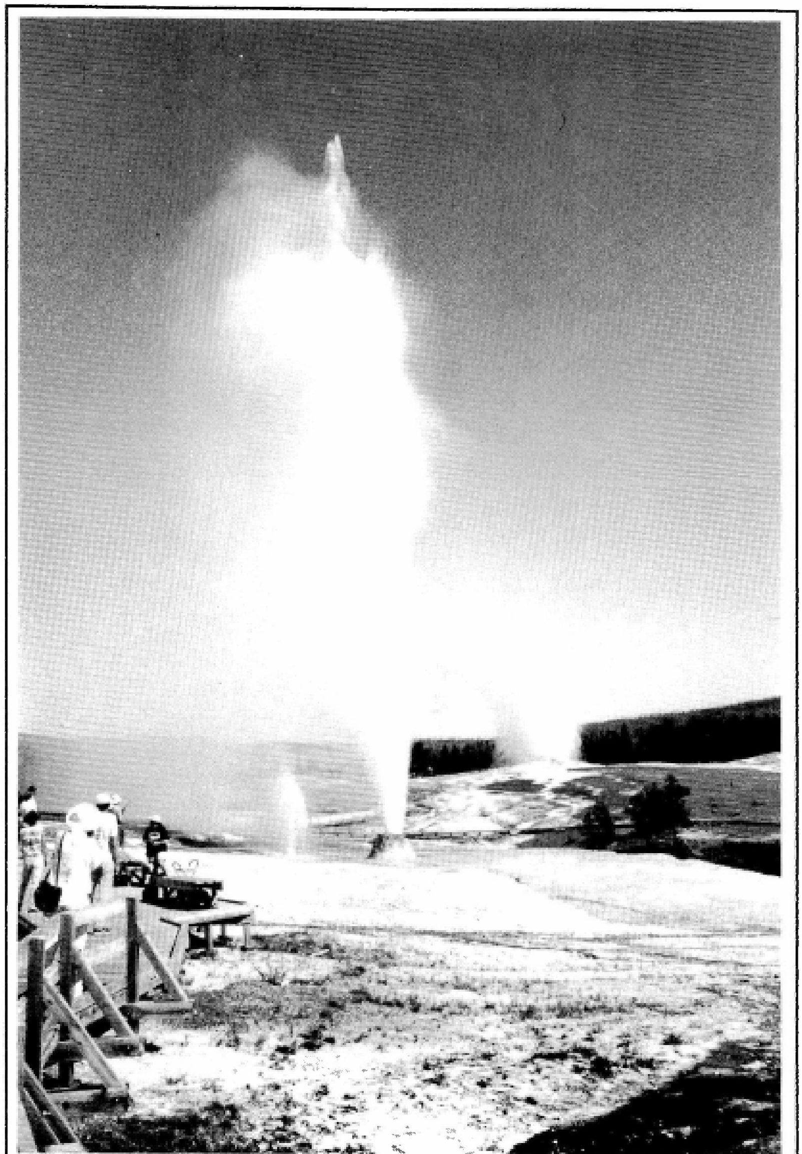

Beehive's Indicator, the jet to the lower left of the cone, erupting on July 7, 1996. This was a normal eruption and is included here only to show the nature of its activity. (Photo by Udo Freund)

PYRAMID GEYSER

UPPER GEYSER BASIN, YELLOWSTONE NATIONAL PARK

September-October 1995

September-October 1996

By: Ralph C. Taylor

ABSTRACT

This report describes the activity of Pyramid Geyser, located near Daisy Geyser in the Upper Geyser Basin in Yellowstone National Park. The report briefly describes the geyser's formation, describes and classifies the observed activity. The activity of Pyramid Geyser was studied by periods of on-site observation and two weeks of recorded geyser activity during each year of the study using a temperature monitor.

INTRODUCTION

Pyramid Geyser is a small geyser located near the Daisy Geyser group in the Upper Geyser Basin in Yellowstone National Park. Pyramid Geyser received little attention until the reactivation of Splendid Geyser during the summer of 1996. This study was performed to determine the activity of Pyramid Geyser in the fall of 1995, and continued for three weeks in the fall of 1996. In September 1995, it was known that Pyramid was active, but few eruptions had been recorded during the summer of 1995 and little was known about the regularity of the activity or even the eruption intervals. In 1996 there had been much more attention to the Daisy Geyser group because of the activity of Splendid Geyser, and some Pyramid times were recorded, but the record was incomplete.

The author had obtained three battery powered StowAway™ temperature recorders manufactured by Onset Computer Corp. for use in another study. Once the initial study was complete in September of 1995, one recorder was placed on Pyramid Geyser at the suggestion of the Yellowstone Research Geologist, Rick Hutchinson. The temperature recorder was placed on Pyramid Geyser again during the author's three week visit to the Old Faithful area in September of 1996. In both cases the sensor was a thermistor placed in the runoff channel just below the sinter platform at a point where the runoff water concentrates.

The majority of this study was performed using the temperature monitor in Pyramid Geyser's runoff channel and deducing the activity by examining the runoff temperature record. Once the pattern of activity was established, two days of visual observation in 1995 and several spot checks in 1996 confirmed the activity and provided additional details about the eruptive activity.

DESCRIPTION OF PYRAMID GEYSER

Pyramid Geyser is located 200 meters (650 feet) west northwest of Daisy Geyser at the base of a white colored hot spring mound called the White Pyramid or White Throne [Bryan 1995]. The mound was formed by a hot spring at the top of the mound, which has almost completely sealed itself in. The site of the spring at the apex of the mound can be seen to steam slightly on cool days, but no liquid water flow occurs today.

Pyramid Geyser itself is a well established feature located on the northwest slope near the base of the pyramid. The geyser formation consists of a well-sintered circular platform with a circular vent 10 cm in diameter near the center of the platform. The platform is an estimated 4-5 meters (13-16 feet) in diameter. The platform is flat, and is surrounded by a gravel outwash area. The sinter on the platform is in excellent condition since Pyramid Geyser erupts frequently and keeps the formation wet. Figure 1 shows the Pyramid Geyser formation from the slope of the Pyramid formation, looking toward Daisy Geyser (visible as a steam cloud in the distance). The space between Pyramid Geyser and the Daisy group is occupied by a marshy meadow. The lodgepole pine logs at the right of the photograph are silicified and have become part of the geyser formation. The runoff water from eruptions makes its way from the vent and catch basins at the right center of the photograph to a well-defined runoff channel at the near side of the formation, dropping over the silicified log at the far left edge of the platform.

Pyramid Geyser September-October 1995 & September-October 1996

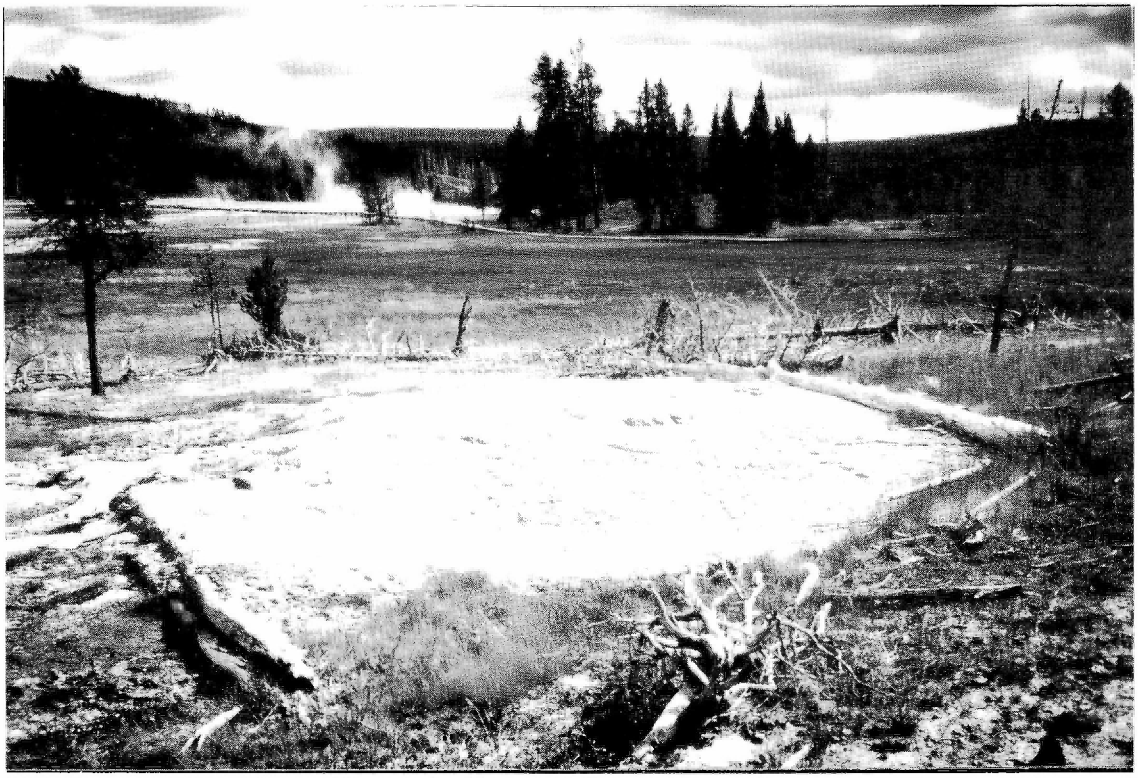

Figure 1 - Pyramid Geyser formation

Figure 2 - Pyramid Geyser vent and catch basins

Figure 2 shows the central part of the platform. The vent, seen just to the left of center, is located in the center of a raised, beautifully beaded geyserite mound approximately 50cm (20 inches) in diameter. The geyserite is a light yellowish gray in color, and the beading is perfectly preserved and maintained by the frequent splashing from minor eruptions. A small catch basin, seen in the foreground of Figure 2 and in a detailed view in Figure 3, contains hundreds of small elliptical "geyser eggs", mostly in the order of 1cm in length. These "geyser eggs" are small pebbles of geyserite with a lustrous, pearly surface.

The vent, shown in Figure 4, is nearly circular, and opens out below the surface to a chamber of indeterminate size. Water can be seen entering the chamber from the northwest side as an eruption approaches. The sides of the vent are covered by coral-like geyserite beading, with small beads about 1mm in diameter covering much of the vent sides. This fine beading, shown in Figure 5, extends about a meter from the vent. Figure 6 shows Pyramid Geyser in eruption in a photo from October, 1981.

Figure 6 - Pyramid Geyser in eruption, October 1981 (Photo: Paperiello)

Figure 3 - Detail of catch basin and vent of Pyramid Geyser

Pyramid Geyser September-October 1995 & September-October 1996

Figure 4 - Close up view of Pyramid Geyser's vent

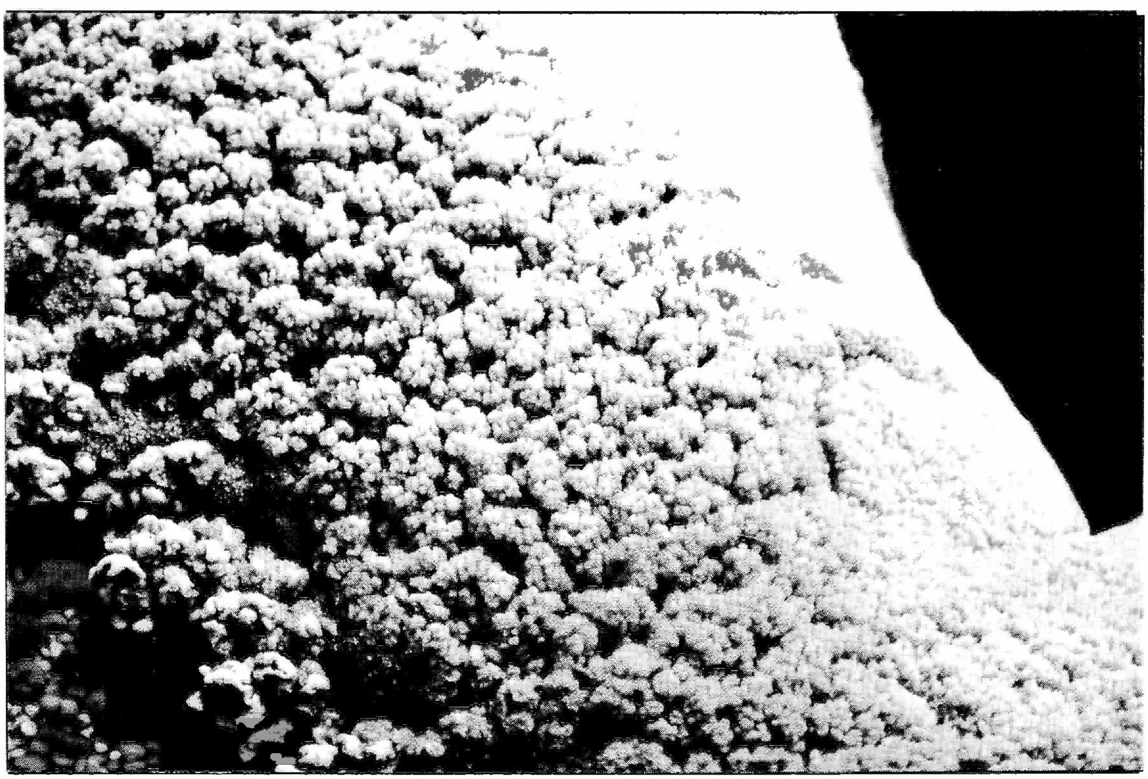

Figure 5 - Beading in the vent of Pyramid Geyser

PYRAMID GEYSER'S ACTIVITY

In the fall of 1995 there was little information about Pyramid's activity. The first deployment of the temperature monitor showed that despite an almost total lack of recorded eruptions during the 1995 season, Pyramid was a regular performer, erupting with a mean interval of 3h10m for 75 measured intervals. The minimum interval was 2h46m, and the longest interval was 4h03m. The standard deviation for the 75 intervals was 16 minutes.

	1995	1996
Number of Intervals	75	80
Mean Interval	3h10m	3h05m
Maximum Interval	2h46m	2h39m
Minimum Interval	4h03m	3h44m
Standard Deviation	16 min.	12 min.

Table 1 - Eruption statistics for the study period

In 1996 the activity was similar to the 1995 activity for the 80 measured intervals. The mean interval was 3h5m, the shortest interval measured was 2h39m, the longest was 3h44m, and the standard deviation was 12 minutes.

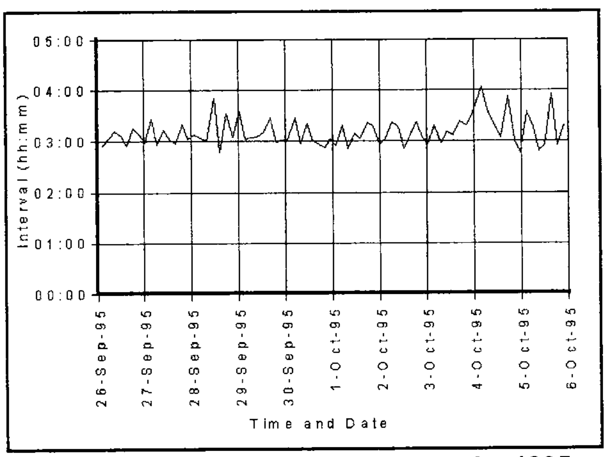

Figure 7 - Pyramid Geyser intervals, 1995

The 1996 record would have contained more than 80 closed intervals, but near the end of one of the deployments a bison kicked the recorder away from the runoff channel and pulled the thermistor out of the water. The data for 07:00 to 20:20 on 19 September 1996 was lost because of this incident.

Figure 7 illustrates the measured intervals for the study period in 1995. The intervals vary during each day, often alternating between longer and shorter intervals. For most of the study period the variation was between 3h0m

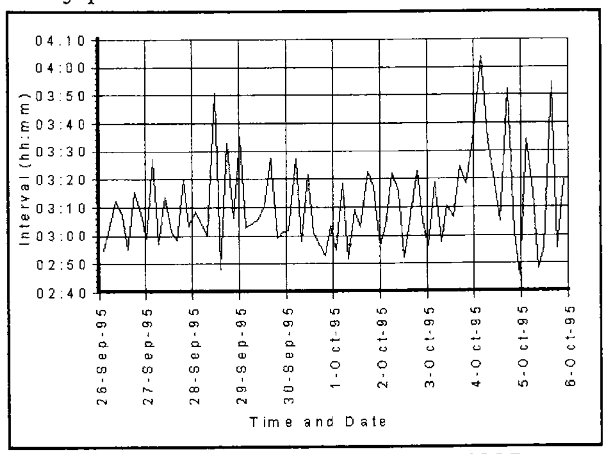

Figure 8 - Pyramid intervals, 1995 (expanded vertical scale)

and 3h30m. On 4 October the variation suddenly increased, with intervals varying between 2h50m and 4h0m. The cause of the change in eruption pattern was not determined. The intervals on 28 September 1995 showed a similarly large variation. Figure 8 shows the 1995 intervals with an expanded vertical scale to illustrate the variation more clearly.

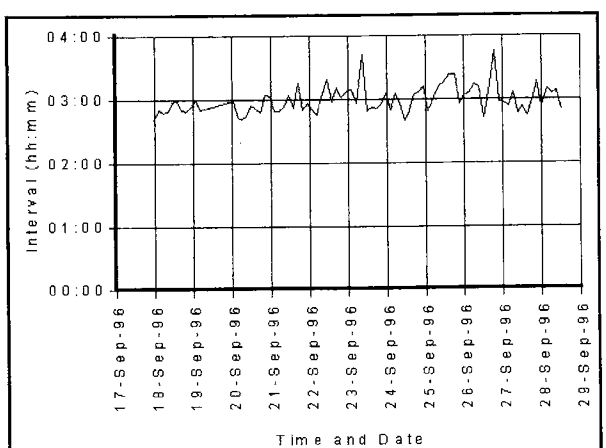

Figure 9 - Pyramid Geyser intervals, 1996

Figure 9 shows the 1996 intervals during the period of this study. The intervals are similar to the 1995 study period. The variation in intervals is present, and appears to be similar in period and amplitude.

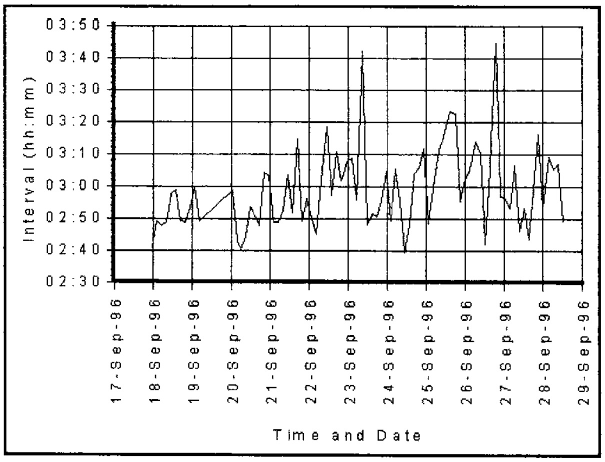

Figure 10 - Pyramid intervals, 1996 (expanded vertical scale)

Figure 10 shows the same data plotted with an expanded vertical scale. There are two points on the graph where long intervals occur, on 23 September 1996 at 9:06 and again on 26 September 1996 at 19:17. These did not correlate with any nearby geyser activity that I could determine. In particular, it did not correlate with Splendid geyser eruptions.

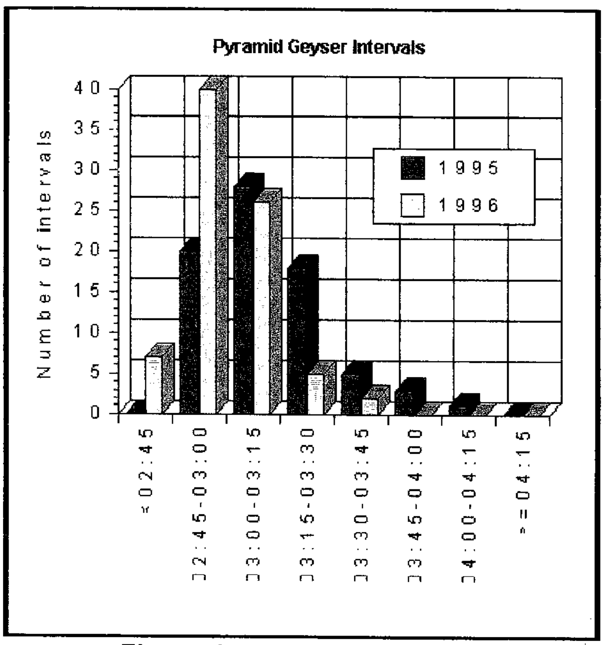

Figure 11 - Pyramid Geyser 1995 and 1996 Interval Distribution

The distribution of intervals changed somewhat between 1995 and 1996, as is shown in Figure 11. The most noticeable difference was the preponderance of intervals in the 2:45 to 3:00 range in 1996. There were also more short intervals (under 2h45m) in 1996, and no intervals over 3h45m. In 1995, there were no intervals under 2h45m but there were five intervals longer than 3h45m. Overall, the pattern of eruptions about every three hours remained roughly the same between 1995 and 1996.

Data Analysis

The intervals discussed in the previous section were computed using a program written by the author. The program scans the entire temperature record, and detects eruptions by looking for the sharp temperature rise in the runoff channel. The program uses a moving window containing twelve consecutive temperature samples, and detects the initial eruption by noting a sharp temperature rise. Considerable experimentation was required to find an algorithm that reliably detects eruptions.

A particular difficulty is finding the *first* temperature reading of an eruption. The method used for the analysis of Pyramid's data detects an eruption if the temperature rises by more than 2.5°C between two samples *and* the temperature rises by at least 12°C for the next sample. Additional tests reject events occurring before 30 minutes following the previous eruption. The results of the program were checked manually and verified for many of the eruptions.

Pyramid Geyser Eruptions

The eruptions of Pyramid Geyser are short in duration, and can occur singly or accompanied by minor eruptions before or after the major eruption. The major eruptions are short in duration, averaging 45 seconds for nine observations. The height of the major eruption is between approximately two and three meters (six and ten feet), estimated from a viewing position on the boardwalk near Splendid Geyser. Minor eruptions vary in duration and height, but are generally shorter in duration and smaller in height than the major eruption. The minor eruption heights observed varied from nearly three meters (ten feet) to about half a meter (under two feet). Durations were a few seconds to 30 seconds.

In between eruptions, the vent was empty and the platform was dry except for a few pools in catch basins. From time to time wispy steam could be seen above the vent on cool days.

One eruption that I watched closely began about 20 minutes before the major eruption with light, steady steam emitted from the vent. At eight minutes before the eruption, water could be seen bubbling steadily about 5cm (2 inches) above the vent. After another 2m30s the height of the water increased to about 30cm (12 inches). The height decreased to about 10cm (4 inches) 4 minutes later (about 1m40s before the major eruption). From that time the height gradually increased from 10cm (4 inches) to 50cm (20 inches) at about 15 seconds before the major eruption, then built to the full three meters rapidly.

Within 30 seconds after the water column stopped, there was only faint steam from the vent. At 6m30s from the end of the major eruption, there was steady steam from the vent. At 7m15s, the water column was back to 50cm (20 inches) above the vent. The height decreased to 20cm 30 seconds later, then within another 25 seconds built to a minor eruption with a height estimated at 1 meter (40 inches) for a duration of 54 seconds. The interval from the major to the following minor was 8m22s.

This pattern, a slow buildup of activity to a major eruption, often followed by a minor eruption eight to ten minutes later, was common during the observation period in 1996. On some occasions the second eruption was nearly as high as the major eruption. The temperature record clearly shows the pre-eruption play as a gradual increase in temperature of the runoff channel as the water makes its way to the sensor. The temperature climbs rapidly to a peak as the water from the eruption runs past the sensor, then the temperature falls exponentially as the sensor and the sinter of the runoff channel cools. The second, minor eruption can be seen clearly in the temperature record also. The temperature record does not allow the height of the minor eruption to be determined. The temperature rise depends more on the quantity of water and the duration of the eruption than it does on the height or force of the eruption.

Frequency of Multiple Eruptions

The data analysis program discussed previously was modified to detect second and third eruptions. The program looks for a second eruption by detecting a temperature rise of more than 1.5°C between consecutive readings *or* a rise of more than 2°C between a reading and the reading four samples (1 minute) earlier. The program also computes the temperature rise for the second and third eruptions, and classifies the second and third eruptions as "small" or "medium" based on the temperature rise. There were not enough visual observations of second and third eruptions to allow the "small" and "medium" eruptions as detected by analyzing the temperatures to be correlated with height of the eruptions.

	1995	1996
Number of Eruptions	77	82
Number of 2nd Eruptions	30	61
Number of 3rd Eruptions	1	2
Mean Interval to 2nd Eruption	11m02s	9m18s
Max Interval to 2nd Eruption	14m00s	11m30s
Min Interval to 2nd Eruption	6m45s	7m00s

Table 2 - Frequency of multiple eruptions

Table 2 shows the statistics for second and third eruptions for the observation period. Fewer than half of the eruptions recorded in 1995 were followed by a second eruption (39%) but 74% of the eruptions recorded in 1996 were followed by a second eruption. A third eruption was recorded in one case in 1995 and twice in 1996. The second eruption followed the major eruption more closely in 1996 than in 1995, by 1m44s. The earliest a second eruption occurred was 6m45s, and the longest pause was 14 minutes. Interestingly the pause was shorter and the spread in times much less in 1996 than in 1995. Since the classification of minor eruptions by the temperature rise was not correlated with visual observation, it is not clear whether the observations are significant, so I have not included this information here.

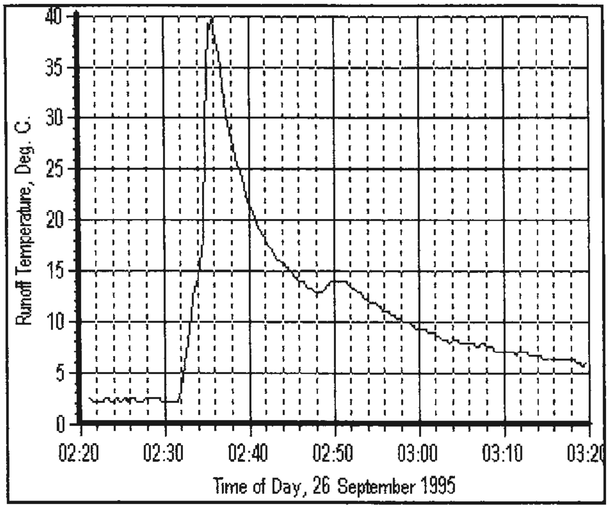

Figure 12 - Temperature record for Pyramid Geyser eruption at 02:35 26 September 1995

Typical Eruptions

Figure 12 is the temperature record for a typical Pyramid Geyser eruption, which occurred on 26 September 1995. The overflow started at 02:32 when the runoff channel temperature rose from the ambient temperature of 2°C. The gradual rise continued as the runoff water flow (which is low volume during the preplay) gradually warmed the geyserite lining the channel. This phase, a gradually increasing temperature reading, corresponds to the low preplay, which by direct observation, reached heights of 5 to 50cm. At 02:35 the temperature rose rapidly to almost 40°C as the major eruption occurred. The duration of most eruptions was under 1 minute, but there was a significant amount of water deposited on the platform. That water poured down the runoff channel, raising the sensor temperature quickly. The runoff lasted longer than the eruption, as much of the water was trapped by catch basins in the sinter platform and drained off slowly. After two minutes or so the flow had slowed and the temperature of the runoff channel dropped exponentially to ambient temperature.

This eruption is typical of eruptions with no minor eruption. The temperature rise was gradual, the eruption peak was sharply defined, and the exponential decay of the temperature was almost uninterrupted. There was a slight rise in runoff temperature at 02:50, probably from a small amount of overflow. Although this rise occurred later than one would expect a second eruption, it is often seen in single eruption temperature traces. I suspect that it represents an aborted minor eruption, or a very small minor eruption.

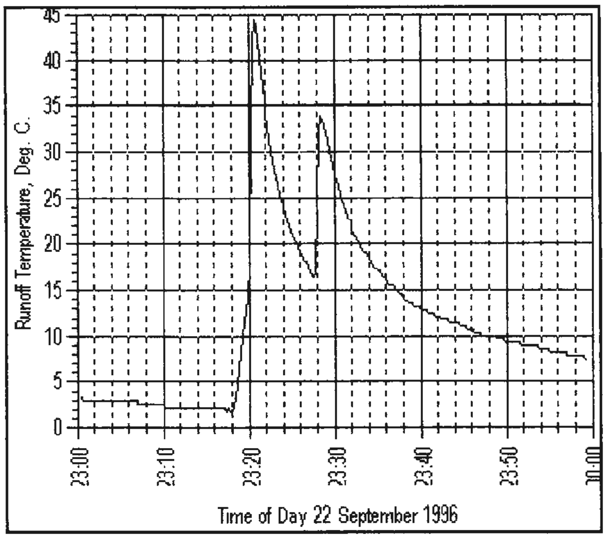

Figure 13 - Pyramid Geyser eruption at 23:30 on 22 September 1996, followed by a minor eruption

Figure 13 shows the temperature record for an eruption at 22:20 on 22 September 1996 which was followed by a minor eruption. The trace of the eruption itself is similar to the eruption shown in Figure 12, but at just over seven minutes after the major eruption the exponential drop in runoff temperature ends and the runoff temperature rose to just over 30°C, then resumed its exponential decrease. The smaller temperature rise for the minor eruption indicates that the rate of flow was less, allowing the water to cool before it reached the sensor. The majority of the second eruptions showed smaller temperature rises than this example. There are occasions in the temperature log where the rise is only a few degrees. This corresponds to observed behavior consisting of low (5-10cm) boiling from the vent with a low quantity of water ejected from the system.

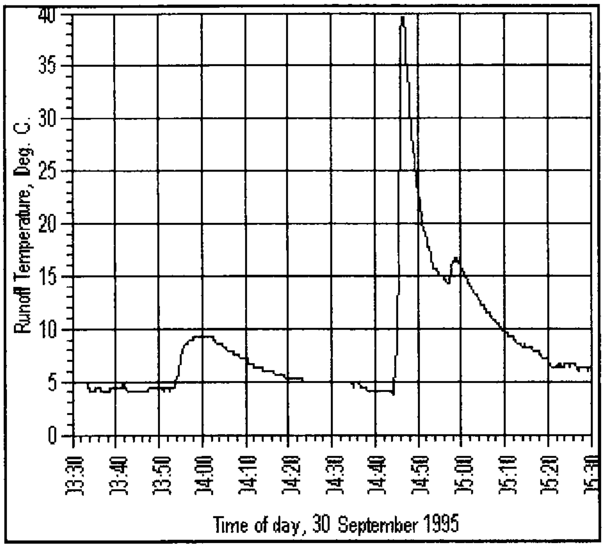

Figure 14 - Pyramid Geyser eruption at 04:47 on 30 September 1995

In 1995, but not in 1996, there are several instances of minor eruptions between major eruptions in the temperature record. Figure 14 shows one such eruption. The runoff temperature rose about 5°C starting at 03:54, peaked at 9°C, and then gradually dropped for the next 20 minutes until it reached ambient temperature. There are several instances of mid-cycle minor eruptions in 1995, but none in 1996. Visual observations confirmed the mid-cycle minor eruptions in 1995.

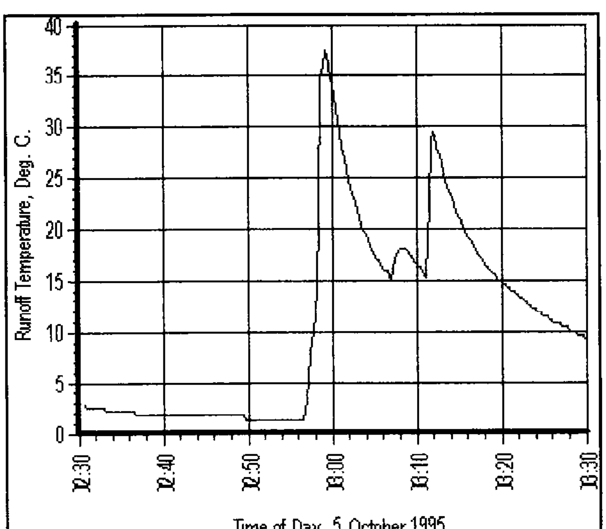

Figure 15 - Pyramid Geyser eruption at 02:59 on 5 October 1995

There were other unusual occurrences in the temperature record. The eruption at 02:59 on 5 October 1995 is shown in Figure 15. The temperature record of this eruption shows the double peak of a major eruption at 02:59 followed by a minor eruption at 03:12, but between these eruptions there was an episode of overflow at 03:08, possibly an aborted minor eruption. Visual observation of other eruptions detected several episodes of overflow with water visibly over the vent to a height of a few centimeters at around 10 minutes after a major eruption. The event in the temperature record for 5 October 1995 is probably one of those events.

Observing Pyramid Geyser

Because of its location 55 meters (180 ft) from the nearest point on the boardwalk it is difficult to observe Pyramid Geyser directly. It is possible to observe the water level from the boardwalk using binoculars; in fact all of the visual observations for this paper were made from the boardwalk between Splendid Geyser and the turn to the south where the path turns toward the trail to Punchbowl Spring. The height estimates are based on the known height of the formation and the nearby logs.

The author made several trips to the formation itself with the requisite permission of the National Park Service. All off-trail work during daylight hours was done with uniformed NPS personnel either with the author or on the boardwalk. Please note that this feature cannot be visited legally without special permission of the NPS.

The bulk of the data was obtained from the temperature record obtained using the author's StowAway recorder. The complete list of all detected eruptions (including minor eruptions following the major eruptions) is available from the author on request.

During this study, the author learned some important lessons about using the temperature recorders. First, it is important to locate the recorder so bison do not kick it away! Second, it is important to locate the sensor under a rock or other object to shield it from direct sunlight; failure to do so produces distorted temperature traces that make it harder to detect minor eruptions. Third, it is important to take the time to "launch" the instrument correctly (failure to do so caused the loss of several days of data during both study periods).

It should be clear from this data presented here that a lot of useful data can be obtained from the temperature record. It must be borne in mind, however, that the temperature data must be validated by direct observation to calibrate the information from the temperature trace against direct observation. This direct observation, when compared to the temperature record, allows the features of the temperature record to be correlated with observed activity of the geyser. It also allows the times determined from the temperature record to be compared to the observed eruption times and thereby calibrated. The temperature recorder normally detects an eruption as much as two minutes (depending on the geyser's overflow volume and the speed of the runoff water flow) after the actual start of the eruption.

CONCLUSIONS

Based on analysis of 77 eruptions in 1995 and 81 eruptions in 1996, it is clear that Pyramid Geyser was a regular performer during the observation periods. The eruptions occurred during periods of increased water level and temperature, at about three hour intervals. The intervals were fairly consistent, exhibiting Standard Deviations of 16 minutes in 1995 and 12 minutes in 1996. The eruptions occurred either singly or in series of two or three eruptions, with the major eruption occurring first in all recorded instances in 1996 and in the majority of the recorded instances in 1995. When minor eruptions followed the major eruption, the time between the major and minor eruption was normally on the order of 11 minutes in 1995 and 9m18s in 1996. Even when there was no minor eruption following a major eruption, there was sometimes an overflow episode visible both in the temperature record and visually from the boardwalk as water bubbling a few centimeters over the vent.

The overall activity did not change substantially between the observation period in 1995 to the observation period in 1996. The intervals were similar, and the appearance of the eruptions was similar.
Two notable differences were the absence of minor eruptions preceding the major eruptions in 1996 and the significantly more frequent series or two or three eruptions in 1996. Also, the second eruption tended to occur earlier in 1996 than in 1995.

There was no obvious correlation between the activity of Pyramid Geyser and the eruptions of Splendid or Daisy Geyser. The author did not make any extensive statistical tests on the Pyramid data compared to the Daisy Geyser records, but no pattern was evident based on a cursory examination of the eruption records. The intervals of Pyramid Geyser did not change noticeably at the time of the several Splendid eruptions whose eruption time could be determined accurately during the 1996 observation period.

DATA

The record of observations that form the basis for this report is available from the author on request. The temperature records are available as ASCII files with temperature readings every 12 to 15 seconds depending on the length of the deployment.

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The Explosive History of Wall Pool and Black Opal Pool in Biscuit Basin

by

Rocco Paperiello

ABSTRACT: This paper is an effort to describe the successive episodes of explosive activity which opened up both Wall Pool and Black Opal Pool in Biscuit Basin during this century.

The early history of Wall Pool and Black Opal Pool as reported by George Marler [1959 p 30, 1973, p 15, 37] is largely incorrect, and consequently these errors have been repeated by other authors [Muffler et al 1971, Whittlesey 1988, p 143-144, & 1945]. Whittlesey added significantly to the history but did not have access to many of the materials used here. The actual origins and history of these pools are much more interesting than the accounts given by Marler.

Today, these two pools lie within a large thermal crater more than 200 feet long and 45 feet wide, situated in Biscuit Basin between Sapphire Pool and the Firehole River. A hundred years ago they did not exist. Clear evidence of their recent explosive origin has been noted by Pat Muffler of the USGS, and by others before him:

> Surrounding [Black Opal Pool in the Upper Geyser Basin] for as much as 100 ft to the south and 400 ft to the north is a breccia mantle resting on the sinter. Angular fragments of the breccia consist of sinter and opal-cemented sandstone and gravel, and range up to about 3 ft in diameter. [Muffler et al 1971]

In the 1930's, Marler [1973, p 15] himself, noted "small chunks of sandstone. . . not less than 1000 feet north of the crater."

Today, the western or upper portion of the large pool that lies within this crater is called Wall Pool. This name was given by George Marler and first appeared in his 1959 annual geyser report. For many years this pool had mistakenly gone by the name of "Black Pearl Pool," or more simply the "Black Pearl." [VanPelt 1926, Haynes 1926, Upton 1929, Ankrom 1931, Childs 1934a, Allen and Day 1935 p 134, King 1937, Davis, 1959]

An earlier name associated for a time with Wall Pool (or perhaps only a portion of this pool) was that of the "Black Diamond." [Childs 1934a] (See entry under 1934). The name of Wall Pool was given by George Marler "in view of the wall-like escarpment which forms the southwestern side of the crater." [Marler 1973, p 37]

The eastern, or lower portion of the large pool, east of the dike of sinter-cemented sands, currently goes by the name of Black Opal Pool. This name was also given by George Marler and again first appeared in his 1959 annual geyser report. The origin of this name is unknown. At its birth in 1934, this pool had originally been given the name of "Black Boulder Geyser" by Frank Childs [1934b], and this name was used for a while in other naturalists' reports. [RofND, Feb, Mar, 1934]

None of the early maps of the Upper Geyser Basin (those made prior to 1900) show any feature existing where Wall Pool and Black Opal Pool exist today, nor do any of the early survey reports mention any feature existing between Sapphire Pool and the Firehole River. [ie. Bechler 1872, Gannett & Mushbach 1878, Peale 1883, Weed 1884, 1887] The 1904 Hague *Atlas*... also fails to show any feature here, and this probably reflected conditions at least as late as 1902 [Whittlesey 1988]. This would seem to indicate the relatively recent origins of these features. Corroboration of this fact is abundant.

There have been at least five known periods of relatively "recent" explosive activity which resulted in the opening of these two pools. Of these 5 known episodes of "explosive eruptive activity," the four later ones (1918, 1925, 1934, & 1953) are documented by written records. The fifth and earliest (between 1902 and 1912) is documented by a photograph taken by Jack Haynes probably in 1912 (if not 1912 then definitely before this date). Also, more "normal" eruptive episodes of today's Black Opal Pool are known for 1937, 1947, and 1948.

Activity between ~1902 and 1912:

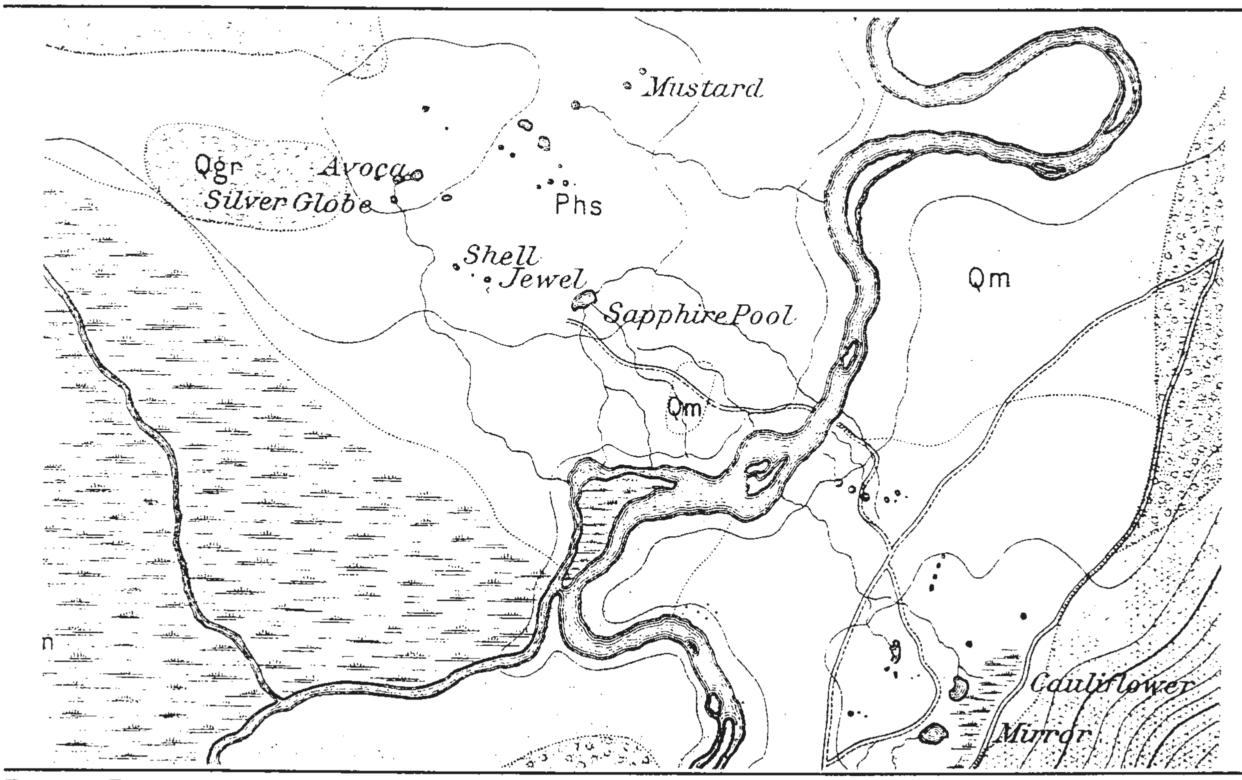
A very early photograph of Wall Pool was taken by Jack Haynes [circa 1912]. (H-6234 of the Haynes collection and numbered 12647 by Haynes himself) This photo, captioned "New Spring at Biscuit Basin," shows a large double basin of the future Wall Pool. (See photo below). As shown, the eastern part of pool is considerably smaller than it is today. Quite a number of boulders are shown strewn about the ground indicating its very recent "explosive" origins. The Black Opal Pool of today did not yet exist.

At about this same time was written an intriguing report by the retired Hiram M. Chittenden of the Army Corps of Engineers, entitled "Geyser Explosion Biscuit Basin." The accession date for this report in the original Park Archives was 1914. Thus it would seem that this report probably described the origins of this "new spring at Biscuit Basin." Unfortunately this report has not yet been located.

1918 activity:

The explosive activity of 1918 is mentioned in two letters, both written in 1926. The first is in a letter to Jack Haynes from Dr. J. R. Van Pelt dated August 15, 1926. Dr. Van Pelt, one of the original ranger naturalists, had spent a number of years in Yellowstone Park. He also stated in this letter that the name of "Black Pearl" was being mistakenly applied to the pool we today call Wall Pool:

> Apparently my letter regarding the explosion in Biscuit Basin resulted in a misunderstanding. There is only one such blowout, and it is located near the river. The "Black Pearl" sign, however, is right beside this pool, having been moved from its proper



BISCUIT BASIN FROM HAGUE'S 1904 *ATLAS*. . .

"NEW HOT SPRING AT BISCUIT BASIN" Haynes Foundation Collection, Montana Historical Society, Helena, MT

position. About 1000 ft. farther west is a pool answering the description of the Black Pearl, and it is marked by a new sign saying "Pearl."

It seems, therefore, that there is no other explosion area in that neighborhood, the one of eight years ago [emphasis mine] on the sinter plain being the only example. The Black Pearl sign, now much the worse for wear, might well be removed. If there is no authorization for its present location, let me know and I'll see that it is taken away from the explosion area.

Even as late as 1959, reports describing the combined pools of Wall Pool and Black Opal Pool, were still erringly using the name of "Black Pearl." [Davis 1959]

The following is a copy of the reply sent from Jack Haynes to Dr. Van Pelt dated August 26, 1926:

Dear Dr. Van Pelt:

Thank you for your letter of the 15th, which I have been unable to answer on account of having been away in Idaho for nearly a week.

I am glad to know that there was but one explosion in the Biscuit Basin area. Without doubt the sign reading "PEARL" placed not far from the footbridge there is improperly placed. It should be removed, and the one reading "BLACK PEARL" at the spring thickly studded with black pearls situated 500 or 600 feet west of the footbridge is correct.

As to removing this sign, I am sending a copy of this letter to Superintendent Albright with the request that if approved, he advise Dr. Conrad, you, and Mr. Neumann the painter. I note that you will remove the sign improperly placed if desired. A change recently was made in Norris Basin which is similar to this, and I note that the Superintendent advised Mr. Neumann to

> remove a duplicate sign, so believe it would be proper to follow the same procedure in this instance. . .
>
> PS After rereading your letter I note that the sign "BLACK PEARL" should be removed from its present position near the river to its correct place about 1000 feet west where there is now a sign reading "PEARL" which should be removed.

1925 activity:

A description of the existing western pool written in 1926 by Charles Phillips [*Ranger Naturalist Manual*, 1927, p 137] related another episode of eruptive activity which apparently was responsible for forming an additional portion of "Wall Pool:"

> As the visitor ascends the slope between the run-off channels of Sapphire Pool he observes on his right a huge cavity in the sinter with fractured walls that bear witness of the power of the subterranean explosion that opened it up in the spring of 1925.

The following short account, written in 1929, alludes to this previous explosive activity:

> Biscuit Basin
>
> Well worth recommending that tourists see it. Jewel Geyser very active for ten years. Black pearl [Wall Pool] interesting on account of its previous activity. [Upton 1929]

Another description, found in the "Geysers of the Yellowstone National Park" by geyser gazer Thomas "Geyser Bill" Ankrom [1931], also indicated that only the double-pooled portion of Wall Pool existed at that time:

> [Here] we cross the Firehole River on a foot bridge, just across and to the right is the Black Pearl [Wall Pool], this consists of two pools of water connected, but one contains hot water while the other is cool. . . [Ankrom 1931]

The "hot" portion of the pool was that closest to Sapphire. That Ankrom is describing only today's Wall Pool is corroborated by Frank Child's reports below.

1934 activity:

By 1934, the opening up of today's Wall Pool was essentially complete. Some additional changes that will have occurred soon after the 1959 earthquake are documented below. The amazing activity now chronicled from January through March, 1934, details the origins of today's Black Opal Pool. (Marler [1973, p 15] erringly reported this activity for the winter of 1931-32). The following are excerpts are from three monthly geyser reports written by Frank Childs.

> January, 1934
>
> Black Pearl Pool.
>
> I am not certain that the above is the correct name for the pool that I have in mind. It is the first pool on the north side of the walk on the west side of the river. Under normal conditions it is a large double pool, milky blue in color. The west half of the pool was always very hot while the east side of the pool was always considerably cooler.
>
> Some time during the past week, about January 20th (estimated) a violent eruption had taken place just east of the Black Diamond. Upon first observation I thought it was part of the Black Diamond that had erupted. Closer observation showed that the now existing pool, forty feet by forty feet in size, had not existed a week before. Evidence of large stones and wash scattered around the new pool shows that the eruption must have taken place with considerable violence and with a large volume of water. The new outbreak has thrown out several tons of rock and broken pieces of formation. Some of the rocks, thirty feet from the pool, would weigh more than six hundred pounds. At present there is a narrow ledge of rock separating the new pool from the Black Diamond. The Black Diamond pool is about fourteen inches above the level of the new pool. A small stream of water flows from the Black Diamond into the new pool, and about six times this amount of this water is flowing from the new pool into the river. At present

the new pool is very muddy and very hot. Violent boiling occasionally takes place on the north side of the new pool. When this occurs a slight shock can be felt several feet from the edge of the new pool. It is interesting to note the number of pine cones and twigs imbedded[sic] deep in the formation that was cast out at the time of the eruption; as at present there are no trees standing anywhere near the pool. [Childs 1934a, see also RofND Jan 1934]

An article in the February 14 edition of the *Helena* (MT) *Independent*, reported this story, using most of the same information found in the above report. It should be pointed out that there is an ongoing confusion with the name of "Black Pearl." As previously indicated by Dr. Van Pelt, the name really belonged on another feature. Further information was given by Frank Childs in his next two monthly reports:

February, 1934
Biscuit Basin.
The new geyser ("Black Boulder Geyser") has not shown any signs of new activity. The pool is almost clear now, but the hot water flow has not diminished. [Childs 1934b, see also RofND February, 1934]

March, 1934 "Black Boulder Geyser."
Erupted again sometime between March 24 and 29. More rocks were thrown out around the pool and at present the pool is still slightly muddy. [Childs 1934c]

The above opening up of an entirely new and relatively large pool must have been amazing. This "Black Diamond Pool" was the name apparently given to the original "eastern half" of the previously existing pool. The name of "Black Boulder Geyser," first used by Childs in February of 1934, was also later used in a few other park publications at about this same time. But this name would not gain common usage. As seen below, the erroneous name of "Black Pearl Pool(s)" will later encompass both pools.

1937 activity:
More "normal" eruptive activity was reported by Jennings J. King for Black Opal Pool in 1937.

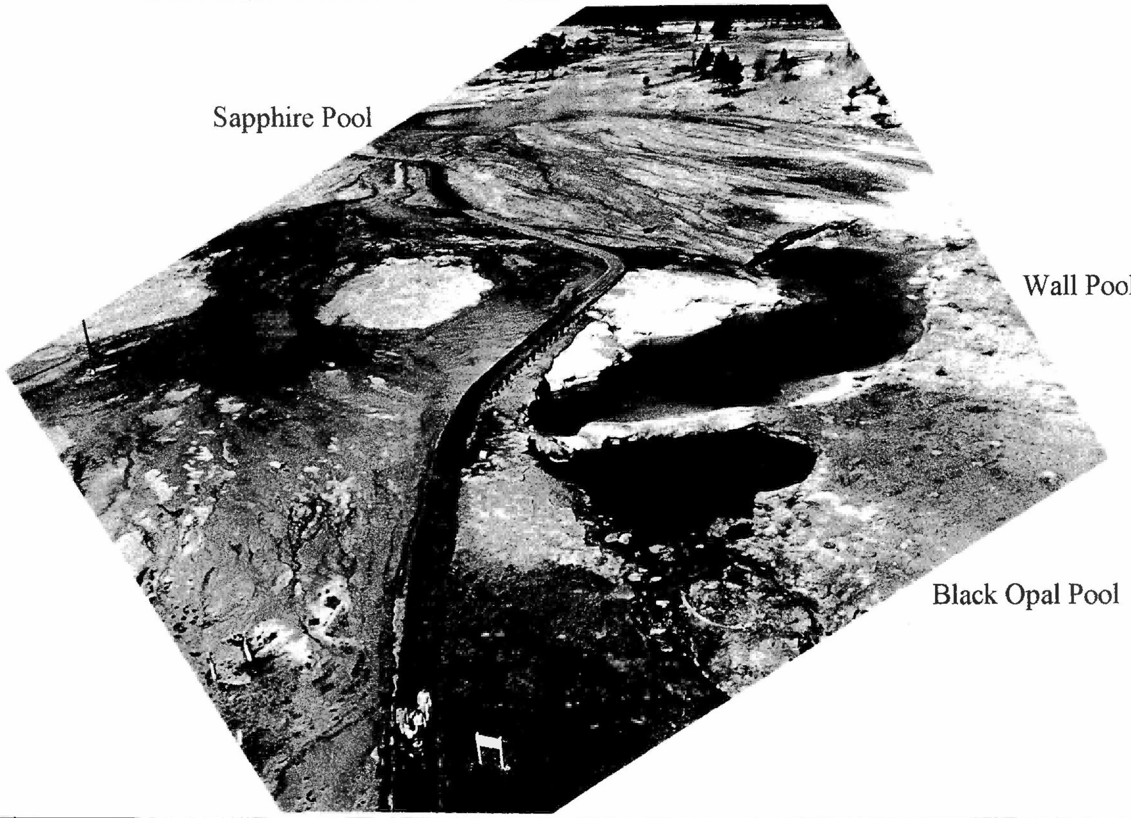
June 29: Today while conducting the "geyser chasing" caravan from Old Faithful a bit of activity was discovered at the Black Pearl Pools in Biscuit Basin. As the party was standing on the walk on the side of the pools a huge gas bubble rose and broke with a great detonation in the lower hot pool [Black Opal Pool]. The unexpected "explosion" startled the visitors and suggested the possibilities of another disturbance such as that of the winter of 1935 [sic read 1934] when huge pieces of rock were thrown from this pool to distances as great as seventy feet.

During previous and prior visits to these pools no such disturbances have been noted. [King 1937]

1947 & 1948 activity:
Rare eruptive activity in Black Opal Pool again is recorded for the amazing years of 1947 and 1948. (It was during this time period that one the greatest reawakenings of geyser activity for Yellowstone Park had taken place).

During the 1947 season Black Opal was known to have erupted two times. The eruptions, as described to me, indicated they began as a sudden bulge of water, giving it a convex appearance. After the momentary bulge the water exploded to a height of 20 to 30 feet. There was evidence of heavy wash about the crater, but I could not discover that any new solid matter had been disgorged. During the 1948 season there was evidence an eruption had occurred. [Marler 1973. p 15-16]

1953 activity:
Two more eruptions were recorded for Black Opal Pool in July of 1953. The second of these eruptions apparently threw out considerable amounts of rock and sand:



Wall & Black Opal Pools (Aug 28, 1959) Yellowstone Museum Archives - Photo #35712

> It was reported at this station [Old Faithful] that the first pool on the right side after crossing the bridge at Biscuit Basin had erupted on the 14th of July, to a height of 15 feet. It played around 2:00 PM. It erupted again more violently the 18th of July leaving considerable evidence of violence. Rocks and sand were thrown for 50 feet around the immediate area surrounding the pool. Close observation has been made for any further eruptions but the pool has again regained its normal tranquility and color. [Ela 1953]

1959 (pre-earthquake) activity:

Although no actual eruptions were recorded, ground disturbances were noted at Black Opal Pool in 1959. This activity was recorded in reports by both Elliot Davis and George Marler:

> Black Pearl Geyser [this reference is actually to today's Black Opal Pool] at Biscuit Basin is banging and thumping due to superheated steam and the ground occasionally shakes noticeably around the crater. [Davis 1959]

> Some seasons Black Opal will have a series of eruptions. The eruption consists of a momentary, huge surge which sends thousands of gallons of boiling water into the Firehole. During 1959, prior to August 18, Black Opal was characterized by dark opalescent coloration. There was no eruptive activity. A continuous thumping sound could be heard. These sounds did not seem to come from any great depth. [Marler 1959, p 30]

1959-1961 (post-earthquake) activity:

Although the 1959 earthquake had astounding effect on some of the features in Biscuit Basin, no

WALL & BLACK OPAL POOLS (Aug 28, 1959) Yellowstone Museum Archives - Photo #35734

eruptive activity was induced, however, in either Black Opal Pool or Wall Pool. The effects of the earthquake on these features were detailed in the reports of George Marler.

1959 activity:

> The most important effect the earthquake seemed to have on [Black Opal Pool] was to destroy its lovely color. The water was very murky at first and did not completely clear during the remaining part of the year.
>
> A constriction of cemented gravel separates Black Opal from Wall Pool. On the morning of the 18th a fracture extended through the length of the gravel. Wall Pool's water which had formerly flowed over this dike into Black Opal had ebbed about 10 inches.
>
> Prior to the quake Wall Pool did not seem to have a source of water of its own. The water was quite cool and was replenished by part of the overflow from Sapphire. Following the quake, springs developed in the northwest end of the big crater resulting in a higher temperature for the pool. [Marler 1959, p 30]
>
> Following the earthquake, the level of both springs dropped about 10 inches. In the later part of 1959, there was a gradual rise in water level. [Marler 1960, p 14]

1960 activity:

> By spring 1960, both [Wall Pool and Black Opal Pool] had completely filled. The thumping activity that was so pronounced in Black Opal before the quake was not heard during 1960... By the middle of the summer [the crack which had extended through the septum dividing the two pools] became completely filled with sediment.
>
> The north side of the large quake-caused rift in the geyserite on the south side of Black Opal is in a state of continuous slumping. Since this fracture appeared, the slumping has lowered Black Opal's south shoulder by about 12 inches. That portion of the same fracture which partially encircled Wall Pool is now completely filled with sediments deposited during Sapphire's eruptions. [Marler 1960, p 14]

1961 activity:

> The south end of the rift [surrounding Wall Pool] grows larger as a result of slow,

but progressive slumping of the geyserite on the side next to Wall Pool. [Marler 1961, p 18]

Discussion:

I believe that many of the reports of "explosive" origins of various thermal features in Yellowstone Park have been erroneous. This is particularly the case with the relatively new unnamed geyser on the hillside of the Rustic Group in the Heart Lake Geyser Basin. [Paperiello 1988] Other recently formed geysers, one in the Lone Star Geyser Basin ("Buried Geyser"), and another in the Kaleidoscope Group (an unnamed geyser immediately west of "Blowout Spring"), have also been described by some as having "explosion craters." This is not the case. Both craters have been formed by the process of erosion and slumping during eruptive episodes.

But explosive eruptive activity does indeed occur, and when it does, it is can be quite extraordinary. The explosion that tore apart the basin of Porkchop Geyser in the Norris Geyser Basin is a very well known example. And there have been number of others.

A small pool in the Fairy Springs area of the Lower Geyser Basin experienced quite a cataclysmic explosion sometime after the 1975 earthquake. The large canted blocks of geyserite have weathered greatly since then, but the evidence is still quite compelling.

A new large mud pool which recently opened up in an unnamed thermal area a few miles west of Elk Park must have been quite extraordinary. A few months after the crater opened up, I was still able to find mud clinging to trunks of trees more than 300 feet from the gaping basin!

But historical evidence indicates that the episodes of explosive activity which opened up the basins of both Wall Pool and Black Opal Pool were some of the more extraordinary in the known thermal history of the park. Considering the past history of these features during this century, it would not be entirely surprising if another episode of explosive eruptive activity occurred some time in the near future in the area of these two pools.

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The following excerpts chronicle an interresting history of:

Jewel Geyser as the *"New Handkerchief Pool"*

August, 1931 (From "Geysers of Yellowstone National Park" by Thomas 'Geyser Bill' Ankrom):

This geyser [Jewel] was first tried as a handkerchief geyser the afternoon of August first [1931] by Ranger Naturalists Frank Oberhansley, and worked 100%. It was used as such by the Auto Caravan as such this morning of August 2nd, reaching there a few mornings later I found a large peice of brush jammed under the ledge so tightly that it had to be broken out, from then on there was some delay at times before the handkerchief was returned. As this is the end of the morning trip we will return to camp, rest, and take the long after-noon geyser hike. [Thomas Ankrom 1931]

A few days later on reaching there I found a brush had been forced under the ledge, and from then on it was no longer reliable, as some of the handkerchiefs might become entangled and not come out. [Ankrom Aug 1, 1931 geyser basin notes]

September, 1931

Jewel Geyser - Interval checked by Mr. Oberhansley and Geyser Bill (Thomas Ankrom) found to be 6 - 8 minutes. The two above discovered the convection currents 8/1/31. Handkerchiefs placed in the vent near the main vent draws them down into Jewel Geyser and are thrown out at the eruption. The feature is in placing the handkerchief in one vent and having it returned by another. Jewel Geyser is fast becoming very popular. I believe a sign should be placed there explaining how Old Handkerchief Pool was destroyed and how to keep this one intact.

Has been functioning very well all season with handkerchiefs. [H. Lystrup 1931, old card file]

June, 1932
Jewel Geyser was functioning beautifully as a "Handkerchief Pool" and furnishes visitors a real thrill. It plays from 5 to 7 minutes. [RofND June, 1932]

July, 1932
Jewel Geyser - Still performing beautifully. Eruptions occurring every 5 - 6 minutes. Ht. 20 - 30 ft. [Lystrup June 1932]

August 1932
Jewel Geyser has been functioning admirably all season as a handkerchief geyser. It proves more spectacular than the Handkerchief Pool. It plays at intervals of five minutes to a height of from twenty to thirty feet, spurting from two to seven times during each eruption. A determined effort should be made to secure cooperation from tourists to prevent the destruction of this feature. Many names have been written on the formation and on two occasions this season I have removed logs from the main vent. [George Crowe 1932]

June, 1933
Jewel Geyser still functions as a "Handkerchief Pool." It plays from 5 to 7 minutes. [RofND June, 1933]

July, 1933
Jewel Geyser ---This geyser is without question one of the most interesting features on the Upper Geyser Basin. The interval is still between 5 and 7 minutes. Handkerchiefs are spectacularly thrown out during an eruption. [Lystrup Aug 3, 1933]

January, 1934
Jewel Geyser. Activity normal. As late as last week an occasional well washed handkerchief is thrown out by the eruption. [Frank Childs Jan 1934]

August 1, 1934
The number following the time indicates the number of spurts during the action.
3.01 P.M. 5: 3.08 P.M. 6: 3.14 P.M. 7: 3.21 P.M. 7:
3.27 P.M. 5: 3.33 P.M. 6: 3.39 P.M. 6: 3.46 P.M. 5:
[This geyser] is located in the Biscuit Basin. The water is thrown toward the West, and reaches a height of about 35 feet. The water between actions comes out of the tube, runs around counter-clockwise and down under a ledge, then back to the tube. [Lystrup Aug 1, 1934 old card file]

June 19, 1935
Memorandum For Chief Ranger Francis D. LaNoue:-

Due to the fact of the Handkerchief Pool failing to function in the last few years, the Jewel Geyser on the Biscuit Basin has been substituted so to speak; to demonstrate the qualities of the Old Handkerchief Pool.

For those who are familiar with the eruption of the Jewel Geyser; it is very evident that it is extremely dangerous to be within range of the geyser while it is playing. There are also several small pools in the vicinity of the Jewel Geyser cone and this tends to add to the hazard of someone being injured.

On the Auto Caravan, the Ranger Naturalist demonstrates the ability of the Geyser to erupt the handkerchiefs that have been placed into the opening near the crater before the eruption. This practice seems to be out of order for a man in the Park Service uniform to perform when it is contrary to Park Regulations to place any article in the Geysers or Hot Springs. It is understood that the Ranger Naturalist explains to the visitors that it is not advisable to attempt the demonstration themselves but this evidently does not relieve the hazard of someone getting injured by attempting the demonstration anyway in the absence of a Ranger.

This situation has been mentioned to Senior Ranger Naturalist Lystrup and he confirms with the above situation and danger of someone being injured. He also stated that he was once burned rather seriously on his back in giving a demonstration at the Jewel Geyser.

There have been no accidents at this Geyser to date, but last season there were several reports of visitors being burned at this Geyser. However, none of these reports were reported by those injured but were reported by visitors thatwitnessed the accidents.

This matter is brought to your attention, to be considered for those concerned to decide if this practice is to be continued at the Jewel Geyser.

George A. Walker
District Ranger, Old Faithful

(Appended to this letter in pencil is the following:)
Believe we should discontinue this laundry demonstration at Jewel Geyser and at all hot pools or geysers. CMB [Clyde Max Bauer]

June, 1935
Jewel Geyser is an exceedingly interesting geyser both for its beauty and active manner of play. The formation a few feet East of Jewel has been broken but has not affected the play. The area however is dangerous and the demonstrations with handkerchiefs has been dispensed with. [Lystrup July 1, 1935]

August, 1935
Jewel Geyser. The average interval for the season has been about 5 minutes. The height varies between 30 and 40 feet. This geyser is no longer featured as a handkerchief geyser because of the danger involved. [RofND Aug, 1935]

Minor Eruptions by Castle Geyser

Interval and Duration Relationships, May 25–June 16, 1995

T. Scott Bryan

Abstract

At no time on record in the past several decades did Castle Geyser undergo as many or as frequent minor eruptions as was the case in 1995. This presented the opportunity to check a number of stories about minor eruptions, and their intervals and durations as related to Castle's "normal" major activity. By and large, the stories are factual enough that with attention to the details of the activity, Castle remains one of the most predictable geysers in Yellowstone, even when so–called unpredictable minor action is common.

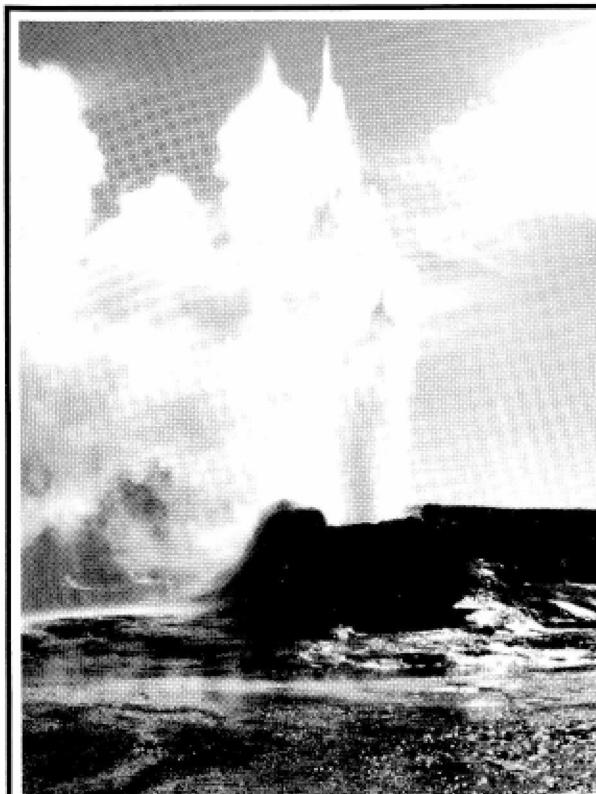
Introduction

Since about 1947, eruptive activity by Castle Geyser has consisted almost entirely of what are now known as normal, or major, eruptions. In fact, any such term is prone to error, especially in a case such as Castle which historically has shown a number of different modes of behavior. A century ago, full–force eruptions occurred as seldom as once every several weeks, but they reached well over 100 feet high and had steam phase action that persisted for several hours. Today's "major" eruptions are by comparison relatively weak and of short duration. They commonly recur every 11 to 12 hours, and consist of a water phase as much as 80 feet high that lasts 15 to 20 minutes followed by a steam phase that persists for an additional 40 minutes [Marler, 1973].

Minor eruptions (so called) appear at first to be identical to major eruptions, but they undergo repeated pauses in their jetting before they quit after just a few minutes. Without resulting in steam phase action, they are followed by several hours of erratic sloshing and weak jetting (sometimes called "sloppy play") before a full major eruption is triggered. These eruptions appear to be very similar to the type of action that took place in the 1800s. Then the weeks–long major intervals were often punctuated by brief, small eruptions that were probably the equivalent of today's minor eruptions.

With that hopefully putting Castle into a proper historical context, in the past few decades Castle's modern form of major eruption has only infrequently been interrupted by minor eruptions, and in some full summer seasons such action has been seen as few as two or three times. Between March 16 and June 16, 1995, minor eruptions took place at least 33 times. On two occasions, there were consecutive minors (that is, minor eruptions without any intervening major), an event recorded just oncebefore, and there were numerous cases of alternating minor–major–minor–major series.

So far as is known, this frequency of minor activity is without precedent. Therefore, I took the opportunity to carefully monitor Castle's activity (with the help of data obtained by other observers) during the period of May 25 through June 16, 1995. The eruptive pattern during this time is shown in Figure 1.



Castle Geyser in June 1995. Photo by T. S. Bryan.

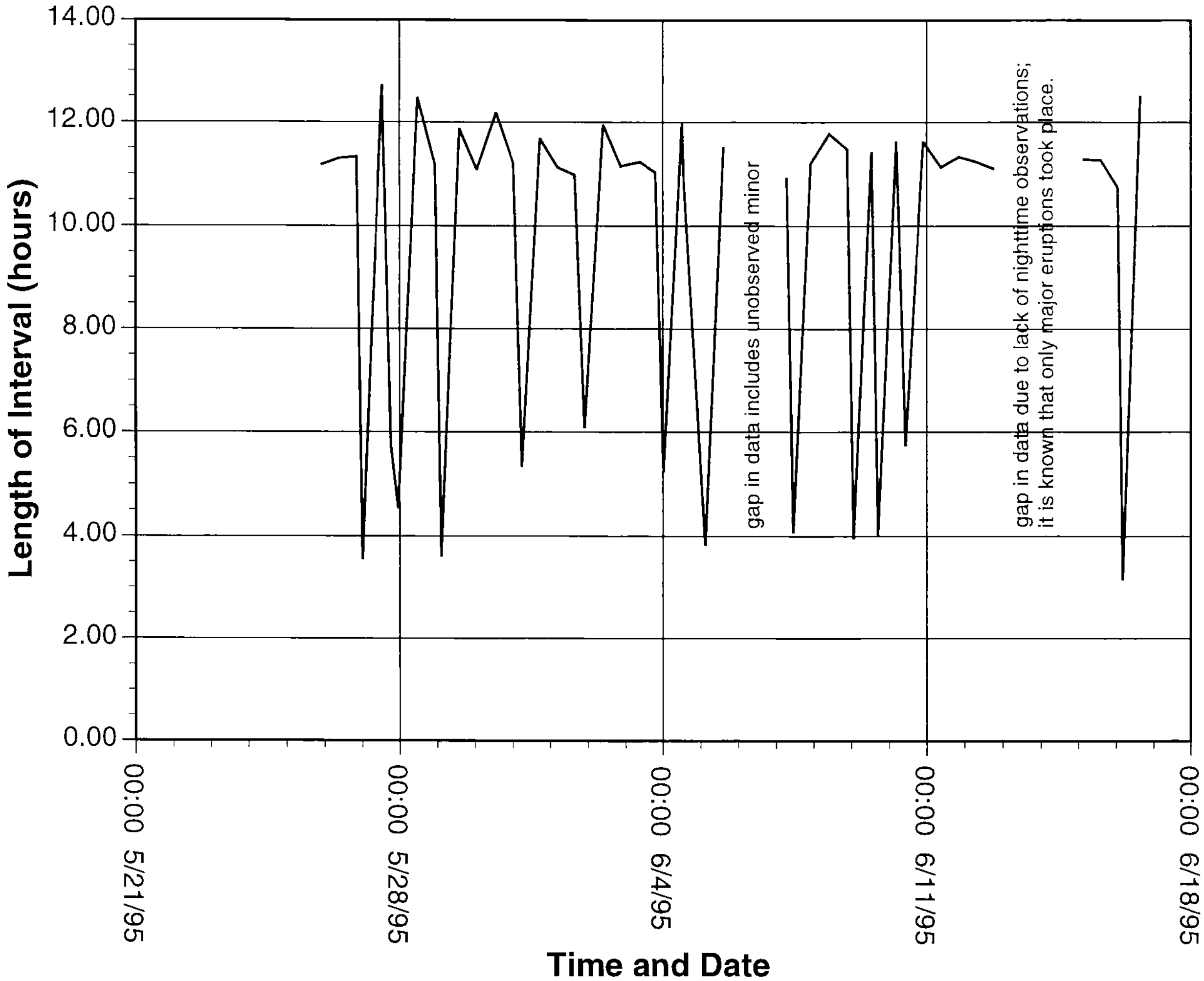


Figure 1. A date–time versus interval chart for Castle Geyser, May 25–June 16, 1995. The sharp dips show the minor–to–major eruption intervals. Note that the first major–to–major interval following a minor is significantly longer than the others.

The goal of this study was to investigate these minor eruptions, and the relationships between their durations, the resulting minor intervals, and the eventual major eruption intervals. This study showed that the "stories" of many years past are largely correct, and these aspects of the activity are briefly discussed here.

Interval Categories

Castle Geyser's modern activity exhibits four distinct interval modes. Each of these is readily observable and dependent on the nature of the eruptive action immediately preceeding or following its time span.

It is clear that there are three distinct categories of major interval, based on length and type of eruptions involved. The populations of these three categories overlap enough that they alone cannot be used to "predict" the nature of the resulting eruption, yet they are distinct when considered as wholes. These population ranges are shown in Figure 2.

Minor eruption intervals, the primary focus of this article, comprise a fourth category of interval.

Each of these modes is summarized in the following paragraphs:

<u>Category #1, Major–to–Minor Intervals</u>— These are the intervals that follow a normal major eruption but result in a minor eruption. Many such intervals were shorter than 11 hours in length, and the average, even when one extraordinarily long case is included, was just 11h 09m. The shorter examples of this category— those less than 11 hours long— appeared certain to result

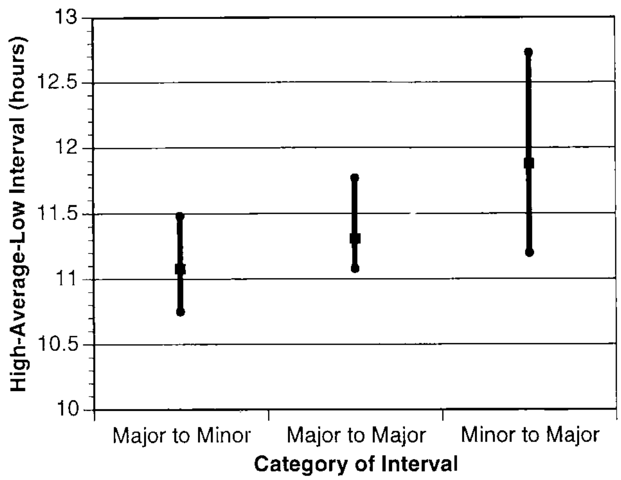


Figure 2. The three populations of major intervals, plotted by category as a high–average–low range chart; data of May 25 to June 16, 1995 only.

in minor eruptions. Minor eruptions always appear weak and include frequent pauses in their action. Since in 1995 they usually started on shorter than normal intervals, it looked as if Castle had started its eruption "too soon," without really being properly prepared to do so— the activity simply could not be sustained.

As a category, these intervals ranged from 10h 45m to 11h 29m, with an average of 11h 09m.

Category #2, Major–to–Major Intervals— This population includes the "normal" category of Castle Geyser intervals, those from one ordinary major eruption to the next major eruption. This is the mode typical of Castle's highly predictable intervals when minor eruptions are uncommon. In 1995, these intervals fell entirely between 11 and 12 hours in length, and showed that were it not for the minor eruptions, Castle could have been predicted within a ±30–minute window with 100% accuracy.

As a category, these intervals ranged from 11h 05 m to 11h 46m, the average being 11h 19m.

Category #3, 1st Major–to–2nd Major Intervals— This category includes the intervals that fell between the major eruption that ended a minor interval and the next major eruption (when there was no intervening minor); in other words, this is the first major–major interval following a minor eruption and minor interval. These intervals were extraordinarily long. Castle had already expended water and energy with the minor eruption, and then still more via the sloppy play during the minor interval. Finally a normal amount of water and energy was expended during the eventual major eruption. It might be expected, then, that Castle's plumbing would be severely exhausted by all this action. And that was clearly the case. These intervals were significantly longer than those of the other categories. Although a few fell within the range of the ordinary major intervals, these often were an hour or more longer.

During this study, the range was from 11h 12m to 12h 44m, with an average of 11h 53m.

Data obtained by the National Park Service TempMentor instrument between March 16 and June 5, 1995 showed a more extreme interval range of 11h 43m to 13h 14m, with a remarkably long average of 12h 17m [NPS, 1995]. In addition to these intervals, the TempMentor data also indicated two members of this category with values of only 10h 38m and 10h 04m. These are puzzling, but probably are not outright data errors. Eruptions, presumably major, apparently did take place at about these times, because the respective following intervals of 12h 52m and 12h 34m indicate that eruptions did take place. This data may represent an additional, fifth category of eruptive behavior.

The NPS data is graphically represented by Figure 3. Because this data was instrument–derived and subject to interpretive errors like that just described, no further statistical analysis of these intervals is being attempted.

Category #4, Minor–to–1st Major Intervals (the "Minor Intervals"

These intervals are those that immediately follow a minor eruption. Describing them and their relationships to the minor eruption durations is the main goal of this article. These points are amplified in the following sections.

It can be noted that consecutive minor eruptions have been observed only four times: 1992, twice in May 1995 (once during this study), and in May 1996.

Summary of Basic Interval Data

To summarize this interval data, while there enough exceptions to make any predictions risky, it is clear that:

1) intervals of less than 11 hours are likely to result in minor eruptions;

2) intervals between 11h 10m and 11h 30m typically produce normal major eruptions;

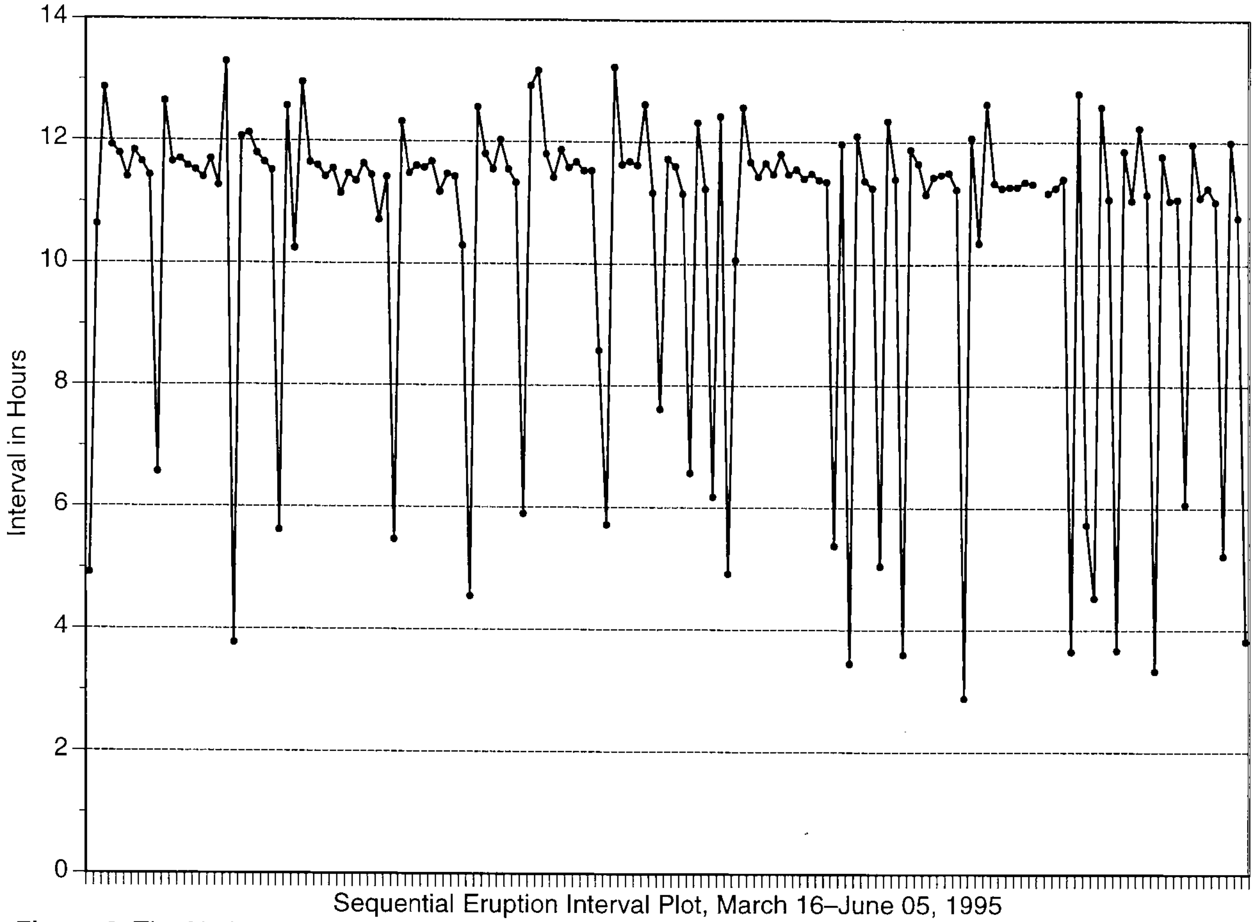


Figure 3. The National Park Service TempMentor record from March 16 to May 11 and May 25 to June 5, 1995; the small gap near the end of the record represents the span of May 11–25 when the instrumentation was in use elsewhere. Note that this is a simple sequential and not a time–line plot. Note also a number of "questionable" intervals. Especially those between about 8 and just over 10 hours may well represent heavy pre–eruptive splashes rather than the start of an actual eruption. (Data courtesy of NPS, Yellowstone Research Office)

3) intervals in excess of 11h 50m uniformly occur as follow–ups to minor eruptions.

As noted previously, the data of the three major interval categories overlap, so that it is *not* possible to predict the nature of the subsequent eruption strictly on the basis of interval length. However, it is possible to make reasonable educated guesses that, in my experience and based on the above values, were about 75% correct. These rules worked as well in 1996 as they had in 1995.

Predicting Major–to–Major Intervals

Accurately predicting Castle Geyser's ordinary major intervals is easy. The differences between Categories #1, #2 and #3 can be completely ignored!

During this study, the average length of all of Castle's major intervals was 11h 27m. A one–hour prediction window would have covered 33 of the 35, or 94.3%, of the eruptions; the long–used technique of "average interval ± 60 minutes" worked very well.

This rule applies only for major eruptions ending major intervals. A different rule must be applied in the cases of minor eruptions.

Predicting Minor–to–Major Intervals

Although the minor intervals fell over a wider shortest–to–longest time range than did the major intervals, they were still quite predictable— even in the face of no data about the duration of the minor eruption.

The observed range during the May 25 to June 16 study was from 3h 09m to 6h 04m. Since the average was 4h 31m, simply allowing a 1.5–hour prediction range would cover most minor intervals.

During the March 16 to June 5 NPS TempMentor study, the range was substantially wider at 2h 53m to 7h 37m, but the average was a similar 4h 58m.

Considering the two sets of data, it appears that a person who knows only the approximate time of a minor eruption can make a reasonably good prediction of the subsequent major eruption: the interval will be 5 ± 2.5 hours. For the full span of March 16 to June 16, 1995, this rule would have been 97.4% accurate (37 of 38 occurrences).

The 38th of those data points was the occasion of an 11h 05m interval produced by a minor duration of only 4 minutes.

Relationship of Minor Duration to Minor Interval

Marler [1964, 1973] described minor eruptions as having durations of "2 to 4 minutes" and at one point stated that this action was followed by intervals of "8 hours."

Sometime circa the mid–1970s people began to hold that there was a direct relationship between a minor eruption's duration and the resulting minor interval— every one minute of duration would result in one hour of interval.

More recently, this rule has been called into question, as there often seemed to be little or no such relationship. However, I believe this conclusion probably resulted from a lack of data— minor eruptions are uncommon in most years, so data is always sparse.

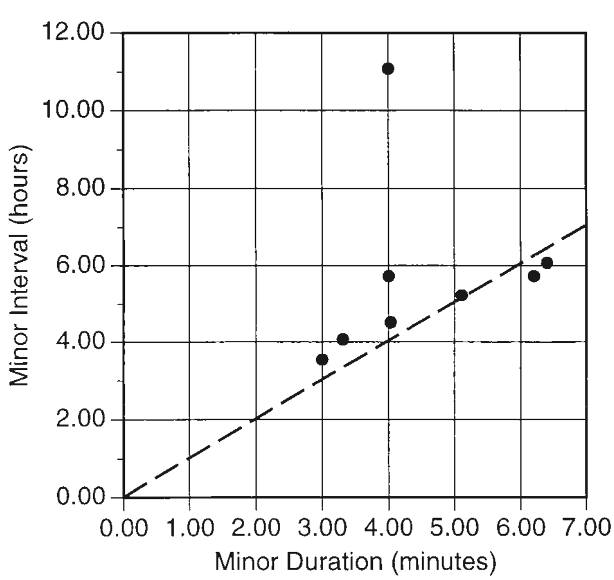


Figure 4. Nearly one–to–one relationship between Castle Geyser's minor durations (minutes) and its minor intervals (hours).

Even here only eight data pairs were obtained, but they are enough to show that the 1970s rule does work in the majority of cases. Graphically shown in Figure 4, I have drawn a straight line with a slope of 1.00 through the 1:1 coordinate values.

(Note: It is not possible to include data from the NPS study within this section. The TempMentor instrument is a temperature–sensing device, and times recorded by it are only those when the hot water of eruptions first reaches the sensor. These tend to correspond reasonably well with observed eruption times— in late May 1995, the visually recorded eruption time and the instrument time for Castle were usually within two minutes of agreement. However, in most cases and definitely that of Castle Geyser, it is not possible to determine eruption durations.)

The obvious outlier in this data is the case, cited earlier, where a minor duration of about 4 minutes produced an interval of 11h 05m, A similar event took place on September 1, 1995 [Schwarz, 1995]. There is no explanation for these aberrant intervals other than to note that both intervals included tremendous degrees of sloppy play and numerous "false starts" for several hours prior to the start of the eventual major eruption.

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Prior to final editing, this article was refereed by Barry Schwarz and Bob Berger.

Sentinel Meadows & Flat Cone "Geyser"

by

Mike Keller

ABSTRACT: Occasional eruptions of Flat Cone have been reported over the past decade. However, by the spring of 1992, Flat Cone Geyser became a regularly eruptive feature. The area was visited on a number of occasions from May through October. This paper reports the activity of Flat Cone and other features.

Sentinel Meadows is located in the northwestern corner of the Lower Geyser Basin. It can be reached by following the Sentinel Meadows Trail located on the left, downstream side of the Firehole River across from Ojo Caliente Spring. From the trail head it is about a mile to the first springs of the group.

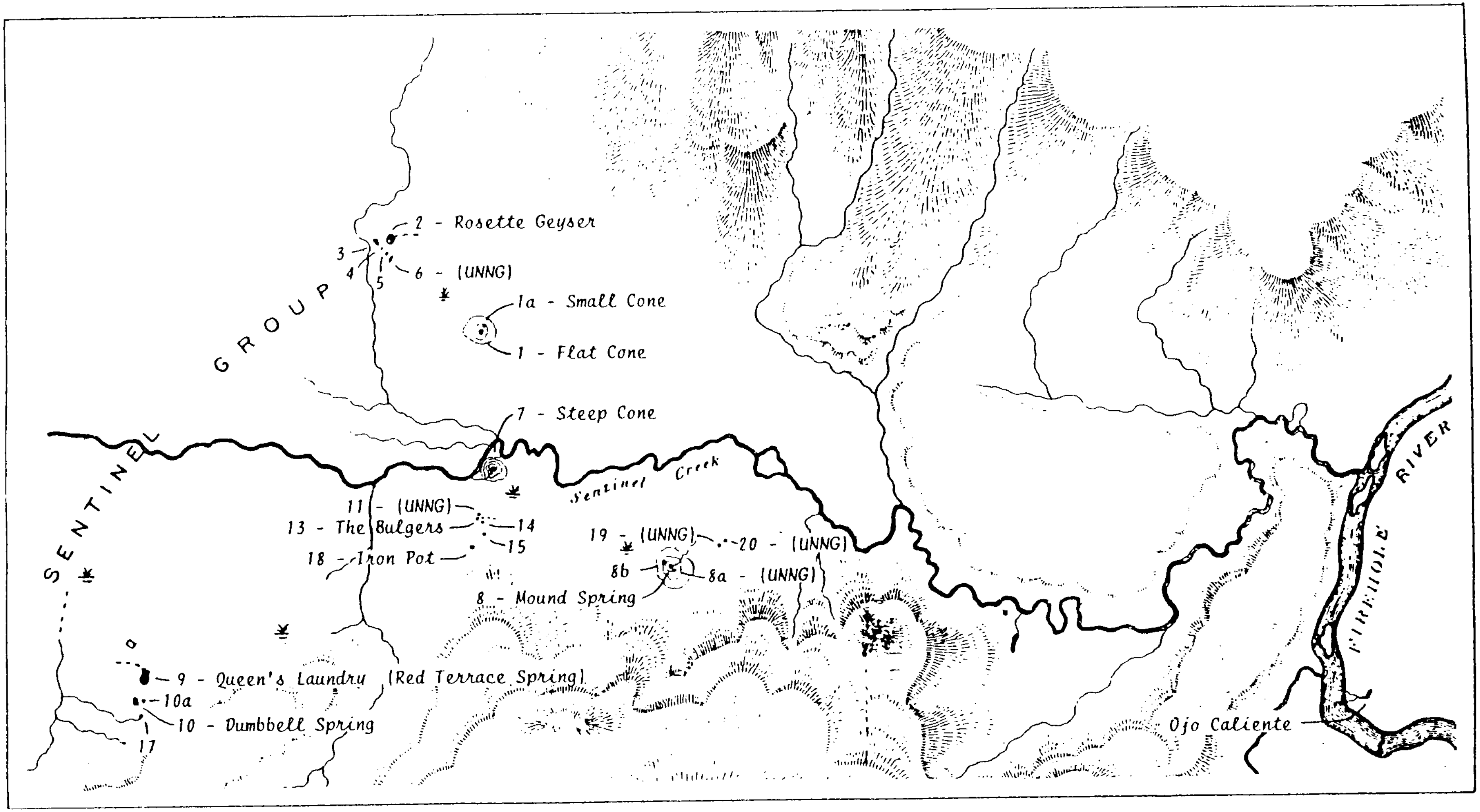
When first entering the meadow, one's attention is immediately drawn to three large mounds of geyserite rising from the grassy landscape. In order from left to right they are Mound Spring, Steep Cone, and Flat Cone. All have been known to have infrequent geyser activity. Dotting the rest of the meadow are several other small hot springs and geysers (see map). During the summer of 1992, four springs were true geysers, while another twelve were perpetually active.

1. FLAT CONE: Over the past few years this feature has demonstrated rare eruptive activity. Newly formed runoff channels leading away from the vent have implied voluminous eruptions, but few were ever observed. It was therefore of great surprise to find it frequently active in the May of 1992! Clark Murray, Rocco Paperiello, and I, visited the area on the 25th of May in the early evening. In September of 1991, there had been large amounts of loose sand and gravel covering the mound. But now the area around Flat Cone's vent was scoured clean. Fresh runoff channels led away in all directions, the largest to the north and east. We found the channels damp, and the water level about 2 feet below overflow. The assumption was that one of its rare eruptions had just been just missed. About 30 minutes later we were approaching Steep Cone. Suddenly we heard great thumps from Flat Cone behind us. Looking back across the meadow, we saw Flat Cone in eruption to about 3 feet. Racing to it we arrived just after it had finished. It appeared as it did when we first arrived about 30 minutes earlier. We waited for almost 45 minutes, hoping to see another eruption, but darkness forced us to leave.

On May 26, Clark Murray returned to the area to try to determine if the activity was frequent. He reported the following:

> Flat Cone is cyclic, based on the markers I would say we were well into a cycle last night. When I arrived this morning, Flat Cone was in overflow. Some of the markers had been washed, but not those in the seldom used channels. At 10:08 there were incredible ground thumps, in my opinion, better than Giantess. Flat Cone. is very much like Vault: heavy overflow, ground thumps, and surging to six feet! The first major lasted two minutes, all the rest were under one minute. The minors also reached five to six feet, but with less total water. The length of the cycle is unknown, but I think they run 4 to 5 hours.
>
> p.s. Some markers did not wash even during the major, but every runoff channel was used. . . A quiet period follows the series, and the second series was not as strong, so they must vary in strength. [Clark Murray 1992]

I visited the area later that evening and found almost the exact same activity. Flat Cone was in overflow. Every few minutes there would be some strong boiling along the edges of the crater. After waiting about 25 minutes, I felt strong ground thumps. They were best felt on the north and northwest side of the mound. At the same time the entire pool level rose about 3 inches, enough to send a circular flood along the entire formation. Corresponding with the thumps, the entire pool level would rise and fall from one to four inches. After



N

500 ft

Map of the Sentinel Group
(Adapted from Gannett, 1878;
by Papericllo, 1990)

◇ = *Norris' bath-house*

• = *Spring or Geyser*

SENTINEL GROUP

20 seconds, heavy boiling reached the surface. At first the entire pool was boiling 12 to 18 inches in height. The boiling then moved and became concentrated on the northern edge of the crater, reaching three to six feet in height. This lasted about a minute, and was

Table I

SENTINEL MEADOWS HOT SPRINGS

NUMBER	NAME	ACTIVITY IN 1992	COMMENTS
1	Flat Cone	G	Height: inches to 18 feet
1a	Small Cone	S	Temp 93.5° C
2	Rosette Geyser	S/PS	Steady boiling
3 - 6	Unnamed	PS	Largest to 1 foot
7	Steep Cone	PS	From 1 to 3 feet
8	Mound Spring	S	Temp 93.7° C
8a	Unnamed	G	Active
8b	Unnamed	S	Sink for Mound Spring
9	Queen's Laundry	PS	Numerous vents
10	Dumbbell Spring	S	Temp 68.8° C
11	Unnamed	S	Temp 92.4° C
12	Unnamed	PS	Low water
13	The Bulgers	PS	From 1 to 2 feet
14 - 16	Unnamed	PS	Subterranean
17	Unnamed	S	Temp 76.9° C
18	Iron Pot	G	From 1 to 3 feet
19	Unnamed	PS	Small
20	Unnamed	G	From 2 to 3 feet

FLAT CONE — Mike Keller Photo

followed by a rapid drop in water level. Within seconds the pool was about three feet below overflow. The boiling within the vent became even stronger, resembling that of Giant Geyser, and Flat Cone started surging about two feet above ground (or five feet above the pool) for around 20 seconds. Gradually this declined and the pool became calm and started to fill. Only 20 minutes later, a second eruption began. At first this was a much weaker eruption, consisting of overflow and thumping. But when the pool lowered, the surging became immense, reaching 12 to 15 feet above the ground, or 15 to 18 feet above the pool. This eruption was the only observed eruption in 1992 to fill the northernmost runoff channel. Following two more small minor eruptions, the cycle concluded. Sometime between May 26 and May 31, Flat Cone's eruptive activity changed, resulting in the termination of cyclic activity. When observed on 31st, Flat Cone was erupting every 23 to 85 minutes. While durations remained unchanged, both the volume of overflow and general power of the eruptions were noticeably weaker. Only one eruption reached five feet in height. It also seemed that the thumping was weaker. Following the eruptions, the pool lowered to the same level as was seen the week before. Additional visits on June 6, 8, and 12, showed no changes in Flat Cone's eruptive activity. It remained in this mode of activity until mid August.

After my August 15 visit, I was not able to return until the 27th. The pool was below overflow and the water around the vent was warm to the touch when I arrived. Two hours later, however, it had not erupted. Since May, the longest known interval had been 86 minutes. I should have suspected that some change had taken place and come back the next day to get more data, but I did not. My next visit to the area was not until September 13.

As I was approaching Flat Cone it erupted. The eruption was identical to those of June and July. Alas, 103 minutes later it had yet to erupt again. I placed markers in every runoff channel and came back the next day. All markers were washed except those in the northernmost channel. Further visits were made on September 24, October 14, and 18. While Flat Cone's eruptions were unchanged, its intervals were. It is unknown why this happened. Apart from Small Cone, located eight inches from the vent, there is no other thermal feature within several hundred feet.

Despite the instability of Flat Cone, its new activity was one of the highlights of 1992. The 72 recorded eruptions are by far the most ever for it in one season. The activity did not end in 1992, either. Eruptions are known for 1993, 1994, and 1995. Given the history of Flat Cone, and the erratic activity it had in 1992, these frequent eruptions may soon be a thing of the past.

Table II

ERUPTIVE ACTIVITY OF FLAT CONE

DATE	TIME	INTERVAL	DURATION	OVERFLOW	HEIGHT (FEET)
5/25	2038ie		> 1 minute		2 to 3
5/26	1008		2 minutes		5 to 6
	1103	55m	1 minute		4 to 5
	1139	36m	1 minute		4 to 5
	1219	40m	1 minute		4 to 5
	1248	29m	1 minute		4 to 5
	1322	34m	1 minute		3 to 4
	1450	88m	2 minutes	1403	4 to 5
	. . .				
	1920		2 minutes	before 1855	3 to 6
	1940	20m	2 minutes		12 to 18
	2023	43m	1 minute		2 to 4
	2055	32m	1 minute		2 to 3

5/29	1924		2m 01s		2 to 4
	2023	59m 32s	1m 16s		3 to 4
	2136	72m 35s	1m 34s		2 to 3
5/30	1740		1m 16s	1735	0 to 1
5/31	0551		0m 48s	0538	0 to 1
	0702	69m 18s	1m 35s	0646	2
	0800	57m 19s	2m 21s	0744	1
	0911	71m 52s	0m 38s	0858	3
	1144		1m 27s	1140	2
	1241	57m 12s	1m	1233	5
	1304	23m 06s	0m 53s	none	3
	1344	39m 29s	1m 02s	none	2
	1457	73m 48s	1m 27s	1423	5
	1623	85m 40s	1m 09s	1605	2
6/01	1119		2m 08s	1115	1
	1217	58m 16s	1m 17s	1204	3
	1324	66m 47s	1m 29s	1304	3
6/08	041817		1m 26s	before 0411	2
	054440	86m 23s	1m 21s	0522	2
	062257	38m 17s	1m 28s	0619	1
	073622	76m 25s	1m 52s	0728	4
6/12	1723		1m 05s	none	1
	1827	64m 24s	1m 13s	1805	inches
	1858	31m 16s	0m 55s	none	2
6/22	1835		2m 02s	1809	3
	1944	68m 55s	1m 10s	1931	2
6/28	1712		1m 18s	1657	3
	1803	50m 36s	1m 16s	1756	3
7/06	1459		0m 52s	1443	4
	1622	81m 50s	1m 40s	1559	3
	1723	61m 28s	1m 34s	1720	3
7/11	0752		0m 59s	none	3
	0904	72m 08s	1m 24s	0846	4
	1006	62m 11s	1m 31s	0951	2
	1115	68m 29s	1m 04s	1059	2
	1158	43m 50s	1m 42s	1154	inches
	1311	72m 48s	1m 56s	1256	1
	1435	83m 55s	1m 20s	1408	4
7/31	1655		2m 03s	1641	5
	1758	62m 38s	1m 40s	1745	inches
	1852	54m 01s	1m 16s	1847	inches
	1946	54m 11s	1m 06s	1939	inches

	2103	76m 29s	1m 30s	2235	2
8/08	1738		0m 49s	none	3
8/15	1655		1m 26s	none	6
	0834	41m 01s	1m 18s	none	7
	0927	52m 46s	1m 28s	0923	inches
	1010	43m 04s	1m 01s	none	inches
	1101	51m 31s	2m 16s	1054	3
8/27	None in 2 hours of observations. Runoff channels damp and recently used.				
9/13	1642		1m 43s	unknown	2
	No further eruption by 1825				
9/14	Markers washed between 1825 (9/13) and 0600 (9/14)				
9/24	1252		0m 57s	none	3
	1509	136m 39s	1m 43s	1349	3
	1704	115m 33s	1m 22s	1557	inches
	No further eruptions by 1900				
10/14	Markers from 9/24 washed and replaced				
10/18	1103		1m 22s	before 1050	3
	1331	148m 48s	1m 45s	1205	1
	1707	215m 42s	1m 54s	1425	2
	1815	67m 31s	1m 29s	1806	3

The remaining features of Sentinel Meadows, while not studied as thoroughly as Flat Cone, were occasionally visited or witnessed to erupt from a distance. Here is a brief summary of what was observed:

2. ROSETTE GEYSER: Not active in 1992. Markers never washed. Steady boiling from 3 to 12 inches in height. Temperature 94.2° C.

3 - 6. UNNAMED: These are the numerous spouters immediately west of Rosette. All were active, the largest reaching a foot in height.

7. STEEP CONE: The second of the monolithic cones in the area was a perpetual spouter in 1992. The play was from 1 to 3 feet in height.

13. THE BULGERS: These have remained perpetual spouters from 1 to 2 feet in height, as seen in previous years.

18. IRON POT: Numerous intervals were recorded and were in the range of 7½ to 10 hours. It appeared the duration, which varied from 45 to 90 minutes, effected the next interval. Heights were from 1 to 3 feet.

19. UNNAMED: In the past several years, this vent has been calm and below overflow. Scott Bryan described it as a geyser which could reach up to 20 feet. It was active in the early 1970's. During the entire summer it overflowed and boiled up from 3 to 6 inches, forming spiny black geyserite around its vent. No other activity took place.

20. UNNAMED: This geyser, informally named "Convoluted Geyser" by Scott Bryan, has shown numerous changes over the past few years. During 1992, the interval was 1½ to 2½ hours long. Eruptions would last 45 to 90 seconds and reach 1 to 3 feet above its vent. Overflow was known only during eruptions.

Discovery of the 1926 Old Faithful Nature Trail Manuscript And a Discussion of Its Implications for Hot Spring Researchers

by

Lee Whittlesey, Rocco Paperiello, & Mike Keller

In May of 1993, Lee Whittlesey was appointed Historical Archivist for Yellowstone National Park. A few days later, Mike Keller came into the research library to look at historic materials relating to Giant and other geysers. He asked for several archive boxes, and Whittlesey brought them out to be examined. After inspecting the contents of box K-10, Keller found something which prompted him to say: "I think you are going to want to see this."

And so began our odyssey with the 1926 document entitled "A Report on Permanent Educational Improvements at Upper Basin, Yellowstone. . . Made During the Season of 1926," by NPS Chief Naturalist Ansel F. Hall. "I had always suspected that such a document existed," said Lee, "but I believed it to have been been destroyed, or in Washington, D.C."

Although the "improvements" made that season did not prove to be so permanent, we believe that this document itself will prove to be one of the more important thermal finds for this decade. We made copies of the original 125+-page document and its large blueprint map for field work.

The document itself was Hall's detailed attempt to set up self-guiding interpretive trails through the Upper Geyser Basin. These trails led not only through the thermal areas from Old Faithful to Riverside Geyser, and from Giant to the Black Sand Basin, but also through the Myriad Group, Pipeline Springs, and the forest surrounding these areas. Stations and interpretive signs along the way carried informational tags that the tourist could read which dealt with hot springs and geysers, wildflowers and plants, trees, birds, and other forest surprises. The signs along the way discussed the features and then pointed the follower to the next station. The document contains not only a full record of what each sign said with detailed thermal information, but also a lot of background comment and history.

Reading the document is like entering a time machine. There are seventy-three photographs pasted into the volume showing tourists, in 1920s' attire watching geysers erupt (including Giantess Geyser), examining bird's eggs (including the climbing of a ladder to peer into a nest), and reading signs erected for their edification. These people stare out at the reader from onion-skin pages, illustrating the method of "mass producing" documents before the era of copiers.

In order to more fully appreciate the value of this document, one must understand the important role Ansel Hall, with this manuscript and its trails, played in the ongoing process of not only providing information to tourists about the thermal features and their activity, but also to new park personnel. With the transfer of park management from the Army to the fledgling Park Service, a great discontinuity in the transmission of thermal information occurred. Toward the end of the military era, a "General Information. . ."[1] pamphlet was finally published which preserved at least some interpretive information concerning the established names and activity of hot springs in the Park.

Fortunately, during the next few years, Milton Skinner, a man who had been a hotel guide in the 1890s, and who had later worked for the Army Corps of Engineers, became interested in all aspects of the Park's flora, fauna, and natural wonders. It was he who revised the thermal tables contained in the above informational pamphlet for 1915 and 1916.[2] Skinner [1920-1922] passed on some

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[1] This pamphlet was published annually by the Department of Interior for quite a number of years, and under various titles. The first in 1912 was entitled: *General Information Regarding YNP, Season of 1912.*

[2] *General Information Regarding Yellowstone National Park, Season of 1914*, and *...Season of 1915*, with Skinner's [1915, 1916] inked in notes and corrections for the following seasons. Milton Skinner [1913] suggested establishing a "Bureau of Information" for the park as early as 1913, and although the idea was turned down by the acting superintendent, Skinner would later

information through three years of his precursor to the *Yellowstone Nature Notes*, and by word of mouth.

But this transfer of information proved inadequate. Many of the signposts on thermal features were either in desperate need of repair, or no longer in existence. Hague's [1904] *Atlas...*, a primary source of information for the NPS in the 1920s, had problems in pinpointing locations of springs, and contained a number of mistakes. Jack Haynes's guidebooks did not go far enough with hot spring information. Thus, aside from what Skinner saved, Hall's manuscript represents one of the few real preservations of older thermal information at the end of that transitional period.

This was the sign erected at the beginning of the self guiding trail which directed the visitor through a good portion of the Upper Geyser Basin -- just "Follow the Arrows." The round trip was 4 miles.

In the Hall manuscript we found references to early (1917-1926) ranger naturalist, and thermal observer, Dr. Van Pelt, somewhat of a phantom figure himself. Rocco Paperiello immediately recognized the enigmatic Van Pelt as the author of a few obscure thermal reports. This manuscript shows that Hall and other park personnel routinely deferred to Van Pelt as one of final authority, yet almost no information from him, or about him, has yet been discovered.

The Hall document describes in great detail the placement of many of the thermal names in use at that time. A few already in place, and others given by either Hall or Van Pelt, are new to us. Some of these newly discovered thermal names are considered by us to be obsolete, because the springs have since been renamed, either officially or through heavy local usage. But other names used by Hall for springs theretofore unnamed are, under rules of historical priority, arguably active. In other cases information found here has led to a new interpretation or clarification of other information already known.

The first trail described by Ansel Hall directs the visitor around Old Faithful and Geyser Hill. One of the first thermal names mentioned by Ansel Hall, sheds light on one of the mystery names found in Allen and Day [1935], that of the "Cloudy Bubbler." Because of Hall we now know this was the name previously given to today's East Chinaman Spring.

Moving to Geyser Hill, Ansel Hall mentioned "two small geysers within a few feet of TOURMALINE SPRING [Silver Spring] which have not heretofore been named on account of their

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be appointed the park's chief naturalist in 1920. Unfortunately his abrasive personality forced him to resign by 1923.

relative unimportance. . . They have been designated 'GNOME' and 'PIGMY'." "Gnome Geyser" at "10 paces" from "Tourmaline Spring" is today's Little Squirt Geyser. At that time, it erupted "at frequent, but irregular intervals to a maximum height of six feet." Pigmy Geyser played "somewhat less frequently..., but to about the same height. During or before the eruption the water [rose] and form[ed] a pool 10 feet in diameter. draining eastward." Today this nearly defunct geyser sputters at unknown but frequent intervals through the gravel. It is located next to the boardwalk between Bronze Spring and Anemone Geyser. Since no other name has replaced that of Pigmy Geyser, this name is still good today.

According to Ansel Hall, the name for Anemone Geyser was freshly rediscovered in 1926:

> Anemone is an interesting little compound geyser, the name which seems to have been lost for many years, as I could find nobody who knew the name...

The interpretive sign then located at Anemone Geyser described its activity:

> [Anemone]... plays about every 20 minutes to a height of 6 to 10 feet... The first eruption occurs from the central opening, nearly all the water being sucked down with a whirling motion into the nearest hole. As this pool suddenly drains, the other pool begins to play to a height of 2 to 4 feet, and simultaneously there is a belching in the steam vent 10 feet southward.

Hall's trail next wound toward Butterfly Spring. (Today, it would appear that part of the original Butterfly Spring is missing). During portions of its history it erupted as a small geyser and was known as "Butterfly Geyser." Next to Butterfly is Dome Geyser, now relatively well known, and occasionally active as a geyser. But in 1926, this was not the case. Ansel Hall wrote about Butterfly and Dome:

> Butterfly geyser has not played for several years. The vents lie just at the base of a huge cone which is topped with a deep and beautiful hot spring [Dome Geyser].
>
> The name Butterfly has been assumed to apply to all three of these features. There are two signs at the base of the cone close to the orifice of the old BUTTERFLY GEYSER. One reads: "BUTTERFLY CONE Be sure to see the interesting hot spring at the summit of this cone. Temperature 195 degrees F. Depth 12 feet. BUTTERFLY was formerly a compound geyser playing from these vents at the base of the cone; now quiescent..."

From this it is apparent that Hall was not aware at this time of the rare eruptive activity for Dome Geyser. Charles Phillips had described its geyser activity earlier that year:

> This double eruption [of Giantess and Beehive] was followed by increased activity on the part of many springs and vents several of which the writer has never seen in eruption before. One of these was the unnamed spring on the high mound beside the Butterfly which played several times in January, on one occasion with sufficient vigor to be heard as far as the Inn. [Phillips 1926a]
>
> The water was thrown out in lateral jets in all directions; height 5 ft.[3] [Phillips 1926b]

According to Hall, atop another of the posts in this same area was an arrowed sign also pointing to Dome Geyser, labeling it "GEYSERITE CONE." This sign was probably the inspiration for Allen & Day's [1935 p 244, Table 43] use of the name "Geyserite Dome" for Dome Geyser.[4]

Hall's trail then passed by "The Oyster" [Infant Geyser] on its way to Vault Spring. According to

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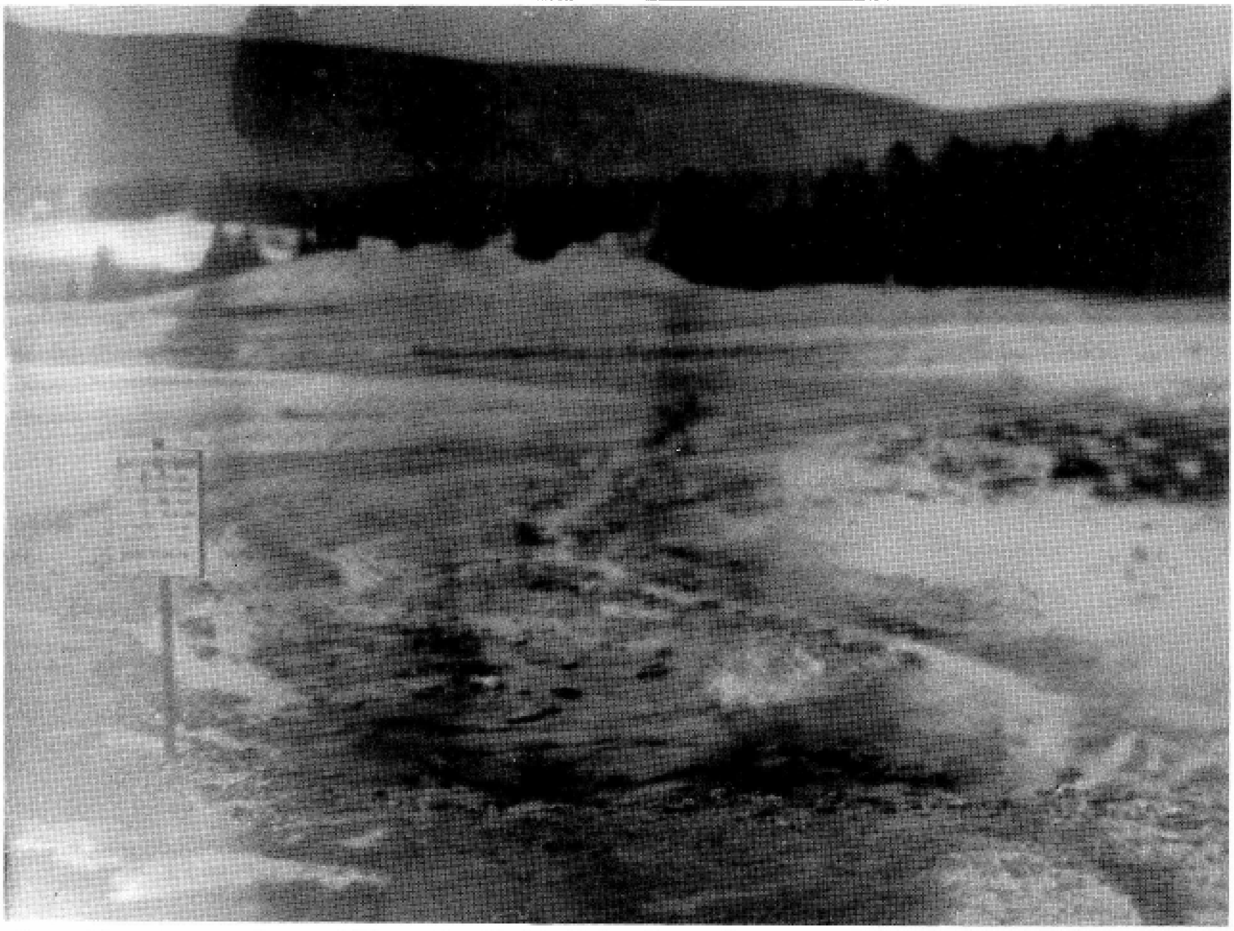
3 The above is the earliest record so far found of Dome's geyser activity. Other rare eruptions were noted by geyser gazer Thomas Ankrom in May of 1932, and a few times in 1936 when it was again called "Butterfly Geyser," this time by Clyde Max Bauer [1937].

4 The name "Geserite Dome," though similar, is different from that attached to the above sign post. George Marler [1959] at first used the name of "Cone Geyser" for this feature, as did McClelland [1960]. Later Marler [1959a] changed this name to Dome Geyser, find this was the name used by Germerraad and Watson [1959].



One of the stops on Geyser Hill was the "Safety Valve Geyser" -- a name given by Ansel Hall to today's Pump Geyser. The Lion Group is in the distance.

Ansel Hall the sign here read in part:

> THE VAULT GEYSER... occasionally erupts (average interval 3 weeks) throwing water from two vents at bottom (south end) out toward the north. The water level is thus lowered 6 to 10 feet...[5]

Another interesting puzzle which Ansel Hall helped us to unscramble was that involving Topaz Spring and Pump Geyser. We realize now that a distinction must be made between a (former) feature called "The Pump" and the one today called Pump Geyser. Hall [1926 with photo] said that the feature which we call Pump Geyser today was then called "Safety Valve Geyser." This name was still apparently in use in 1928-9, as it is found in a table of temperatures by Baker and LaNoue prepared in those years and used by Allen & Day. [1935, p 244]

Hall makes it clear that "the Pump" of that day was not the same feature we today call Pump Geyser, but rather a small thumping hole about 12 feet north of Topaz Spring. Walter Weed's [1887] description supports this, as he writes of an

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5 George Marler stated it was not until March 23, 1958, that had he ever observed Vault erupt in response to a Giantess eruption. [McClelland 1958] Before this date, Paperiello has been able to find record of only two eruptions of Vault which occurred in response to an eruption of Giantess Geyser. These occurred in March of 1926, [Phillips 1926b] and on June 3, 1932 [Skinner 1932]. In fact, for many years, an eruption series of Vault, was regarded as a precursor of a Giantess eruption, which would sometimes occur by the next day. Arnold Hague [c1911] wrote: "The Vault is really a geyser, which when it plays is always a few hours, possibly a day, before the Giantess." (Vault was apparently dormant from 1938 through 1946.)

"intermittent boiler" with "bronze deposit" [Topaz],[6] a "gurgling hole" ["the Pump"], and to the west an "intermittent spring" which "may be a small geyser" [present Pump Geyser].

Hall's discussion of "The Pump" also ends our long time confusion with the accounts of Landsdowne and Phillips. In [1923] Landsdowne stated that "The PUMP is named for the sound it makes. It goes all of the time." But its location was not spelled out. A few years later Phillips [1926c] wrote:

> The chief distinction of the Pump is the fact that it is the only one of the several thousand of thumping holes in the Park that has a name."

Again Phillips' location was vague, and from it most people believed that today's Pump Geyser was perhaps the same feature but now erupting. However the Ansel Hall manuscript clears everything up; "The Pump" and Pump Geyser were and are two separate features:

> The sign at THE PUMP[7] reads: "THE PUMP Although THE PUMP and TOPAZ POOL are side by side, they have no underground connection. If connected underground, the water in both would stand at the same level. All hot springs and geysers are fed by slow seepage of ground water from rain and snow. Rarely are adjacent pools connected underground; there is no large dentral cavity as a reservoir."
>
> About ten paces westward form TOPAZ and PUMP is an interesting little geyser which is exceedingly active. In a cavity a few inches beneath the ground there is a continuously violent boiling and every few minutes the action becomes so intense that a quantity of water is violently expelled to a height of four to six feet and occasionally as high as ten. This geyser had no[t] heretofore been named and so it was labeled "SAFETY VALVE" on account of its action which periodically seems to relieve the pressure and permit boiling again. The sign here reads as follows: "SAFETY VALVE GEYSER Plays at irregular but frequent, intervals whenever the pressure becomes great enough. Height 5 to 15 feet. Note the hissing sound from small crack on south side, caused by escape of steam."

From this description and accompanying photos, Hall's "Safety Valve Geyser" is clearly today's Pump Geyser. By 1931 the name "Safety Valve" was no longer in use. Instead, as was the habit of the day, an erupting feature was sometimes tagged with the name of a nearby thermal feature. Hence the name "Pump Geyser" apparently came into being from the feature near it called "The Pump." A report by Lystrup in June of 1931 illustrates this, and from it we learn what happened to Topaz Spring:

> Topaz Spring, which last season was one of beauty with its numerous layered ledges, is almost completely drained. The water is below the uppermost ledge to a depth of between eighteen and nineteen feet...
>
> The Pump Geyser is in almost constant play though not playing as high as last season. Whether or not its constant activity this season has to do with the drainage of Topaz just beside and above it cannot at this time be stated. If connected, however, the level in each should be the same.[8]

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[6] Weed named this feature "Bronze Spring."

[7] From an included photo, this sign lay in front of a small steam vent about 10 to 12 feet north of Topaz.

[8] This report is further bolstered by a report in the *Minneapolis Tribune*, July 26, 1931:

> Yellowstone Park, Wyo., July 25.– Notable changes on the upper geyser basin since last season as pointed out by Herbert Lystrup, ranger naturalist at Old Faithful Museum, includes[sic] the almost constant activity of Pump geyser. This geyser is now almost constantly playing, whereas last season it was irregular. It is not spouting as high as last year, however, Lystrup points out.
>
> Close by Pump geyser is Topaz spring, which last season was one of beauty, with numerous ledges. Today it is almost completely drained, with the water below the uppermost ledge and to a depth of between 18

Hall's trail then passed the Lion Group and the springs he called "Triangle Hot Spring" [North Goggles Geyser], and "Algous Pool" [Pendant Spring], arriving at the area of Doublet Pool, Beach Spring, and today's Aurum Geyser. The manuscript not only sheds new light on the history of Aurum, but also corrects some misconceptions we have had about another feature, Dragon Spring. It now appears that the "Dragon Geyser" of the 1920s was not present day Dragon Spring -- as previously assumed -- but Aurum Geyser instead! Here is the reconstructed history of Aurum Geyser.

The earliest known reports we have of Aurum erupting is found in the Old Faithful Log for [1922-1923], and in an article by Landsdowne [1923]. The old log reported a smattering of eruptions through 1922 and 1923, and merely labeled it the "new geyser." Landsdowne had trouble remembering the spring's name:

> (I can't recall the name of this [spring], located right beside the BEACH SPRING and near the DOUBLET POOL). This. . . plays about 15 feet high a few times a season... for about three minutes. It is chiefly of interest because it has two vents, one in the center, the other here at the side. Sometimes it plays from one, sometimes from the other. (The later information is from [Milton] Skinner.)

But Hall's interpretive trail signs now provide additional information, and his manuscript tells us that today's Aurum was the "Dragon Geyser" of the 1920s:

> About 15 feet of log courderoy[sic] were laid between DOUBLET POOL and THE DRAGON [Aurum Geyser] over a muddy area. At DRAGON GEYSER the sign reads: "DRAGON GEYSER An active geyser playing about 10 feet high at irregular intervals, usually from 1 to 6 times per day. The main eruption is from the largest crater; as this dies down a number of violent spurts of superheated steam escape from one of the small holes. Several momentary periods of overflow from the large crater precede the eruption.

With that in mind, and recalling that at the end of Aurum's eruption its main vent, along with a minor side vent, can spout steam and water (representing the two vents of a dragon's nostrils), the following, found in the 1927 *Ranger's Naturalist Manual*, takes on added significance concerning the rationale for the name "Dragon":

> The DRAHON[sic] is a small geyser that plays half a dozen times a day spitting fire and smoke (in this case water and steam) after the manner of orthodox dragons. [Phillips 1926c]

Other reports of a "Dragon Geyser" erupting in 1925, and in 1927 [MRofS], we realize now, were NOT references to present day Dragon Spring, but instead, to Aurum Geyser.

It was Clyde Max Bauer who confused the name of "Dragon Geyser" with Dragon Spring, and this interpretation was later adopted by Jack Haynes in his guidebooks starting in 1946.[9] That appears to have cemented the mistake for fifty years.

Further complicating matters, the name of "Dragon Geyser" was even made an official name in 1927, referring to present day Aurum Geyser.[10] So which name should we now use? Arguably the name Aurum is too entrenched in literature and usage to try to change it **back** to Dragon. But **Dragon Geyser** is the officially approved name of today's Aurum Geyser. Thus, in our opinion, the park place names committee needs to petition the USBGN to set this straight by officially approving the name Aurum, by approving the

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and 19 feet. "Whether or not the constant activity of Pump geyser has anything to do with the drainage of Topaz, just beside and above it, cannot be stated at this time," Ranger Lystrup says. "If connected, the level of the water in each should be the same." [from: anon., "Geysers Changing in National Park"]

[9] Perhaps the only historical report of Dragon Spring ever erupting was that made by Bauer in [1939]: "On geyser hill - Reported in eruption once in 1939 - height 3 to 5 feet. CMB." During this same year, George Marler [1939 Geyser Report, YNP Research Library] was calling Aurum Geyser "Beach Geyser."

[10] See: Lindsley, Albright, Jack Haynes, & (Day), "Place Names of Yellowstone National Park, Including the Principal Duplications and Errors Determined in 1927," *Ranger Naturalist Manual*, 1928, pp. 137-148.

name Dragon Spring for the feature farther south, and by dropping the name "Dragon Geyser."[11]

In 1926, Hall's trail to the Black Sand Basin wound its way through the Myriad Group. (Interestingly it kept away from the area near Spectacle and Abuse, since this area at the time had buildings on it, and these springs were used as sources of hot water). A number of "new" names have been discovered in Hall's manuscript for features in this area. These names include Quartz Basin, Sinter Pool, Hematite Mud Spring, Colonnade Pool, Hourglass Pool, Egyptian Spring, Arch Spring, Spectacle Pools, and Surging Spring. None of these have been renamed in the interim. Thus, under the rules of historical priority, these names remain active. (See map).

Hall also included some interesting remarks regarding geyser activity in the Myriad Group. One spring between Hourglass Pool and Egyptian Spring was labeled a small geyser. (See map). (Although not active in 1994, it had, at that time, all the appearances of past geyser activity.) Another statement concerning an attractive spring about 90 feet south of Arch Spring illustrates the ongoing debate concerning the definition of a geyser. At this spring Hall referred to the following 1926 sign:

> IS THIS A SPRING OR A GEYSER?
>
> This large pool, boiling in one place, has the appearance of an ordinary hot spring. More violent boiling, which occurs from time to time, reaches to a height of two to three feet, and gives it geyser-like characteristics."

Hall's trail continued to Three Sisters Springs. He indicated that here were "...the first geysers of any size which have been encountered along this trail." The 1926 sign read:

> THREE SISTERS
>
> This pool contains ten craters, seven hot springs and three geysers. Two geysers, one in the small lobe close to the road, and the other near the stump, play several times a day to a height of 5 to 10 feet. These geysers are evidently on the same fissure, as indicated by the connecting line of small hot springs between them. Note how the geyser nearest the road overflows before eruption and drains rapidly afterward, probably due to condensation of steam in the tube.
>
> The third geyser plays less frequently from the opening in the center.

This provides new information concerning the activity history of these geysers. The first geyser "in the small lobe" is today's Little Brother Geyser, the second is Three Crater Geyser, and the third is the present day "Mugwump."

Continuing on his Nature Trail, Hall finally arrived at Black Sand Basin. The first feature he encountered was Whistle Geyser, whose sign read:

> WHISTLE GEYSER
>
> This geyser erupts about once every four weeks to a height of 50 feet. Its name comes from the roar caused by steam rushing out of the narrow opening during the eruption--a noise which can be often heard as far as a half mile away. A fine spray of water is thrown out with the steam. Duration is 20 to 30 minutes.

Although Whistle is known to have been active in the 1920s, this frequency of eruption is new to us, and uncorroborated by other known sources.[12]

From Black Sand Basin, Hall's trail continued to the Daisy Group. In route, Hall mentioned a "Cerulean Spring," today's Pentagonal Spring. This was another of Allen and Day's mystery names [p. 244].

In the Daisy Group, is Daisy's Thief Geyser. According to Scott Bryan [1986], "the size of its cone and the nature of erosion in its surroundings indicate that the past has seen a great deal of activity." But much of its little known history must predate the establishment of the park. Hall adds the

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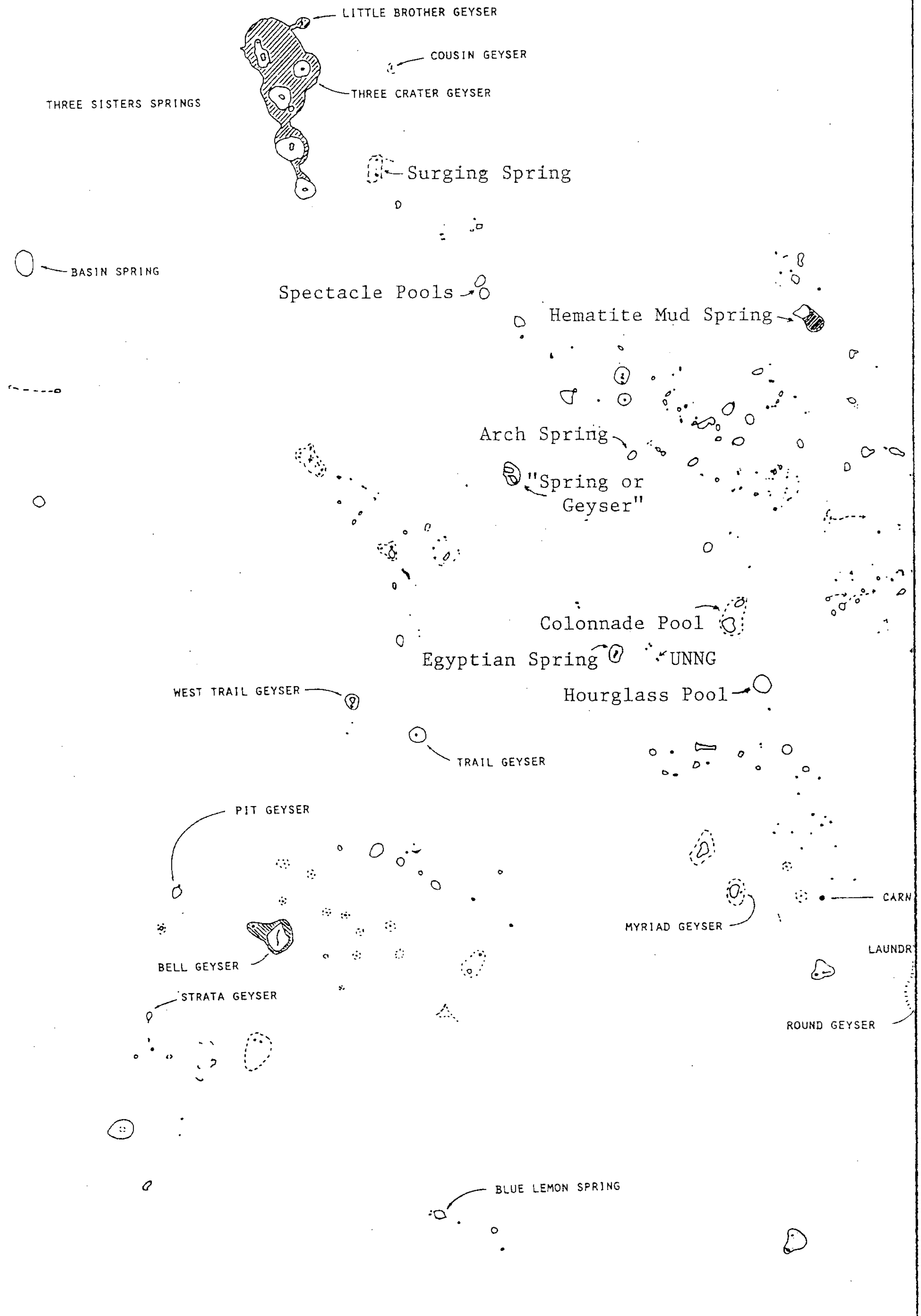
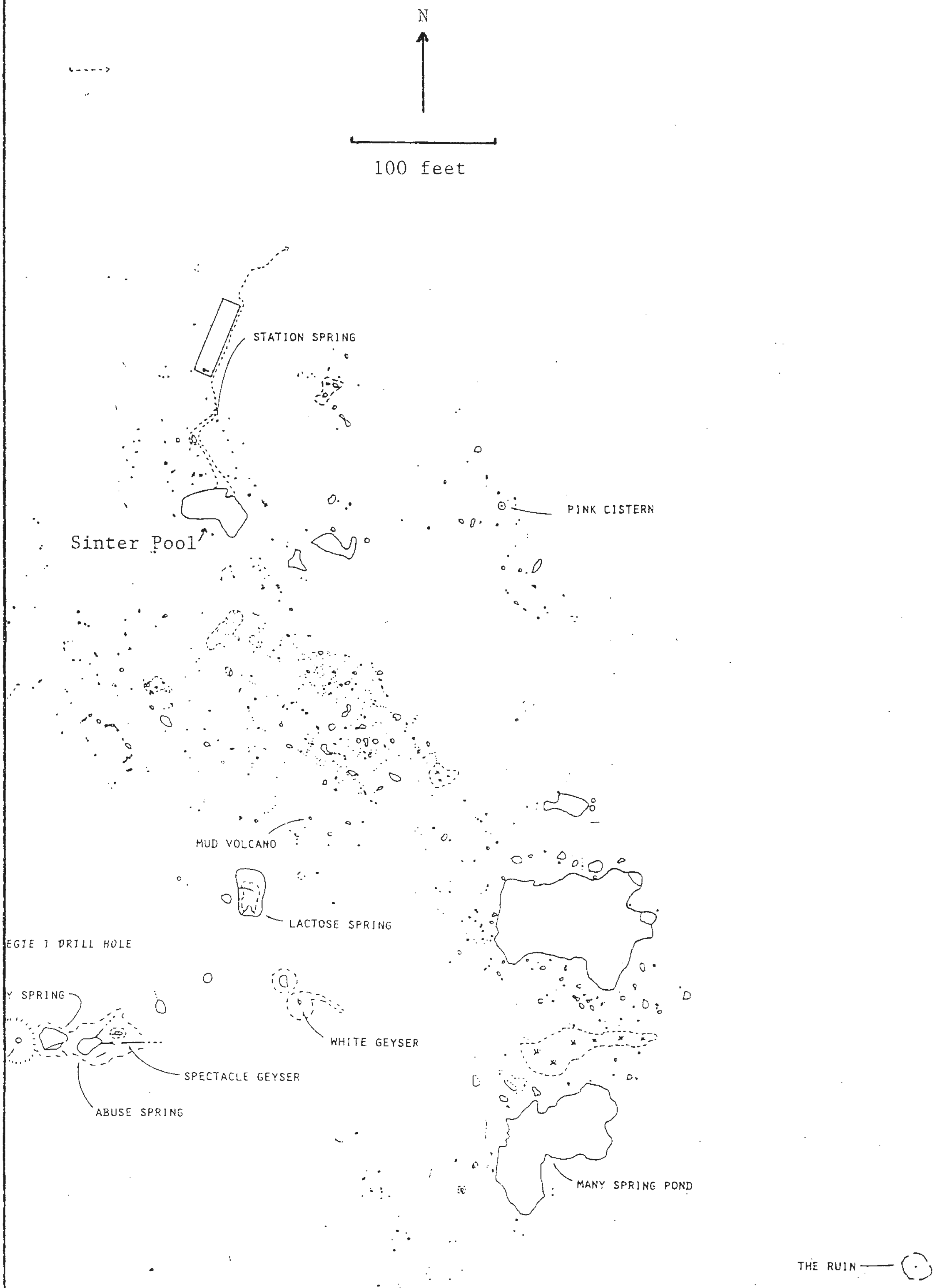
[11] We suppose that the name Aurum is too well entrenched to have it changed back to Dragon -- a name one of the authors here much prefers.

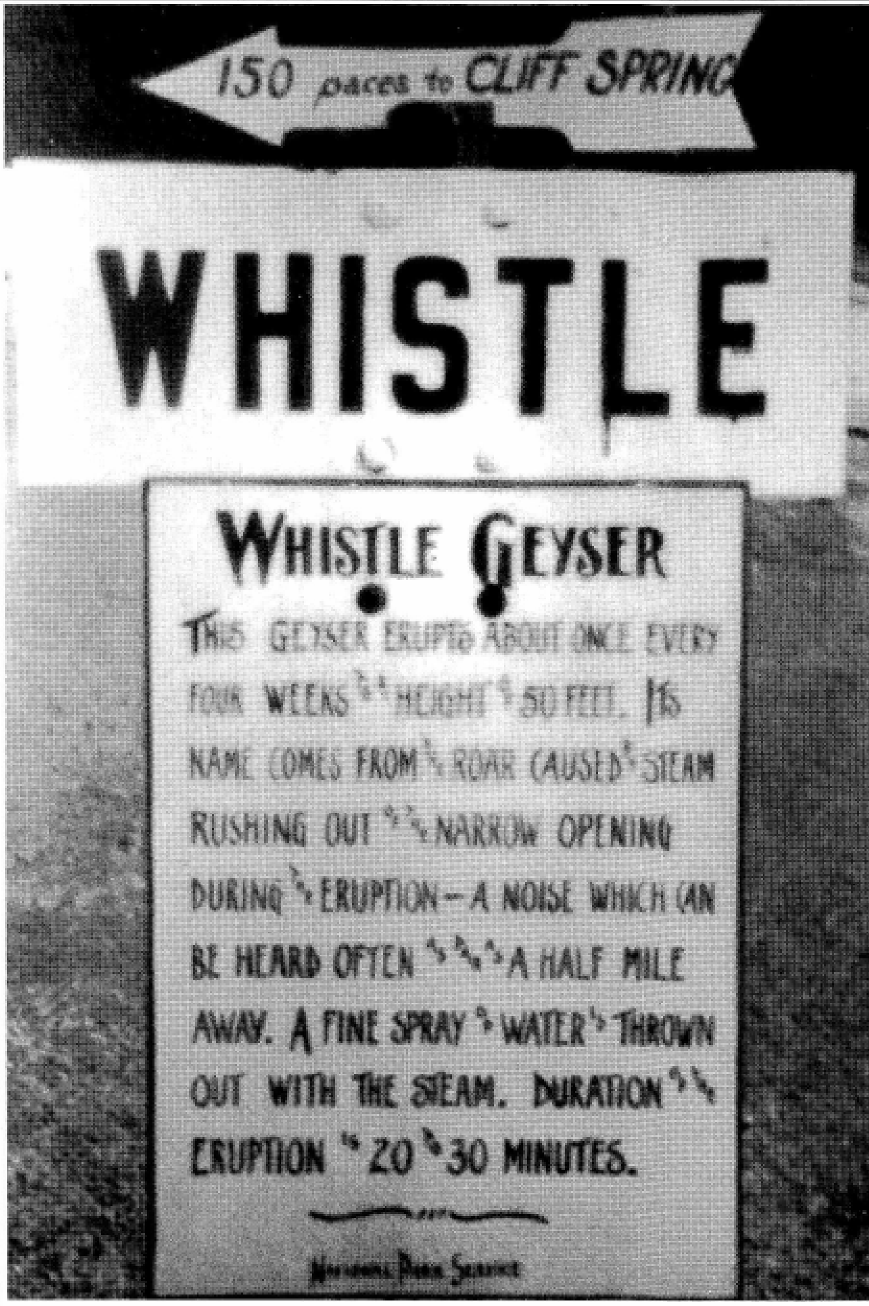
[12] From all other known sources: In 1922 - 1 known eruption [OFL 1922], 1923 - 1 possible eruption [Landsdowne 1923]; 1924 - 2 known eruptions [MRofS Aug, 1924]; 1926 - 1 known eruption [Martinsdale 1926]; 1927 - 1 known eruption [MRofS Aug 1927]; 1929 - 1(or more) known eruptions [E.J.B. 1929].


LITTLE BROTHER GEYSER
COUSIN GEYSER
THREE SISTERS SPRINGS
THREE CRATER GEYSER
Surging Spring
BASIN SPRING
Spectacle Pools
Hematite Mud Spring
Arch Spring
"Spring or Geyser"
Colonnade Pool
Egyptian Spring
UNNG
Hourglass Pool
WEST TRAIL GEYSER
TRAIL GEYSER
PIT GEYSER
MYRIAD GEYSER
CARN
LAUNDR
BELL GEYSER
STRATA GEYSER
ROUND GEYSER
BLUE LEMON SPRING

MYRIAD GROUP



Map by Rocco Paperiello 1995
adapted from may by Germerraad & Watson 1959



A typical sign on the guided trail giving a description of the present feature, and directions to the next.

following to our small knowledge of its history, confirming the fact that "Dewey Geyser" was its old name:[13]

> DEWEY GEYSER This geyser has no label as yet; Skinner says it erupted often in 1898 and occasionally in 1899. (Note: Label as "a dead geyser." Pipe installed. A.F.H.)[14]

"Pipe installed" meant that Hall erected a pipe to display the new "Dewey Geyser" sign.

Even before Hall, Bonita Pool had at one time been known as an indicator for Daisy Geyser. According to him, the sign at Bonita so indicated:

> BONITA POOL
> This pool is an indicator for the DAISY GEYSER. It usually fills up and overflows into the road before the eruption of the DAISY and drains slowly during and immediately after the eruption of the DAISY...

The trail next arrived at the Grotto Group. Here Hall gives us what is now the earliest mention of Grotto's "marathon eruptions":[15]

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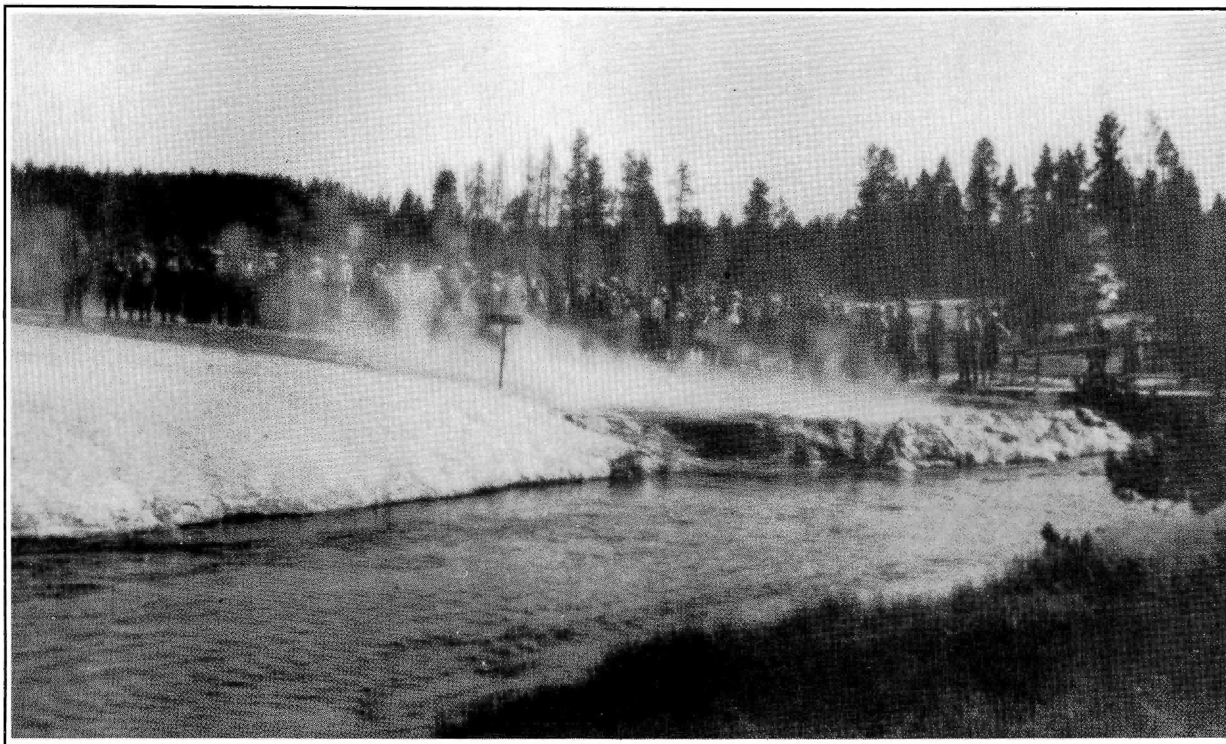
[13] A photo in Olin D. Wheeler's *Wonderland 1904*, captioned as "Dewey Geyser," had been tentatively identified as present Daisy's Thief Geyser by Marie Wolf. We now know that Marie was correct.

[14] Additional eruptive activity is known for at least 1936, 1937, 1940, 1947, and 1949. [Marler 1937, 1940, 1947, Beal 1949]

[15] In relatively recent years it has been "rediscovered" that Grotto Geyser can have unusually long durations which can affect other features with some more or less predictable events. Durations for Grotto Geyser, usually ranging from 1½ to 2½



A ranger led walk at Cliff Spring. The next stop on their tour will be the famous Handkerchief Pool.

hours can occasionally last as long as 5 hours, to even more than 10 hours.

Some of the more notable occurrences due to these longer eruptions include:

1) the gradual lowering of the water level in "Variable Spring" by 4 feet or more; (From this much reduced water level, this spring has been known to have had some eruption of 2 to 6 feet above water level).

2) large eruptions of Spa Geyser usually beginning at about 5 hours into the grotto "marathon";

3) eruptions of "Marathon Pool" toward the end of very long "marathons" of Grotto Geyser.

There have been other earlier records of these "marathons" of Grotto. One noted by [Stewart 1930], lasted longer than 11 hours. In his reports of 1931 and 1932, Thomas "Geyser Bill" Ankrom had coincidentally called this "marathon eruption," a "long run":

> After a long run of the Grotto Geyser, 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.

> GROTTO GEYSER
> Grotto is quiescent from 2 to 8 hours. Eruptions vary from 15 minutes to 8 hours, and so it is in eruption about half the time...

About the Chain Lakes area, Hall noted that the sign there read:

> CHAIN LAKES REGION Contains large and beautiful pools as well as at least two geysers which erupt at irregular intervals a few feet high...

Coupled with information from Ankrom [1931, 1932-3], and others, it is most probable that these two geysers are Link and North Chain Lake.

Hall's trail then doubled back to Giant Geyser. The sign at Giant read:

> During 1926 [Giant] erupted about once every three months... Several small openings around the GIANT play at irregular intervals, thus probably causing some delay in the eruptions of the GIANT.

Although this last conclusion is no longer held to be true, we do recognize here one of the few early references to the Giant's hot periods, from which the huge geyser can erupt.

Hall's trail moved on to Wave Spring; the sign there read:

> The water rises, with occasional bubbles of gas (carbon dioxide) in the larger pool, and flows into the smaller one where it sinks out of sight...

This description confirms the fact that the second (and final) change of location for the name "Wave Spring" had already taken place by the mid-1920s. This name was originally given to the feature we now call Economic Geyser. [Peale 1883] But Walter Weed [1888], and later the [1904] Hague *Atlas*..., placed the name "Wave Spring" on today's East Economic Geyser. This first shift by Weed and Hague was most likely made because the original pool started erupting and took on the name of Economic Geyser. The second shift of the name Wave Spring moved it to today's location -- the large pool northwest of East Economic Geyser.

The Hall manuscript also shows that the signs reflected the switching of some names at Grand Geyser by at least the early 1920s. The name of "Turban Geyser" had been placed on today's Vent Geyser, and the name "Burning Pool" had been placed on today's Turban. These names persisted through at least the mid-1930s.

Interestingly, the sign at Grand Geyser at this time read that "Four or five similar spurts follow [the first], although cases are on record where the GRAND has erupted as many as 50 times consecutively." The most bursts of Grand for which we now have specific record is 45. This occurred in the Spring of 1926 [P.U.], and on September 9, 1949 [Beale].

Hall also gives us the earliest reference to Rift Geyser's eruptive activity. He wrote that the sign there stated:

> GROUP OF NEW GEYSERS In 1924 these new geysers broke out from crevices in the lave[sic], illustrating the way in which new geysers appear... The activity of these, as of most other new geysers, has been increasing, probably due to the enlarging of their channels...[16]

A parenthetical note by Hall may give us a surprising new insight into the location of the long wondered-about Surprise Geyser. From its first edition in 1890 through that of 1909, the original *Haynes Guides* were authored by photographer Frank Haynes under the pen name of A. B. Guptill.[17] 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 today that this geyser was also called "Liberty Geyser" and was located somewhere in the vicinity of present-day Liberty Pool. [Whittlesey 1988] Using Peale's descriptions, and Walter Weed's original sketch of the pool through which Liberty erupted, an effort was made by Whittlesey and Paperiello to determine its original location. No pool in the area quite fit, and, almost by default, we supposed that perhaps present day Liberty Pool was indeed the original geyser. But we now read in Hall:

> The original Liberty Pool [lay] 150 feet east [of Tardy Geyser], but it has dried up and is now an uninteresting crater...

Thus our new speculation is that this dead crater -- lying between Liberty Pool and Tardy Geyser, and still dry today -- might have been the site of the original Liberty Geyser.

Hall's trail then dropped down to the Firehole River, crossing it at about the same place as the foot trail does today. Hall's manuscript relates a curious coincidence involving South Scalloped Spring. This

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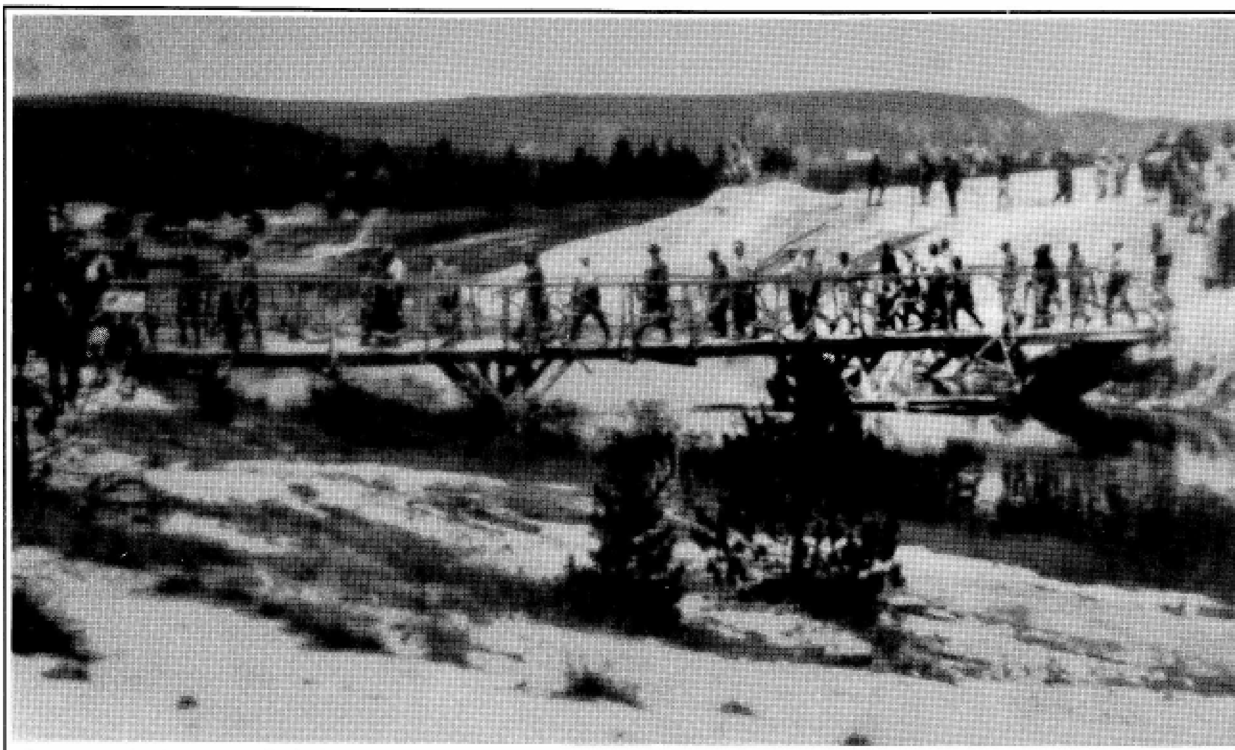
[16] The next known references to eruptions of Rift were those made in [1932-3] by the geyser gazer Thomas "Geyser Bill" Ankrom, who named them the "Six Fissures Geyser." Later, in an August, 1938 report, George Marler stated: "So far as I can determine these little geysers have never been named. They are located at the foot of the hill near the Triplets. I have designated them as "Rift" because they are but rifts in the naked rhyolite." This above report by Marler was reprinted in the August 1938 *Report of the Naturalist Division*, with authorship claimed by Clyde Max Bauer, Marler's boss. Until Marler's original report was found, it was believed that Bauer was the originator of the name Rift Geyser.

[17] A. B. Guptill was the accountant for Frank Haynes.



A ranger led group winds its way along the Old Faithful Formation Trail, past "Gargoyle Spring," Teakettle Geyser, and [South] Scalloped Spring over the old bridge toward Terra Cotta and Castle Geyser.

spring was labeled "Scalloped Spring" on an 1870s stereopticon slide by photographer John Crissman. Though that name did not survive, Hall proposed the same name fifty years later:

> We found the above spring mis-labeled "WITCHES' CAULDRON"; the name on the old maps is given as TEAKETTLE [sic -- an incorrect map interpretation], but we already have another TEAKETTLE which shows on the same old maps; this spring was therefore called SCALLOPED SPRING; this name proposed by me. A.H.

Eventually, the name Scalloped Spring was somehow transferred to a feature a short distance to the northeast. That feature had been named "Gargoyle Spring" by Ranger Naturalist Dr. Van Pelt, because of a "gargoyle-shaped projection just below the surface."

Following Hall's trail across the river, we find that he has added new information to an historical puzzle concerning Terra Cotta Spring. It seems Hall knew the correct location of Terra Cotta Spring, a brick-colored mud spring:

> TERRA COTTA SPRING is a peculiarly colored spring near the south bank of the river about 250 feet from [west of] the bridge. (Note: A post is needed here, and a label ... should be written up...).

Today's Terra Cotta Geyser (a feature different from Terra Cotta Spring), according to Hall, had a post (with missing sign) -- indicating that it had been given a name prior to 1926, and that the "old name should be ascertained." (Apparently, Hall did not know of the name which had been used for this feature). A number of years later, in a fashion typical of the 1930s and 40s, this spring was given the name Terra Cotta Geyser for its proximity to Terra Cotta Spring. Hall's narrative shows that the naturalists were aware of the location of the real (first) Terra Cotta Spring. There is argument among us as to whether this refutes present day speculation that the name of Terra Cotta Geyser was placed mistakenly on this feature.

The activity of Castle Geyser at the time of

A ranger and some tourist are examining Midas Spring. Bend Cone can be seen in the distance.

Ansel Hall is interesting. He wrote that the sign there stated:

> ...Water spurts from this cone almost continuously to a height of 10 to 20 feet. Eruptions of 75 to 150 feet occur almost daily for about a week, then cease for a period of 5 to 60 days. Eruptions are sometimes followed by a long and violent steam period.

This describes activity far different from that typical of today. Perhaps Castle's spectacular cone resulted from this kind of "sloppy" activity occurring over much of its history.

A third trial described by Hall wound its way across the Firehole River, investigated the thermal springs in and around Pipeline Meadows, climbed to the overlook above Geyser Hill, and arrived at Solitary Geyser.

Hall's manuscript now reveals the origin of the name "Deer Tracks" which has long been applied to a party site on the Firehole River just south of the Mallard Lake trailhead. There are described "petrified deer tracks" in rocks in the river which Ansel Hall wanted tourists to examine on his nature hike. Mike Keller confirmed that they are still there today. Whittlesey had wondered for years where the name Deer Tracks had come from.

The first feature described at the entry to Pipeline Meadows is Bend Cone, (neither of these more modern names were used by Hall). About this large cone Hall wrote:

> This is a large and interesting hot spring with three vents which has built up a large cone. The small temporary label written up by Van Pelt for the interesting and spectacular feature has been lost. Rewrite at the beginning of the next season.

The trail then soon brought the visitor to Midas Spring -- a previously unknown name. (See photo).

> MIDAS SPRING (The label for this interesting hot spring has been lost and should be duplicated by Van Pelt next season. He should also take the temperature. The pool is lined with beautiful golden algae; hence its name.)

A photo of Solitary Geyser found in the Hall Manuscript. "Water is thrown to a maximum height of about 30 feet."

In recent times this spring had acquired the informal name of "Pipeline Meadows Geyser." It apparently did not erupt at the time Hall built his trails.

A few yards away the trail came to a small unnamed geyser which has in recent years become quite active. Deep furrows newly cut through the meadow by its runoff channels in the late 1980s attested to its relatively recent rejuvination. Thus Halls comments become very interesting:

> A small active geyser. The sinter deposits surrounding this orifice shows that it is a geyser. We have no data on its activity and would therefore appreciate any action being reported to the Ranger Naturalist at Old Faithful Ranger Station.

Having examined the Hall manuscript and read of his self-guiding nature trails with all their interpretive signs, we must now ask ourselves what happened to the trail, and why so many of these thermal place names were lost or changed. We do not know the complete story, but big changes in park thermal place names did occur by the 1930s probably because of major turnovers in park personnel.

By 1931, all of the thermal place names introduced by Hall and Van Pelt, and a couple others, were gone, and so were the self-guiding nature trails. The self guiding trails appear to have been dismantled sometime between 1929 and 1931. Some of these lost names appeared in tables used in Allen & Day. These tables were prepared in 1927-29, and no report after 1930 used these names. The Hall trails were quickly forgotten as was much of what thermal information it had saved from Van Pelt, Skinner, and the army era. While we do not know the motivation for this, we can speculate that four thermal deaths in four consecutive years (1926-29) generated a park concern for safety of persons walking through thermal areas. Perhaps that influenced the decision to remove the self-guiding trails. With the loss of the nature trails, perhaps some of the signs were removed with them. In addition, there was a huge turnover in park personnel from the twenties (Van Pelt, Hall, Landsdowne, Phillips, Martinsdale, etc.) to the thirties (Bauer, Lystrup, Marler, Stewart, etc.) Perhaps the new crew decided that these "new" names of the Hall and Van Pelt era did not merit retention.

Whatever the reason, there was indeed a loss of many names, and other thermal information. One has to wonder what added thermal names and information would have been passed down to us today if Ansel Hall had been as good a friend to Jack Haynes as was Clyde Max Bauer. Many thermal names introduced in the thirties by Bauer survived because of their publication in the *Haynes Guides* by Jack Haynes.

The names and accompanying information used by Ansel Hall on his 1926 nature trail were lost until the day Lee Whittlesey brought an archival box out for Mike Keller to examine.

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Hall Manuscript			Original Name	Today's Name
Already in Place by 1926	Name Rediscovered	Newly Named by Hall or Van Pelt		(official or accepted)
Old Faithful			"	"
Black Sand Basin			Emerald Group	Black Sand Basin
Blue Star Spring			"	"
		Cloudy Bubbler	Cloudy Bubbler	East Chinaman Spring
The Sputterer			"	Sputter Spring
Chnaman Spring			"	Chinese Spring
Beehive Geyser			"	"
Beehive Indicator			"	Beehive's Indicator
Cascade Geyser			"	"
		Tourmaline Spring	Tourmaline Spring	Silver Spring
		Gnome Geyser	Gnome Geyser	Little Squirt Geyser
		Pigmy Geyser*	Pigmy Geyser	none
	Anemone Geyser		Anemone Geyser	Anemone Geyser
		Butterfly Cone	Butterfly Cone	Dome Geyser
Butterfly Geyser			Butterfly Spring	Butterfly Spring
Mottled Pool			Mottled Pool	Mottled Pool
The Oyster			Infant Geyser	Infant Geyser
Vault Geyser			Vault Spring	Vault Spring
Giantess Geyser			Giantess Geyser	Giantess Geyser
Teakettle			Teakettle Spring	Teakettle Spring
		(The New Geyser)	Plume Geyser	Plume Geyser
Topaz Spring			Topaz Spring[1]	Topaz Spring
The Pump			The Pump*	none
		Safety Valve Geyser	Safety Valve Geyser	Pump Geyser
Sponge Geyser			Sponge Geyser	Sponge Geyser
Lion Geyser			Trinity Geyser[2]	Lion Geyser
Lioness Geyser			Lioness Geyser	Lioness Geyser
Little Cub			Little Cub	Little Cub Geyser
Big Cub			Big Cub	Big Cub Geyser
Goggles			The Goggles	Goggles Spring
		Triangle Hot Spring	Triangle Hot Spring	North Goggle Geyser
Ear Hot Spring			Oyster Spring	Ear Spring
Algous Pool			Algous Pool	Pendant Spring
Doublet Pool			Doublet Basin	Doublet Pool
Dragon Geyser			Dragon Geyser[3]	Aurum Geyser
Beach Spring			Primrose Spring	Beach Spring
		Quartz Basin*	Quartz Basin	none
		Sinter Pool*	Sinter Pool	none
		Hematite Mud Spring*	Hematite Hot Spring	none
		Colonnade Pool*	Colonnade Pool	none
		Hourglass Pool*	Hourglass Pool	none
		Egyptian Spring*	Egyptian Spring	none
		Arch Spring*	Arch Spring	none
		Spectacle Pools*	Spectacle Pools	none
		Surging Spring*	Surging Spring	none
Three Sisters			Three Sisters Spring	Three Sisters Spring
Whistle Geyser			Whistle Geyser	Whistle Geyser
The Spouter			Great Spouter	Spouter Geyser
Green Spring			Emerald Spring	Green Spring
Handkerchief Pool			Handkerchief Pool	Handkerchief Pool
Cliff Geyser			Cliff Geyser	Cliff Geyser
Sunset Lake			Sunshine Lake[4]	Sunset Lake

		Cerulean Spring	Pentagonal Spring	Pentagonal Spring
Black Sand Pool			Black Sand Geyser	Black Sand Pool
Punchbowl Spring			Punch Bowl	Punchbowl Spring
White Pyramid			Pyramid	White Pyramid Geyser Cone
Dewey Geyser			Dewey Geyser	Daisy's Thief
Brilliant Pool			Brilliant Pool	Brilliant Pool
Comet Geyser			Spray Geyser	Comet Geyser
Daisy Geyser			Comet Geyser	Daisy Geyser
Bonita Pool			Bonita Pool	Bonita Pool
Grotto Geyser			Grotto Geyser	Grotto Geyser
Rocket Geyser			Rocket Geyser	Rocket Geyser
Spa Pool			Spa Pool	Spa Pool
Chain Lakes			Connecting Springs	Chain Lakes
Riverside Geyser			Riverside Geyser	Riverside Geyser
Giant Geyser			Giant Geyser	Giant Geyser
Oblong Geyser			Oblong Geyser	Oblong Geyser
Mastiff Geyser			Mastiff & Bijou Geysers [5]	Mastiff Geyser
Bijou Geyser[6]			New Faithful Geyser[7]	Bijou & Catfish Geysers
The Motorboat			The Motorboat	Motorboat Vent
The Ink Well			Inkwell Spring	Inkwell Spring
Chromatic Pool			Chromatic Pool	Chromatic Pool
Beauty Pool			Beauty Pool	Beauty Pool
Wave Spring			Wave Spring	Wave Spring
Economic Geyser			Wave Spring	Economic Geyser
Calida Spring			Calida Spring	Calida Spring
Seashell Pool			Lime Kiln Springs	Seashell Spring[8]
		Toadstool Paintpot	Toadstool Paintpot	Milk Cauldron
		Spurting Spring	Spurting Spring	Craters of the Moon
Witches Cauldron			Witches Cauldron	Witches Cauldron
Turban Geyser			Vent Geyser	Vent Geyser
Burning Pool			Turban Geyser	Turban Geyser
Grand Geyser			Grand Geyser	Grand Geyser
The Triplets			The Triplets	N, E, & W Triplet G.
		(New Geysers)	Rift Geyser	Rift Geyser
Bulger			Bulger Geyser	Bulger Geyser
	Spasmodic Geyser		Spasmodic Geyser	Spasmodic Geyser
Handsaw Geyser			Steamboat Geyser	Penta Geyser
Sawmill geyser			Sawmill Geyser	Sawmill Geyser
		Liberty Pool	Tardy Geyser	Tardy Geyser
		Gargoyle Spring	Gargoyle Spring	Scalloped Spring
		The Retort	Doublet	Deleted Teakettle G.
		The Churn[9]	The Churn	Flume Spring
		Scalloped Spring	Scalloped Spring	S. Scalloped Spring
Terra Cotta Spring			Terra Cotta Spring	Terra Cotta Spring
The Spanker			Spanker	Spanker Spring
Crested Pool			Fire Basin[10]	Crested Pool
The Tortoise Shell			Castle Junior	Tortoise Shell Spring
Castle Geyser			Castle Geyser	Castle Geyser
		Midas Spring*	Midas Spring	none
Solitare Geyser[11]			Solitary Spring	Solitary Geyser

* Name still good

1 Bronze Spring of Walter Weed
2 Name by Comstock 1873, (included Lioness & Big Cub), also Niobe Geyser of Peale 1878
3 Not today's Dragon Spring

4 Great Hot Basin of Bechler 1872
5 The original Mastiff included only its front vent, the name Bijou was given by Hague to the back (or eastern) vent
6 Included Catfich Geyser
7 Included both Catfish & Bijou Geysers, and later the name Catfish was also meant to include both features
8 One of the vents of Lime Kiln Springs
9 Name misplaced by Hall
10 Circe's Boudoir of Norton 1872
11 Solitary Geyser

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[Note: All photographs found in this article have been copied by Smokey Sturtevent from photos found in the original Hall manuscript.]

Recorded Observations of Thermal Activity at Shoshone Geyser Basin, Yellowstone National Park: 1988 -1997

by

Jeff Cross

Introduction

Information for this report is based on observations conducted at Shoshone geyser basin by the author and by the following people mentioned below :

July 16, 1988	with Carlton Cross
July 15, 1989	"
August 5-7, 1990	"
July 16-18, 1991	with Tara and Carlton Cross
July 19-21, 1992	"
July 10-13, 1993	with Adam Johns, David and Michael Goldberg, and Tara, and Carlton Cross
August 11-13, 1994	with Adam Johns, and David and Michael Goldberg
August 11-13, 1995	with Tara and Carlton Cross
August 3-5, 1996	"
July 7, 1997	with Tara Cross
August 4-5, 1997	with Tara and Carlton Cross

The maps used are after Paperiello [1989, 1992] Thus the numbering system used here refers to the numbers on this set of maps.

Little Giant Group

"Trail Geyser" #2

July 1988: active
July 1989: active
August 1990: no eruptions seen
July 1991: active (irregular?)

Notes: we saw one small eruption from the small gurgling vent just northwest of Trail's crater.

July 1992:
I = about 8 minutes (2 closed intervals)
D = 30-45 seconds (3 durations)

July 1993:
I = 6-9 minutes (3 closed intervals)
D = 20-60 seconds (4 durations)

August 1994:
I = 6-13 minutes Mean = 8 minutes, 42 seconds, std. dev. = 27% (9 closed intervals)
D = 20-60 seconds Mean = 24, std. dev. = 32% (10 durations)

August 1995:
I = 7min to 10min 16sec Mean = 8m53s, std.dev. = 15% (7 intervals)
D = 37-57 sec Mean = 45, std.dev. = 17% (7 durations)

August 1996:
I = 6 min 48 sec - 10 min 59 sec Mean = 8m46s sec, std.dev. =18.1% (7 intervals)
D = 37 - 64 seconds Mean = 48.4 sec, std.dev. = 18.0% (8 durations)

August 1997:active

Notes: Heights have usually been around 1 meter. Eruptions have at times been preceded by one or more false starts.

"Double Geyser" #10

July 1988: active
July 1989:
I = 62 minutes (1 closed interval)

August 1990: active
July 1991:
I = 62-63 minutes (3 closed intervals)

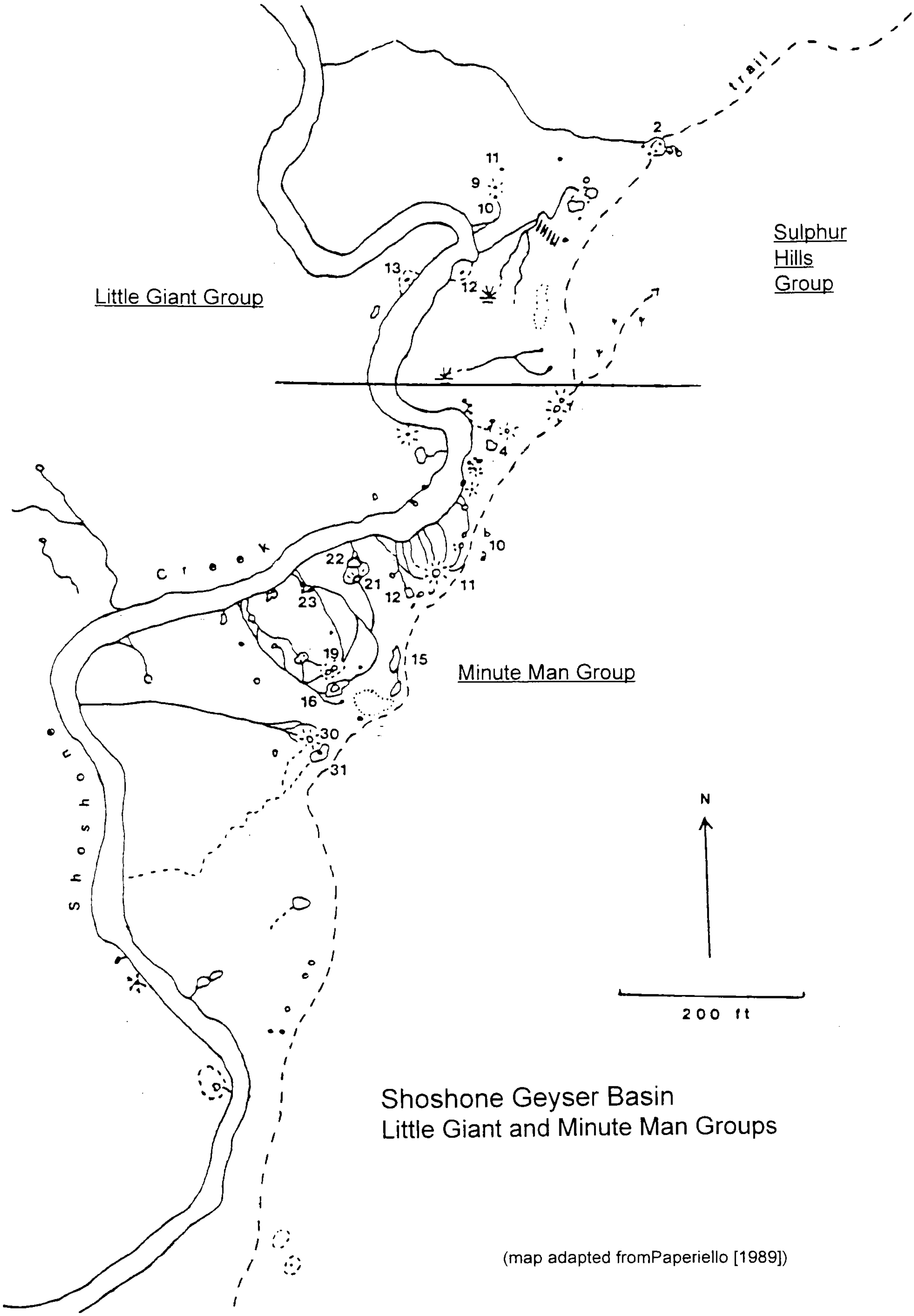
July 1992:
I = 52-56 minutes, Mean = 54m30s (4 closed intervals) std. dev. = 3.2%

July 1993:
I = 55 minutes (quite regular) Mean = 54 m35s (10 closed, 1 double interval) std.dev. = 5.6%

August 1994:
I = 67-74 minutes Mean = 69 minutes, 06 seconds (3 closed, 2 double, 1 triple interval)

August 1995:
I = 66-67 min Mean = 66.4, std.dev. < 1.3% (7 closed, 1 double interval)

August 1996:



trail
2
11
9
10
Sulphur
Hills
Group
13
12
Little Giant Group
4
10
Creek
22
21
12
11
23
19
15
Minute Man Group
16
30
31
Shoshone
N
200 ft
Shoshone Geyser Basin
Little Giant and Minute Man Groups
(map adapted fromPaperiello [1989])

I = 59-62 minutes
8/3/96 Mean = 59.77 std.dev. = 3.37% (9 int)
8/4/96 Mean = 61.32 std.dev. = 0.83% (7 int)
8/5/96 Mean = 60.94 std.dev. = 2.48% (4 intervals)
D = 5-7 minutes
H = 3-4 minutes
July 1997
I = 59-60 minutes
Mean = 59.47 std. dev. = 0.70% (3 intervals)
D = 5-7 minutes
H = 3-4 meters
August 1997
I = 60-63 minutes (mean = 61.42 std. dev. = 1.53% (4 intervals)

"Double Geyser" 1982

Notes: Durations have been fairly consistent at approximately 6 - 7 minutes, heights at 2 - 4 meters. One exceptional burst in 1995 shot water to 5 meters. As shown by the data above, Double is a remarkably regular geyser. In August of 1996, the intervals were very close to 60 minutes. In fact, the first eruption noted on 3 August occurred at 12:05, while the last eruption on 5 August was at 15:14, indicating that a stable, hour-long interval was held over a period of 51 hours with only 9 minutes of accumulated error. In 1997, the regularity continued, except for one unusual interval of 81 minutes (excluded from the above anaylsis). This, the longest interval we have recorded, occurred while a powerful storm front was moving through the Shoshone Geyser Basin, and the attendant atmospheric unrest may explain things somewhat. Its more typical intervals of 60-63 minutes then resumed.

Small vents southeast of Double

I = sputtering just before Double
H = sputter

Notes: Just southeast of Double is a small complex of holes which have sometimes sputtered just before Double starts; the water level has always dropped when Double starts.

Little Giant Geyser #9

I = starts just after Double starts
D = continues after Double stops
H = ½ meters (1-2 meters in 1997)

Notes: I have not at any time seen obvious signs of major activity (H > 3 meters) from Little Giant. Paperiello [1992] noted in October of 1991 that the runoff channel had been scoured along most of its length, implying that major activity had occurred. In 1997, there were no signs seen of any recent "large" eruption.

Little Giant Group #11

1991-1996:

I = starts 15-20 minutes after Double
D = stops with Double
H = 10-30 centimeters

Notes: Related to Double and Little Giant, this small vent begins sputtering to 10 centimeters about 15-20 minutes into Double's interval. This continues until a few minutes after Double starts, at which time it increases in vigor, spraying water 20-30 centimeters into the air for a short period. This is followed by a weak steam phase, and another period of quiet ensues.

"Meander Geyser" #12

July 1991: active; splashing eruption to 50-60 centimeters
July 1992: not recorded
July 1993: active; seen twice; either the duration was in excess of 90 minutes, or there were two eruptions within this period
August 1994: active; seen in eruption 7 times over a total of 5-6 hours; this probably reflects long durations and rather short intervals; the northern of the small vents right next to Meander sputtered intermittently during at least one of Meander's eruptions.
August 1995:
I = hours
D = hours
H = 1 meter
August 1996: active
August 1997: active

Locomotive Geyser 1982

Locomotive Geyser #13

July 1988: not seen
July 1989: active, seen once and photographed
August 1990: not seen
July 1991: not seen but active?
July 1992: dormant?
July 1993: dormant?
August 1994: dormant
August 1995: dormant
August 1996: dormant and platform deteriorating
August 1997: dormant and platform deteriorating

Minute Man Group

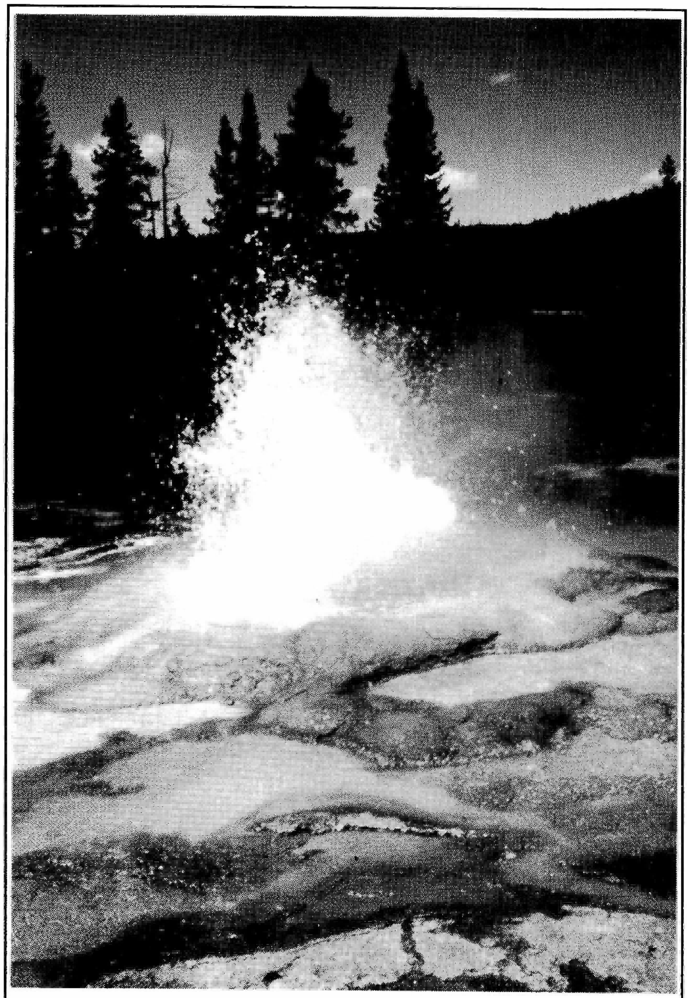
Unnamed unnumbered spouter

In August 1994 I came across a small perpetual spouter between the Little Giant Group and the Minute Man Group. Located on the east side of the creek, it was invisible from the trail. It is north of another perpetual spouter which erupts from a well defined fracture [Minute Man Group #3 (USGS #22)]. Though small, the crater seemed well established, but Paperiello [1989] does not map it. Splashing was minor. It was bubbling in 1995, 1996, & 1997.

Minute Man Group #10a

1992 - 1996: active
1995:
I = 68-81 sec Mean = 76, std.dev. = 5.6 (7 intervals)
D = 39-49 sec Mean = 42, std.dev. = 3.2 (8 durations)
H = 10-30 cent

Notes: This small geyser is in a deep hole on the north side of Soap Kettle's mound. The water is cloudy.



Soap Kettle 1993 Jeff Cross photo

Soap Kettle #11
1991- 1994:
I = 7-12 minutes
D = 2-4 minutes
H = 1-2 meters
August 1995:
I = 6-12 minutes (12 consecutive intervals)
D = 40 sec- 3½ min (11 durations)
August 1996
I = 6-14 minutes
D = 45 sec - 3 min 13 sec
H = 1-2 meters
August 1997
I = 125-1375 seconds (mean = 400 std. dev. = 57.7% (10 intervals)
D = < 70-268 seconds (mean = 179 std. dev. = 34.0% (7 durations)
H = 1-2 meters

Notes: Soap Kettle's activity has been fairly stable over these years. The 1995 data is based on 110 minutes of continuous observation. I considered the eruption to start with the first splash over the rim and ending with the drain that follows the eruption. Longer intervals tended to follow longer durations, and eruptions tended to come in groups of 2 to 3, with the last eruption of the group being longest and largest.

In 1996, the data was based on 115 minutes of continuous observation. Patterns were similar to previous years, but no cyclic pattern was evident this year. Again, in 1997, Soap Kettle's durations and intervals varied considerably, following no recognizable pattern.

Little Bulger Geyser #12
1991- 1994:
I = minutes (east vent)
D = long
H = 1 meter
August 1995:
I = 10-21 minutes
D = 8 - 18 minutes
H = up to 1 meter
August 1996:
I = minutes
D = minutes
H = 1 meter
August 1997: East vent active to 1 meter.

Notes: In 1994 I made the unpleasant discovery that someone had recently vandalized the west vent by placing in it numerous large flat rocks. Another large rock was found perched on the edge of the east vent, one more rock on the south side; more large rocks rested at the base of the hill immediately to the south, and several smaller rocks were scattered about the crater.

The 1995 data was taken over a continuous 110 minutes of observation. Eruptions started with flashing steam bubbles over the east vent -- there were occasional splashes. All the longer pauses of Little Bulger's east vent occurred following large eruptions of Soap Kettle.

In 1996, eruptions were not very well defined. There were still a few rocks over the main vent.

Minute Man Group #22 (USGS #12)
1991-1995:
I = 1-3 minutes

D = 1-2 minutes
H = overflow, rolling boil
August 1996: similar activity
August 1997: similar activity

Minute Man Group #21 (USGS #11)
1991-1995:
I = 9-12 minutes
D = 1-2 minutes
H = boil
August 1996: similar to above
August 1997: Due to the continuous activity of Shield Geyser, which poured a constant stream of cold runoff into the crater, this vent seemed to be nearly dormant.

Notes: Activity has been quite consistent. This spring is almost inactive when Shield overflows into it, though it can overflow at these times. With apparently more frequent activity from Shield and Gourd in 1995 & 1996, this geyser was much of the time squelched by their overflow.

Though uncommon, this geyser is capable of boiling violently during overflow periods, with superheated surges to nearly a meter. This type of activity was seen by Paperiello in 1995.

Five Crater Hot Spring #23
1991-1994:
I = 5-7 minutes
D = 1-2 minutes
H = 50-60 centimeters
1995-1996: only very weak activity seen
August 1997: Due to the continuous activity of Shield Geyser, which poured a constant stream of cold runoff into the crater, this vent seemed to be nearly dormant. Orange bacteria were growing in one of the craters. Occasionally there would be an episode of anaemic waving.

Notes: Data summarized from notes, 1991-1994. I have seen true eruptions from Five Crater every year, 1991-1994. These consist of rather loud sputtering from the small holes that constitute the upper part of the complex and overflow and heaving from the two small pools the lower part. In 1995 and 1996, Five Crater was difficult to catch in eruption. Overflow periods were weak. Its activity is less vigorous when Gourd and Shield overflow into it, as was the case much of the time when seen in 1995. It does not erupt at these times, though it still overflows on lengthened intervals.

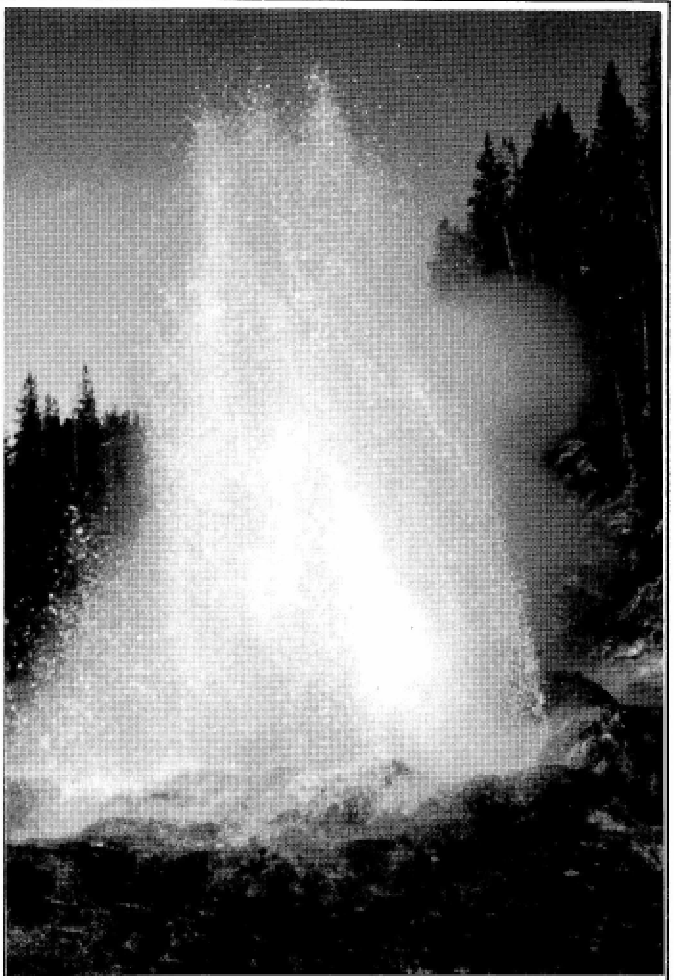
Shield and Gourd Geysers #16 & #19
1988-1994
I = < 3 hours
D = < 2 hours
H = 1-2 meters (Shield)
H = 1 meter (Gourd)
August 1995:
I = 1 hr 12 min - 2 hr 9 min (8 intervals)
D = 25 - 70 minutes
August 1996
I = 58 min - 1 hr 52 min (11 intervals)
D = 22 - 61 minutes
H = 1-2 meters (Shield)
H = 1 meter (Gourd)
July - August 1997: These two geysers were in near-continuous eruption with only brief pauses (on the order of seconds long) on both visits. It is unclear what has caused these formerly periodic geysers to begin perpetual activity, although a 4.2 Richter scale earthquake that occurred on the Pitchstone Plateau on 28 July may have been responsible for this change, which persisted through 05 August.

Notes: These two geysers have been active from 1988 to 1996. Generally, intervals have been less than 2½ hours, durations less than 1½ hours. These geysers seemed more active in 1995 and 1996; Intervals and durations during 1995 were about 15% shorter than during 1993 and 1994.

Rosette Spring #15

I have noticed intermittent activity from Rosette at various times since 1988. In 1994, however, the water level was a few centimeters lower than usual and pulse waves were faintly discernable. Nearby Iron Spring was overflowing into Rosette.

Minute Man Geyser #30
Active every year from 1988 through 1996.
I = 5½ to 7½ hours (known intervals from start to start of series)
I = seconds to minutes (during series)
D = about 2 hours (series duration)
D = seconds (single eruption)
H = 1-9 meters



Minute Man Geyser 1993 Jeff Cross photo

August 1996
(for series)
I = 6 hr 18 min, & 5 hr 20 min
D = 2 hrs - 3 hrs (4 durations)
(individual eruptions)
I = minutes
D = seconds
H = 1-9 meters
July 1997
One series lasted around 150 minutes. A lone pair of eruptions preceded the start of the series by 55 minutes.
August 1997
One series lasted at least 5 hours, and another the next day lasted over 2 hours. Eruptions reached heights of up to 9 meters.

Note: Both in 1995 and 1996, Paperiello noted series which started with a few isolated eruptions and then paused for a half hour or more till the series restarted. The intervals between these first few eruptions were a bit longer than those much later in the series. This pattern was also seen in 1997.

Minute Man's Pool #31
1993: active
1995: Paperiello noted activity to a few feet toward the end of Minute Man's series.
1996:
I = 3½ - 5 minutes (when seen)
D = 20 seconds
H = 1-2 meters
August 1997
I = 1-8 minutes (20 intervals)
D = 6-37 seconds (20 durations)
H = up to 1 meter

Notes: I caught Minute Man's Pool in an active phase in 1993. The Pool erupted to 1 meter for 15-30 seconds from a low water level, always in concert with Minute Man. Though Minute Man had eruptions between those of the Pool, the concerted activity was about the highest I had seen from Minute Man -- sustained jetting, more vertical, accompanied by a whooshing sound. The Pool's series lasted for at least 30 minutes, with eruptions occurring at 11:55, 12:07, 12:13 (short and weak), 12:16, and 12:24. This seemed to be the end of Minute Man's eruptive series; as of 12:42, no further eruptions of either it or the Pool had occurred.

In 1996 one series of eruptions was again observed. This activity was similar to that seen in 1993. One or more solo eruptions of Minute Man occurred between eruptions of the Pool. The observed 1996 activity was in progress about 100 minutes after Minute Man had started a series; it was still in progress 50 minutes later. Many of the small holes between Minute Man and Rosette Spring were nearly empty during this series of eruptions.

On 4 August 1997, Minute Man's Pool began its eruptions at least 2 hours before Minute Man's series ended. (Minute Man's series lasted more than 5 hours). All eruptions of the Pool were in concert with Minute Man Geyser, beginning shortly after Minute Man's eruption started, and continuing for a few seconds after it's eruption ended. Intervals between Pool eruptions were typically 4-6 minutes. Eruptions of Minute Man were more powerful when in concert with eruptions from the Pool. Typically one or two solo eruptions of Minute Man would occur between eruptions in concert with the Pool.

Small hole west of Minute Man (in runoff channel):
July 1992: first recorded observation of small hole (steam venting)
July 1993: a second, larger hole appeared since last year (full of water, occasional waving)
August 1994: same
August 1995: 2 eruptions were seen
August 1996: 2 eruptions seen to 10-20 centimeters
July 1997: One eruption seen.

Notes: This feature lies in Minute Man's west (main) runoff channel and is a rather small hole that I first noticed in 1992. Minute Man had been quiet for several hours and the small hole was venting steam. When Minute Man started, the first overflow covered this vent and was sprayed up in a little rooster tail.

In 1993 a second, larger hole had broken out next to the first and under proper lighting I could see that there was a cavity of some size just under the surface. Both in 1993 and 1994, its activity consisted of a period of waving and sputtering while Minute Man was between series.

In 1996, this pair of small holes was seen twice erupting to about 10 to 20 centimeters. They occurred hours after Minute Man had finished a series. Both eruptions ended when Minute Man started its next series and inundated the runoff channel. Perhaps this is only a spouter which get stopped by the runoff from Minute Man Geyser.

We saw one eruption on 7 July, 1997. It was in progress about 140 minutes after the end of a Minute Man series. Heights were around 0.1-0.2 meters.

Orion Group

Taurus Spring #6

I have never seen anything more than the usual calm superheated boiling from Taurus. Small eruptions to 1 meter have been reported at various times over the last several years, Paperiello [1997] having seen such activity in 1994.

Then on 4 July 1997, Clark Murray saw Taurus Spring erupt to 15 meters (50 feet), lasting less than 60 seconds. When he had arrived at Taurus around 9:30 that morning, it was clear that Taurus had previously undergone one or more large eruptions:

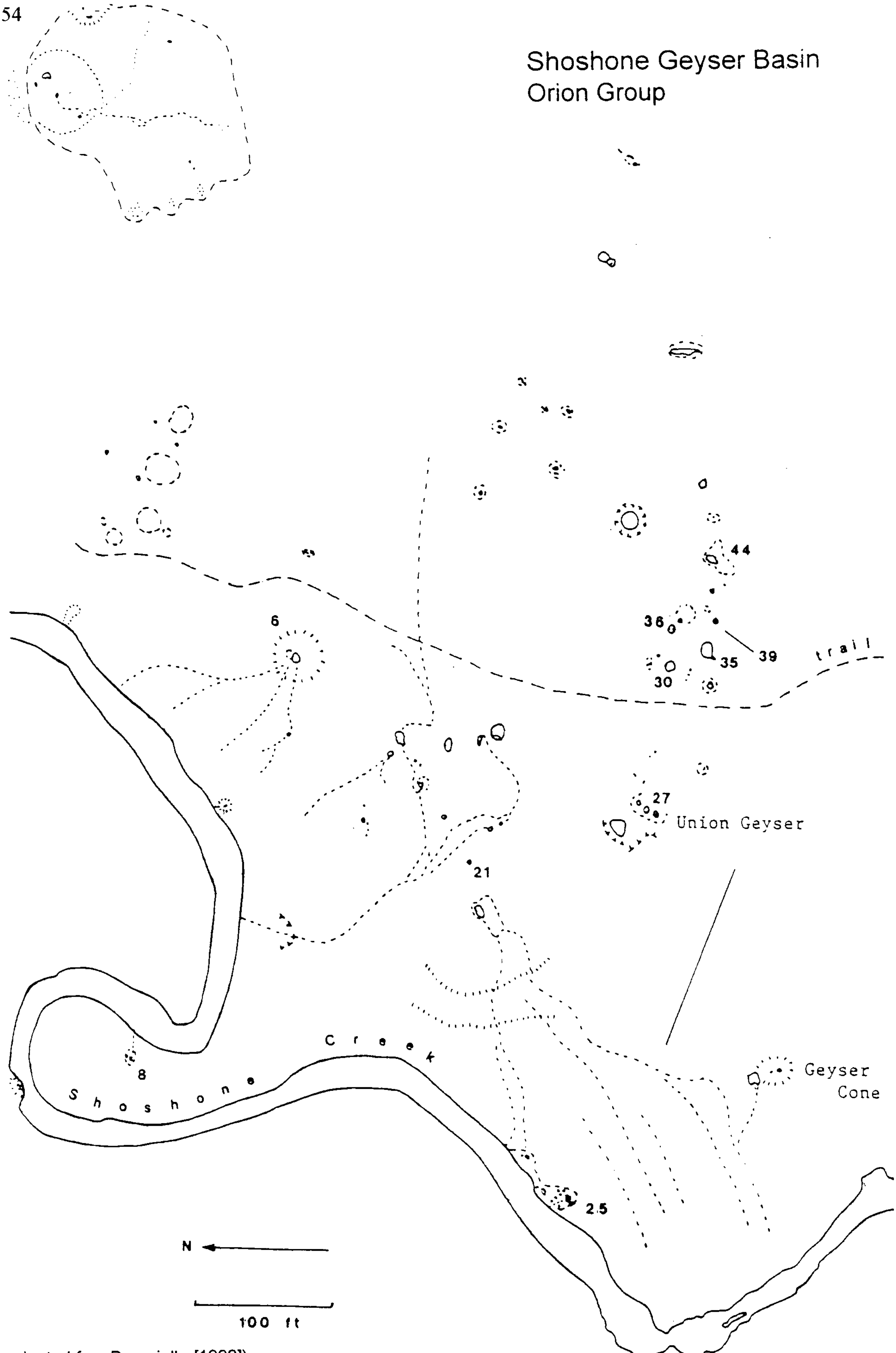
I first noticed a large washed area on the north side of the geyser mound. This extended to [Shoshone] Creek where a small delta had formed. Rocks, tree stumps, sinter gravel, and a rusty pocketknife were found near the crater. The runoff channels were damp and cold, so the prior eruption(s) were probably many hours before. The water level was down about 8 - 10 inches below overflow and the water was superheated and boiling up every few minutes. The water level was slowly rising. Throughout the day I saw frequent small three foot eruptions and assumed this was the current level of activity.

Later in the day, while near Frill Spring in the North Group, I heard a noise like the cracking of a whip. At 12:51 I looked up to see Taurus rise rapidly to a height of about 50 feet. It held this height for about 15-20 seconds, then dropped. The total duration [of the eruption] was less than one minute. The [erupted] water was light grey. . . and formed a perfectly shaped column.

After the eruption the crater steamed lightly for about 30 minutes, and a deep rumbling could be heard from across [Shoshone] Creek. I did not return to Taurus until 16:30. At that time the water level was down about 12 inches and rising slowly. The water was superheated with occasional large bubbles rising to the surface. From 16:30 to 19:00 the bubbles became more frequent until they were nearly constant. It seemed another eruption was near. I waited until darkness forced me to leave. [Clark Murray]

On 7 July 1997 a party (including myself) spent a day at Shoshone Geyser Basin with the object of seeing an eruption of Taurus. The geyser's activity, however, remained essentially the same -- calm boiling and steady overflow with occasional small surges -- from 8:00 through 18:00, making it unclear whether the activity was continuing, and if so, on what magnitude. Taurus may have been having small eruptions at least, for the runoff channels were damp when we arrived in the morning. Perhaps this unusual activty of Taurus could be explained by nearby seismic activity. Notably, a 4.2 tremor, centered below the Pitchstone Plateau south of Shoshone Geyser Basin, occurred on 28 June 1997, six days

Shoshone Geyser Basin
Orion Group



(map adapted fromPaperiello [1992])

before the activity of 4 July. On 4 August it was clear that no major eruption had occurred since. The pool boiled up to ½ meter on occasion, as has been the norm in years past.

The only other known major activity from Taurus occurred following the 1959 Hebgen Lake earthquake. It is mentioned briefly in a report by Mebane [1959, in Paperiello 1992], which read thus: "Taurus Geyser now erupts to about 50 ft., its heavy discharge eroding the soil and sinter around the vent".

Orion Group #44 (USGS #92/Bryan SHO-4):
I have never seen this spring erupt.

Union Geyser #27
1989-1997: low water, violent, noisy boiling in central cone, calmer boiling in north cone, nearly inaudible boiling in south cone.

Notes: In 1994, I made an unpleasant discovery -- the top vent on the south cone had been invested with a stick which nearly blocked the vent and which I hadn't the proper tools to remove.

White Hot Spring #35
July 1989: splashing from low level
August 1990: same
July 1991: same
July 1992: splashing from a water level high enough to cover quite a bit of the wide crater
July 1993: near "geyser-like" activity (H < 1 meter)
August 1994: splashing from a low level
August 1995: splashing from a low level
1997: On 7 July, water levels in this spouter were high enough to partly fill the wide shallow crater. Splashing was constant. By 4 August the water level had receded somewhat, but the constant splashing continued. The water levels may change seasonally.

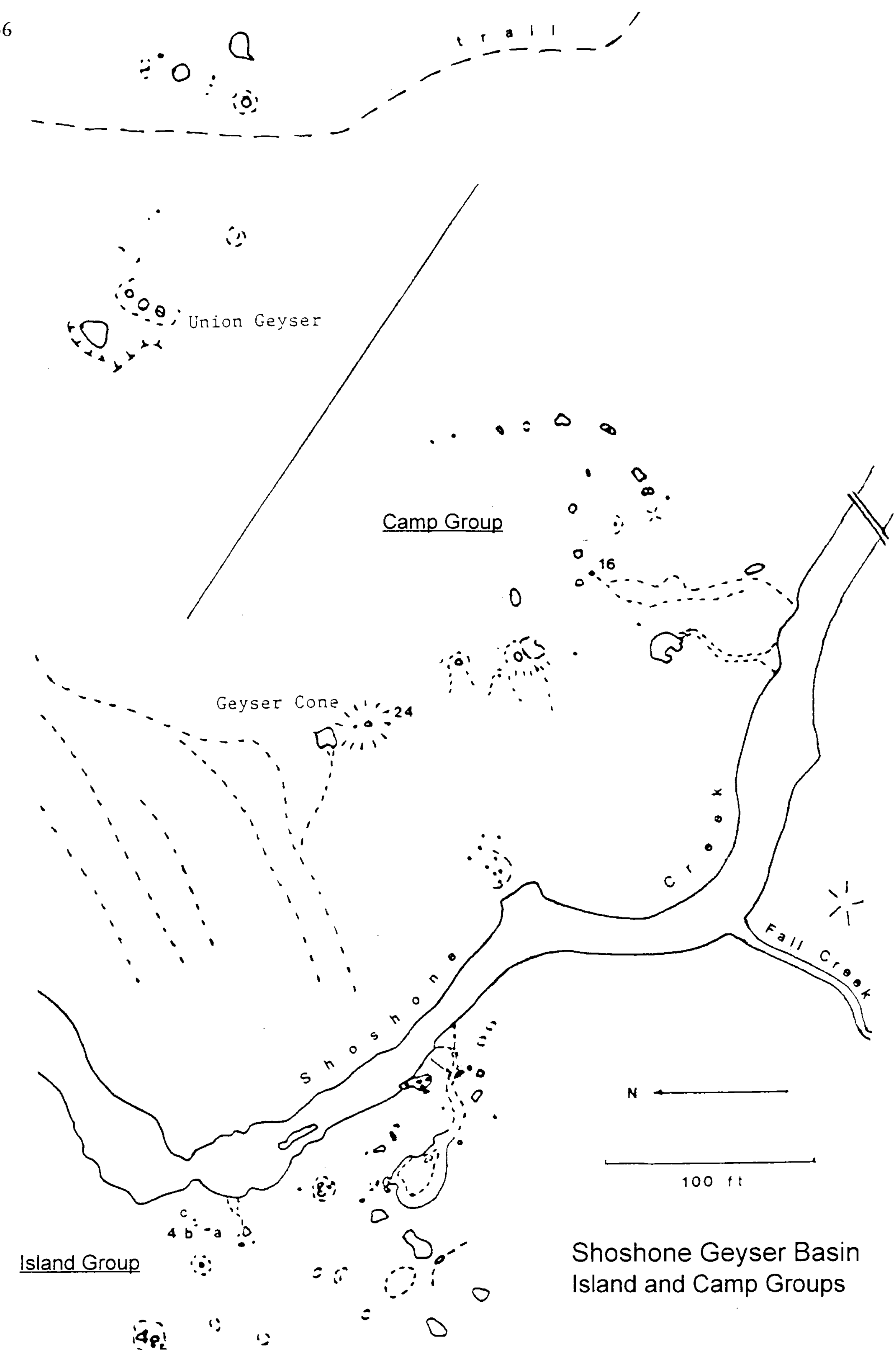
Orion Group #36
July 1997: Water levels in this small symmetrical funnel-shaped vent rose and fell intermittently, occasionally producing hollow thumping sounds.

"Sea Green Pool" #30 (Bryan #14 SHO-1)
August 1995: intermittent

"Fifty Geyser" #39
August 1995: sputtering under the sand
July 1997: sputtering under the sand.

Orion Group #21 (USGS #86a):
July 1989:
I = 2 min 58 sec - 3 min 41 sec Mean = 3 min, 15 seconds (4 closed intervals)
D = 50-69 seconds Mean = 58 (5 timed durations)
August 1990:
I = 91-160 seconds, Mean = 116, std.dev. = 18% (12 closed intervals)
D = 24 -50 seconds, Mean = 40, std.dev. = (13 durations)
July 1991: though the sinter around the small pool was a little wet, I saw no eruptions
July 1992:
I = 60-120 seconds, Mean = 96 seconds (12 closed intervals)
D = 25-45 seconds, Mean = 34 seconds (13 timed durations)
July 1993:
I = 60-120 seconds, Mean = 89 seconds (18 closed intervals)
D = 20-60 seconds, Mean = 35 seconds (21 timed durations)
August 1994:
I = 75-120 seconds, Mean = 107 seconds (13 closed, 2 double intervals)
D = 15-40 seconds, Mean = 27 seconds (16 timed durations)
August 1995:
I = 37 sec - 2 min 44 sec Mean = 98, std.dev. = 28% (18 intervals)
D = 15 - 40 seconds Mean = 32, std.dev. = 25% (22 durations)
August 1996:
I = 51 - 120 seconds Mean = 79.9, std.dev. = 23.4% (15 intervals)
D = 33 - 78 seconds
H = ½ meter
July 1997
I = 107-139 seconds (mean = 122 std. dev. = 12.0% (5 intervals)
D = 28-33 seconds (mean = 29 std. dev. = 12% (6 durations)
H = ½ meter

Notes: Heights have been consistent at < = ½ meter.



(map adapted fromPaperiello [1992])

Orion Group #25
July 1997: Active as a geyser to 2 to 3 feet. Intervals and durations not determined. [report by Paperiello] This is the first activity noted since 1976. [Martinez 1976]

Camp Group

Geyser Cone #24
July 1993:
- I = 29-30 minutes (start of series)
- I = 3-4 minutes (during series)
- D = 6-9 minutes (complete series)
- D = 25-95 seconds (eruption in series)
- H = 1 meter

August 1994:
- I = 26-31 minutes (start of series)
- I = 1.5-3.5 minutes (during series)
- D = 6-10 minutes (complete series)
- D = 30 seconds - 2 minutes (eruption in series)
- H = 1 meter

August 1995:
Series:
- I = 36-48+ minutes (3 intervals)
- D = 7 - 17+ minutes (4 durations)

Individual eruptions:
- I = 2 - 10 minutes
- D = 47 - 3 min 19 sec
- H = 1 meter

August 1996: dormant
August 1997: Dormant, water gurgling at depth. The formation is dry and desiccated.

Notes: Geyser Cone's activity was the same in 1994 as in 1993. A series progressed as follows: 1) period of quiet; 2) rise in water level with intermittent gurgling; 3) series of 2-3 eruptions on intervals of a few minutes with continuously high water; 4) drain, followed by a loud steam and spray eruption lasting up to a minute; 5) gurgling at depth; 6) period of quiet leading to next series.

The 1995 activity was much less predictable than that of 1993 or 1994. A steam phase might come in the middle of a series, and more than one might occur in a single cycle, interspersed with water eruptions.

Sometime between August 1995 and August of 1996, something caused this cone to have a violent explosive eruption. Much of the loose sinter was found washed off the mound and deposited in long debris flows that reached about 16 meters from the vent. Many of the small sintered pebbles that had rested in the crater were strewn about the top of the mound. Based on the distribution of the sinter fragments and direction of the wash, we assumed that the eruption probably came from both vents, and might have been a meter or two in height. Geyser Cone was dormant and the formerly erupting vent was rather dried out.

Camp Group #16
August 1996: noted active by Paperiello

Yellow Crater Group

Unnamed Geyser
1996:
- I = 72-83 seconds Mean = 77 sec, std.dev. = 4.5% (10 intervals)
- D = 41 - 64 seconds
- H = ½ meter

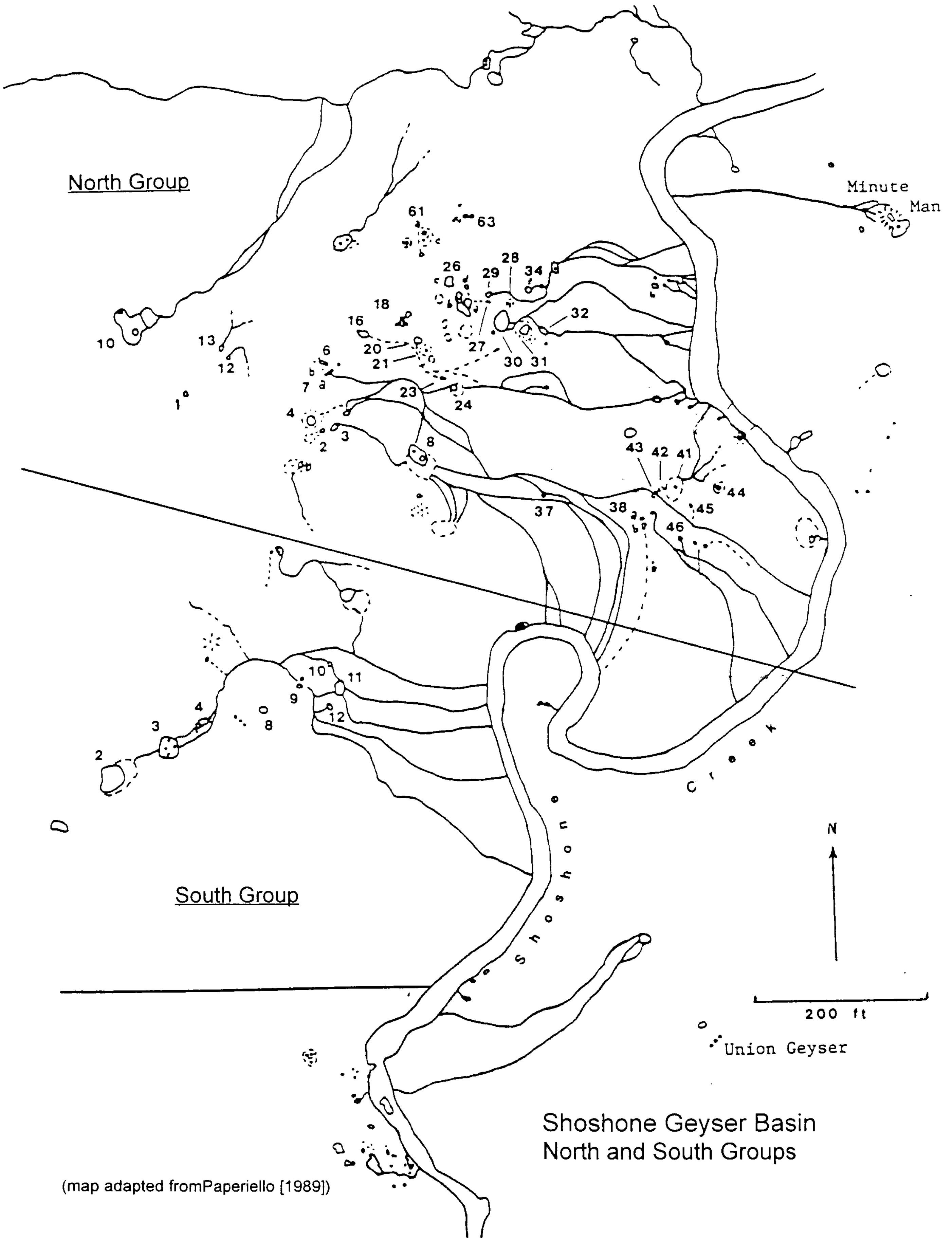
Notes: This geyser erupts from a pool atop a low isolated mound in a meadow well north of the North Group. There are several vents in the pool, two of which were active periodically.

North Group

Lion Geyser #41
July 1988: active
July 1989: active
August 1990: dormant?
July 1991: dormant?
July 1992:
- I = 2 closed intervals: 3 hours, 38 minutes; 3 hours 23 minutes
- D = 9-10 minutes
- H = 5-6 meters vertical, 7-8 meters horizontal

July 1993:
- I = 63-110 minutes
  Mean = 97 minutes (5 closed intervals) std.dev. = 20%
- D = 3-4 minutes
- H = 1-2 meters

August 1994:
- I = 2 closed intervals of 88 and 75 minutes, another I > 90
- D = 4 minutes (approximately)
- H = 1-2.5 meters



Shoshone Geyser Basin
North and South Groups

(map adapted fromPaperiello [1989])

Lion Geyser 1992 Jeff Cross photo

August 1995:
- I = 79 - 84+ minutes Mean = 81, std.dev. = 2.0% (6 closed intervals, 1 triple)

August 1996:
- dormant, growth of bacteria well established

July 1997
- I = 99 and 106 minutes (2 intervals)
- D = 6-8 minutes (3 durations)
- H = 2-4 meters

August 1997
- I = 111 and 118 minutes (2 Intervals)
- D = 7-8 minutes (3 durations)

Notes: My visits in 1988 and 1989 each netted one eruption of Lion. These seemed to be average eruptions of a few minutes' duration and 1-3 meters in height. I saw no eruptions or conclusive evidence of eruptions in 1990 and 1991. In 1992, however, I discovered that Lion was having relatively large eruptions with durations of around 10 minutes. These were much more violent than any Lion eruptions I had seen before or have seen since. The bursts came at the rate of about four per second; this rate varied with a distinct periodic pattern. The highest jets reached an estimated 5-6 meters vertical and 7-8 meters horizontal. Discharge was heavy. Following the eruption the pool drained completely with two counter-rotating whirlpools and some gurgling after the water had fallen out of sight.

During my visits since 1992, Lion has erupted in a much weaker, more usual manner, never exceeding 3 meters. The eruptions of 1993 seemed quite weak at times; the eruptions of 1994 seemed a little better, comparatively.

Lion's eruptions were stronger in 1997 than in 1996. Occasional jets of water landed 4 - 5 meters from the vent. Curiously, following the onset of a rainstorm on 4 August we saw no further eruptions from Lion, nor did we see any on the next day, which was also rainy. Whether the rain could have caused the change is debatable, but Lion has shown considerable sensitivity in years past to the amount of surface water flowing into the crater, and rain would certainly increase that quantity.

North Group #45

Notes: Related to Lion, the water in this small vent is usually boiling and often rises during an eruption of Lion and falls afterward. This hole has a faint runoff channel and looks like it could erupt a little but I have never seen it do so. There are no signs of recent activity.

North Group #42 (USGS #79) and **#43**

August - October 1991: According to Paperiello [1992] #43 blew the sand and sinter out of its vent, and was active at times during this season.

Notes: Both these small craters are related to Lion. When they were clear of debris the water level dropped during Lion's eruptions. In 1992 and 1993 both craters were open. By the summer of 1994, however, both craters were filled (#43 completely) with debris washed in by runoff coming down the hill. This condition has remained the same through 1996.


Frill Spring 1996 Paperiello photo

Iron Conch Geyser #46

July 1989: active (I = 10 minutes?)

August 1990: active; small consecutive eruptions build to a full eruption (H = ½ meter)

July 1991:
- I = 5-7 minutes
- D = 1-2 minutes

July 1992:
- I = 10-15 minutes (approximately)
- D = 1 minute

July 1993:
- I = 9-16 minutes
- D = 40-90 seconds

August 1994:
- I = minutes
- D = minutes

August 1995:
- I = 4 min 36 sec - 6 min 46 sec Mean = 5 min 48 sec, std. dev. = 13% (9 intervals)
- D = 1 min 36 sec - 3 min 31 sec Mean = 2 min 22 sec (7 durations)
- H = up to ½ meter

August 1996:
- I = 4 min 43 sec - 9 min 20 sec Mean = 6 min 23 sec, std.dev. + 21.8% (9 intervals)
- D = 1 min 31 sec - 5 min 37 sec Mean = 2 min 35 sec, std.dev. = 51.% (11 durations)
- H = ½ - 1 meter

July 1997
- I = 325-360 seconds (mean = 343 std. dev. = 4.54% (4 intervals)
- D = 116-213 seconds (mean = 164 std. dev. = 25.0% (4 durations)
- H = 1 meter

August 1997
- I = 300-400 seconds (mean = 354 std. dev. = 9.37% (7 intervals)
- D = 170-300 seconds (mean = 229 std. dev. = 21.0% (8 durations)

Notes: A visit made by Adam Johns over 8-9 July 1994 saw I = 5-7 minutes. Heights have always been around ½ meter. Intervals were timed from the start of overflow to the next overflow.

Bronze Spring #38

This geyser has been dormant since the mid-1980s, as noted by Paperiello [1997].

Frill Spring #31

1992-1996: active

August 1997
- I = 334-885 seconds (mean = 656 std. dev. = 24.3% (11 intervals)
- D = 7-21 seconds (mean = 17 std. dev. = 24% (14 durations)
- H = 3-7 meters

Notes: Until 1997, the most I have seen Frill do is overflow intermittently with waves and bubbles. Until then, Frill hadn't erupted any time I was in or near the basin, though its runoff channels stayed washed.

On 5 August 1996, we saw a series of three strong overflows and a fourth attempted overflow spaced 12-15 minutes apart. Coincident with each of these overflows, a pool to the west (North group #30) stopped overflowing. (This pool also lowers a few inches during a series from Frill). An eruption of Frill seemed imminent a couple of times. Given the extent of the wash around the crater, Frill must have been quite active this summer.

Observed activity, noted by Paperiello in 1994, and again in 1996, shows that this geyser erupts in a series which lasts at least 6 hours or more. Intervals within that series are from 10 to 20 minutes with longer intervals occurring at the end of the series. (The last few intervals can be even longer). Durations are less than a minute. During a series, the water remains violently agitated within the vent. As the series continues, the water level within the vent and pool gradually gets higher, and less agitated. When the series ends the water drains to a few feet and then gradually fills over the next few hours.

In August, 1997, we finally saw a series of eruptions of Frill Spring. The above data represent most of a series of 15 eruptions. The series was seen in its entirety, lasting 167 minutes from the initial eruption to the final eruption. Just before the first eruption the pool rose and flooded the surroundings. Splashing then built to a 3-5 meter eruption. Between eruptions the water, churning and splashing violently, receded into the vent, occasionally sending jets to 1-2 meters. Intervals between eruptions were fairly constant throughout the series. Ten minutes after the last eruption there were two false starts, and 15 minutes later the churning water became suddenly placid and receded deep into the vent. We judged this to indicate the end of the series. By the next morning, 18 hours after the series began, Frill had filled up with water and was overflowing every 2½ minutes.

Frill Spring had another documented series of eruptions on 4 July 1997, seen by Clark Murray. Three days later on 7 July it was overflowing heavily every 8-14 minutes. We saw no eruptions that day, however.

Pearl Spring #32

1996: During a series of eruptions from Frill Spring seen by Paperiello in 1996, Pearl Spring was erupting every 5 minutes or so to about ½ meter. The eruptions were barely discernable after the series of Frill ended.

Unnamed Geyser (unnumbered)

1994 - 1996: South of Pearl Spring is a very small vent which does not seem to have merited a number on the map. But in 1994 and 1996, this vent was observed having small eruptions to about 10 centimeters about every 25 minutes. The eruptions would last less than 20 seconds. [Paperiello 1997]

Mangled Crater Spring #26

July 1988: probably active
July 1989: probably active
August 1990: active
July 1991: probably active
July 1992:
I = 92-108 minutes (4 closed intervals) Mean = 101, std.dev. = 6.7%
D = 5-20 minutes
July 1993:
I = 104-127 minutes (6 closed intervals) Mean = 119, std.dev. = 12%
D = 15-20 minutes
August 1994:
I = 92-128 minutes (4 closed intervals) Mean = 109, sdt.dev. = 14%
D = 15-20 minutes
August 1995:
I = 1 hr 27 min - 1 hr 59 min Mean = 1 hr 42min, (3 closed, 2 double intervals)
D = 15+ min (south vents)
D = 10-11 min (north vent)
August 1996:
I = 1 hr 32 min - 1 hr 52 min Mean = 1 hr 44 min, std.dev. = 7.41% (5 intervals)
D = 15+ minutes (south vents)
D = 9-11 minutes (north vent)
July 1997
I = 100-110 minutes. Mean = 104 (1 closed, 1 double interval)
D = 15+ minutes (south vents)
D = about 10 minutes (north vent)
H = 1-2 meters
August 1997
I = 103-107 minutes Mean = 104 (2 closed, 1 double interval)
D = 15+ minutes (south vents)
D = 9-12 minutes (north vent)

Notes: Heights have always been about 1 meter (occasionally 2 meters). This geyser has 3 erupting vents. The two to the south are in its main convoluted basin, while the north vent lies below a sinter shelf. The southern vents always started first, with minor splashing preceding the north vent by 10-20 minutes. While the south vents erupted the water level rises in the all vents, accompanied by some thumping which

Knobby Geyser 1991 Jeff Cross photo

could be felt and heard near the crater. When the water in the north vent begins boiling, the activity in the main crater becomes much stronger. A small vent to the east (#27) also may enter into the eruption. Vent #28 overflows after the eruption has continued for some time. The extensive preplay may have been the cause of some difficulty in estimating its durations in previous years. In 1997, discharge water was seen escaping from the main basin during the eruption -- this is unusual.

Mangled Crater Spring seems to have been vandalized in the past. In 1993 I discovered what looked like evidence that a substantial chunk of sinter had been chopped from the formation immediately surrounding the main vent. The indentation was concave and large enough that the detached peace could have weighed several pounds.

Grotto Spring #34

This pool used to be surrounded by several shelves of ornate sinter. Most of these shelves seem to have fallen into the pool in the last few years; it is unclear whether they fell in naturally or were helped by vandals and/or bison.

"Knobby Geyser" #24

July 1988: active, cyclic, H = > 3 meters
July 1989: active
August 1990: active, cyclic, H = 4-7 meters
July 1991:
"majors"
I = 2-4 hours (series start); 2 intervals
"intermediate"
I = 9-10 minutes (in series) or 17-19 minutes (last interval before major); 2 series of 4 eruptions each
D = up to 4 minutes ("majors" are longer)
H = 4-7 meters ("majors")
July 1992:
I = 4 hours, 38 minutes (series start); 1 interval
I = 3-5 minutes (in series); 2 complete series of 14 and 7 eruptions
D = 10-20 seconds
H = 1-2 meters
July 1993:
I = 3-4 hours (series start); 3 intervals
I = 5-8 minutes (in series); 5 series of 2 eruptions each; twice, a third eruption occurred after the series ended, 18 minutes in one case, 34 minutes in the other
D = 10-20 seconds
H = 1-2 meters
August 1994:
I = 2-4 hours (series start); 2 intervals
I = 3-10 minutes (in series); 3 complete series
D = 30-70 seconds
H = 1-4 meters
August 1995:
"minors"
I = 14 sec - 2 min 41 sec
D = 7 - 27 sec
H = up to 2 meters
"intermediate"
I = 9 - 11 minutes Mean = 10 min 11 sec, std.dev, = 4.6% (11 intervals)

D = 21 sec - 1 min 29 sec Mean = 50, std.dev = 28% (11 durations)
H = 2-3 meters
"majors"
I = 48 min - 2 hr12 min Mean = 1 hr 38 min, std.dev = 44% (5 intervals)
D = 2 min 29 sec - 4 min 16 sec Mean = 3 min 22 sec, std.dev. = 20% (5 durations)
H = 3-5 meters
August 1996:
"minors"
I = < 2 minutes
D = seconds
H = 1-2 meters
"intermediate"
I = 10 - 13 min or 17 - 18 min (19 intervals)
Mean = 11.8, std.dev. = 9.2% (of 15 "short" intermediate intervals)
D = 35 sec - 1 min 50 sec Mean = 64, std.dev = 30% (11 durations)
H = 2-3 meters
"majors"
I = hours?
D = 2½ - 6 minutes
H = 3-5 meters
July 1997
"minors"
I = minutes
D = seconds
H = 1-2 meters
"intermediate"
I = 11-13 minutes (6 intervals)
D = 25-82 seconds (9 durations)
H = 2-3 meters
"majors"
I = 4 hours (1 interval)
D = 3 and 5 minutes (2 durations)
H = 3-5 meters
August 1997
"minors"
I = minutes
D = seconds
"intermediate"
I = 9-12 minutes (mean = 636 std. dev. = 11.61% (7 intervals)
D = 20-85 seconds (mean = 58 std. dev. = 32% (11 durations)
"majors"
I = 7½ hours (1 interval)
D = 2 minutes (1 duration)

Notes: During the years from 1988 to 1995, Knobby has exhibited two different styles of activity.

In the first style of activity, observed from 1988-1991, and 1995-1997, Knobby's crater remained empty between eruptions. During 1990, 1991, 1995, 1996, & 1997 (and probably in 1988-1989) eruptions took any one of three forms which I have called minor, intermediate, and major. 1) Minors occur for up to 50 minutes following majors, and with short intervals of less than 3 minutes. They reach less than 2 meters and have short durations. 2) Intermediate eruptions often precede majors (but not always), and occur on intervals of about 10 minutes. [Note that in 1996 a few of these had intervals of 17-18 minutes]. They last between 1 and 4 minutes, and reach about 2 to 3 meters. 3) Majors occur on long intervals of 1 to 4 hours, last 2½ to 5 minutes, and reach 3 - 7 meters. In 1997 intervals from the last intermediate eruption to the major eruption were 2-6 minutes. In one case there were two of these short intermediate intervals prior to the major eruption. Minor eruptions continued for up to 1½ hours afterward.

The second style of activity was observed during 1992-1994. Knobby's crater remains full of water most of the time, possibly because cold water was entering from above. Eruptions tended to be small, under 2 meters, and both intervals and durations short. The multi-modal activity is not obvious. In 1996, a small steam vent just above the crater was making quite a "commotion" during Knobby's eruptions.

We have not found any strong relationship between Knobby and nearby Velvet Spring. Velvet was quite active in 1988 and again in 1994, while during Knobby's weak activity in 1992 and 1993, it still showed only very minor activity of 1 to 3 feet (or even less). Likewise, eruptions of one geyser seems to have no effect on the other.

North Group #23
July 1991: nearly invisible, inactive
July 1992: covered, inactive
July 1993: sputtering from sandy crater
August 1994: weak sputtering from sandy crater
August 1995: not active
August 1996: covered
August 1997: covered

North Group #20 (USGS #52) and **Bead Geyser #21** (USGS #53):
Notes: A few very small eruptions of #20 were

seen by Paperiello in the early 1980s. From our data, 1991-1995, water in both springs can rise and fall. In 1992 I noticed that their water levels vary sympathetically, one always being down when the other is up; the same has been true through 1995. In 1995, four timed cycles were 10-12 minutes. From 1992 through 1997, #20 has had a sand berm which completely encircled it, implying that there had at some time been eruptive activity without runoff.

"Snail Geyser" 1992 Paperiello photo

North Group #18 (USGS #51):

Notes: Boiling, at times intermittent (1991-1996). Splashed continuously in 1996 and 1997.

Small Geyser #16

1991-1994: minor intermittent activity
August 1995:
I = ~2 min
D = ~ 25-45 sec
H = up to 1 meter
August 1996: similar activity
August 1997: similar activity

Notes: In 1992 some splashes reached 2 meters. Usually, 1 meter seems to be more common; no overflow. In 1997 close observation of Small Geyser's basin and runoff channel suggested that it had had a brief episode of major activity. There was a faint sand berm around the north side, and faint wash marks lined the runoff channel.

Yellow Sponge Spring #6

1988 - 1997:
I = seconds
D = seconds
H = 1-3 meters

North Group #7a

Notes: Since 1993 I have been aware that the spouting from this long fissure stops erupting for a short period several times an hour.

Fissure Spring #2 (geyser, USGS #61), and **#4 "Snail Geyser"** (USGS #62):

1988-1989: dormant (Unnamed Spring #3 active with spouting vents).
July 1991: two eruptions seen; I = 3-6 hours?; D = 5-7 minutes
July 1992: two closed intervals, 2 hours 20 minutes and 2 hours 40 minutes; D = 4-8 minutes
July 1993: I = 2-3 hours (2 estimated intervals); D = 3-4 minutes
August 1994: I = two closed intervals, 3 hours 30 minutes, 3 hours 09 minutes; D = 4-6 minutes.
August 1995: dormant
August 1996: dormant
August 1997: dormant

Notes: When active, these geysers erupt together. Heights have been less than 1 meter. Overflow from

Velvet Spring 1994 Jeff Cross photo

#4 has preceded eruptions by 45-60 minutes. The water level in #3 has always dropped when #2 and #4 start erupting. The eruption from #4 continues for some time after its water level falls.

In 1991, the runoff channel from #2 looked quite fresh and recently cut, while the runoff channel from #4 looked recently enlarged. In the channel from #2 was a clump of grass; the outside was brown but the center was still green, implying that heavy overflow from #2 was a recent occurrence.

Despite clean runoff channels, no eruptions have been seen in 1995 and 1996. Activity has reverted to #3 which again has had periodic overflow and spouting vents around its edge. This exchange of function has been clear over the years.

I think that "Snail Geyser" is apt for #4-- the funnel-shaped crater looks something like a snail.

North Group #1 (USGS #66):

July 1992: cone is intermittent with reciprocal activity with nearby pool

July 1993: intermittent activity not seen

August 1994: cone is intermittent

August 1996: intermittent activity not noted

Velvet Spring #8

July 1988: active, H < 2 meters

July 1989-July 1993: intermittent overflow and boiling

August 1994: active

I = 12-15 minutes with extremes of 11-18 minutes, Mean = 13 minutes, 44 seconds (22 closed intervals)

D = 100-160 seconds

H = 1-3 meters

August 1996: barely active to about a foot

August 1997: frequent boiling eruptions, occasionally to 1 meter, but with not regular pattern.

Notes: The 1994 eruptions began from below overflow, usually when the water had risen to the level of the platform between the two vents. The eruptions were impressive; the upper vent surged throughout the eruption, and could get up to 3 meters; the lower vent burst in wide sloshes and usually reached 2 meters, though it occasionally reached 3 meters. Sometimes one vent would start before the other, in which case both were playing within 25 seconds. After an eruption the water dropped 1 meter in the lower vent and often boiled in the upper vent for a short period.

An interesting variation of the activity was the "delay." In a delay the water rose until an eruption was imminent and then ebbed without an eruption. This always resulted in a few minutes' delay, so that the interval was in the 15-18 minute range. We twice observed delays at about the time Knobby Geyser was finishing a series, but since we also observed delays at other times there probably was no relation between the two events.

Velvet was also active during my first visit to Shoshone in July of 1988, at which time it erupted to less than 2 meters on intervals that, as I recall, were over 10 minutes in length. Between 1988 and 1993 all I saw from Velvet was frequent overflow and occasional boiling episodes. We recorded enough of Velvet's overflow activity in 1992 to determine that it overflowed frequently but with no obvious pattern.

North Group #37

This spring, in the past, has received discharge from above. As a consequence, it is partially covered by a thin sinter sheet growing out from the uphill side of the formation. Though usually a quite spring, in July 1997, it was having continuous splashing to about 1 foot. [Paperiello 1997]

Glen Spring #10

August 1994: seen in eruption once
August 1995: weakly active
August 1996: no eruptions seen Aug 3-5, but definite minor eruptions a few weeks later by Paperiello.
August 1997: We saw no eruptions from this spring, though damp areas around the crater implied that it overflowed heavily at times, perhaps erupting also.

Notes: The single recorded eruption in 1994 was seen by David Goldberg, who reported that it was a series of widely spaced splashes from the back (northwest) vent, accompanied by turbulence and bubbling over the central vent and heavy overflow over much of the pool rim. The duration was in excess of 40 seconds. About an hour later, no further eruption had occurred, though heavy flow from the northwest vent occurred on intervals of about 8 minutes, sometimes accompanied by bubbling from the central vent.

North Group #13 (USGS #64):

July 1992: intermittent; I = hours
August 1994: intermittent; I = hours
August 1995: intermittent; overflow saturates area to the north and east
August 1996: intermittent overflow
July 1997: An eruption was seen by Paperiello to less than ½ meter in the morning, but no activity was noted later in the day.

Brown Sponge Spring #12

July 1992:
I = 20-30 min
D = 5-10 min
H = rolling boil
August 1995: active
August 1996: active
August 1997: active

North Group #63a

This small geyser erupts from a vent under a ledge at the uphill margin of a shallow basin in which are also located two pools. Draining the complex is a runoff channel which was formed during August 1996, but which has been enlarged since then. Though unseen, the activity must have been about ½ meter high and discharged a large quantity of water, judging from the wash and the size of the runoff channel. It was definitely active on 05 August, 1997

South Group

Flake Spring #11

July 1992: intermittent
August 1994: active as geyser, seen once
D = minutes
H = 1-2 meters (estimated)
August 1995: washed areas imply ongoing eruptions
August 1996: washed areas imply ongoing eruptions
August 1997: washed areas imply ongoing eruptions

Notes: Flake Spring erupted on 13 August 1994. As seen from across the creek at Geyser Cone in the Camp Group we at first confused it with Outbreak Geyser. What we saw of the eruption was large blue domes of water rising from two vents to about half a meter with splashes reaching about a meter; some splashes may have been higher (2 meters). I quickly crossed the river and came up on the end of the eruption, in time to see that the erupting vents were along the back (northwest) side of the crater, one vent in each corner.

The water was a little cloudy after the eruption and ebbed 15-20 centimeters before beginning to rise. The refilling was periodic with weak splashing from the northernmost vent. Ten minutes later it had not resumed overflow.

Flake had looked quite hot on the days previous, so it may have had other eruptions before the one we saw.

South Group #10
July 1992: active as geyser
July 1993: waving
August 1994: dormant, cold water
August 1995: dormant but hotter than last year
August 1996: hot but dormant
August 1997: hot but dormant

South Group #12 (Bryan SHO-7):
July 1988-August 1994: not seen
July 1993: drain
August 1994: vent filled with sediment
August 1995: vent cleared since last year, hot
August 1996: dormant, full of silt
August 1997: dormant

(1994 Blowout) #9
Notes: On 12 August 1994 I found what appeared to be a recent blowout in the midst of the terrace above Flake Spring and #10 and #12. Sinter sheets had been broken upward and thrown around a small crater which contained visible water, and a large bar of sand or sinter chips had been washed or thrown out of the crater and some distance down hill. No activity was seen in 1995 - 1997. It is gradually being sealed up by deposits.

"Outbreak Geyser" #8
1988-1990: active
July 1991:
I = 29-32 minutes (3 intervals)
D = 2 minutes
H = 3-6 meters
July 1992:
I = perpetual
H = 0.5 meters
July 1993:
I = 28-36 minutes, Mean = 31 minutes, 52 seconds (12 closed, 2 double intervals), std.dev. = 8.9%
D = 110-150 seconds
H = 2-3 meters
August 1994:
I = 25-36 minutes Mean = 30 minutes, std.dev = 9.2% (16 closed intervals)
D = 90-99 seconds (4 durations)
H = 1-2 meters
August 1995: perpetual spouting to ½ meter only
August 1996:
I = 33-39 minutes Mean = 36, std.dev. = 3.5% (16 intervals)
D = 1 min 41 sec - 2 min 34 sec (9 durations)
H = 1-2 meters
July, August 1997: dormant, continuous splashing to ½ meter.
Note: Splashing precedes most eruptions. The intervals we recorded in 1996 were very regular. However, when seen a couple weeks later by Paperiello, the intervals were occasionally erratic with periods of minor spouting from one vent in mid-interval. At these times intervals could be as long as 45 to 55 minutes.

South Group #4
(late) August 1995: active as a frequent small geyser [Clark Murray]
August 1996:
I = 5 min 20 sec - 11 min 56 sec Mean = 8 min 26 sec, std.dev. = 23.7% (9 intervals)
D = 1 min 33 sec - 3 min 28 sec Mean = 2 min 24 sec, std.dev. = 51.3% (9 durations)
H = 1 - 1½ meters
August 1997:
I = 510-593 seconds Mean = 548 std. dev. = 6.26% (4 intervals)
D = 82-129 seconds Mean = 102 std. dev. = 17% (5 durations)
H = 1-1½ meters
Notes: The geyser's pool is 4.2 meters northwest of the rim of Three Crater spring. It measures 1.8 by 1.2 meters. The erupting vent is 20 cm long At the southwest end of the pool, in the runoff channel, is another small spouting vent.
This geyser used to be flooded with cool water from Three Crater Spring. Sometime since August 1995, something broke the sinter rim (probably it was a bison -- we found bison prints in Three Crater Spring), and the overflow now issues from the break and flows around the geyser, rather than through it.

Coral Pool #2
July 1991: intermittent
July 1992: intermittent
August 1995: intermittent
August 1996: a small "eruption" seen by Paperiello -- barely a few small blurps over the vent
August 1997: intermittent

Island Group

Island Group #4a-c
July 1993: perpetual to 20-30 cm
August 1994: inactive
August 1995: dormant
August 1996: sputtering but no real discharge
August 1997: dormant

Western Group

Western Group #2 (USGS #132):
August 1994: thumping and bursting a little
August 1995: splashing, periodic?
August 1996: no periodic activity
August 1997: active as a geyser to ½ meter, intervals not determined

Western Group #10 (USGS #133):
August 1994: active as geyser, H < 1 meter
August 1996: no periodic activity
August 1997: no periodic activity

Western Group #9 (USGS #134)
August 1994: one vent burst and sputtered a little

Western Group #12
July 1991: active
July 1992: active
July 1993:
I = 11-12 minutes (2 closed, 2 double)
D = 1 minute
H = boil
August 1994:
I = 12 minutes (1 interval)
D = 1 minute
H = boil
August 1995: active
August 1996:
I = 23-24 minutes
D = 3-4 minutes
H = ½ meter
July 1997:
I = 25 minutes (1 interval)
D = 98 and 160 seconds (2 durations)
H = ½ meter

Notes: This old vent reactivated as a geyser in 1987; its beautiful sinter deposition has occurred since then. [Paperiello 1992] (In my 1991 Transactions article, I misidentified this spring as "Pecten Geyser.")

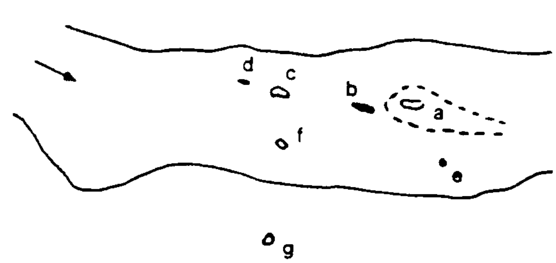
In 1996 intervals seem to have doubled. Eruptions begin with a rapid filling and overflow followed by bursting, which in turn continued as the water level dropped. A noisy boiling period ended the eruption. Discharge from this geyser kept #13 full of water.

"Pecten Geyser" #14 (USGS #136):
July 1992: active, H = 1 meter
July 1993:
I = 2-3 minutes
D = splash
H = 1 meter
August 1995: active
August 1996:
I = seconds
D = seconds
H = up to 1 meter
August 1997: perpetual spouter

Notes: This feature connects a small pool with a larger one with a short fracture vent. It is the fracture that usually erupts. At times it behaves more like a spouter than a geyser. This geyser has been much more active in recent years than in the later 1980s. [Paperiello] In 1996 eruptions actually came from the vent in the pool.

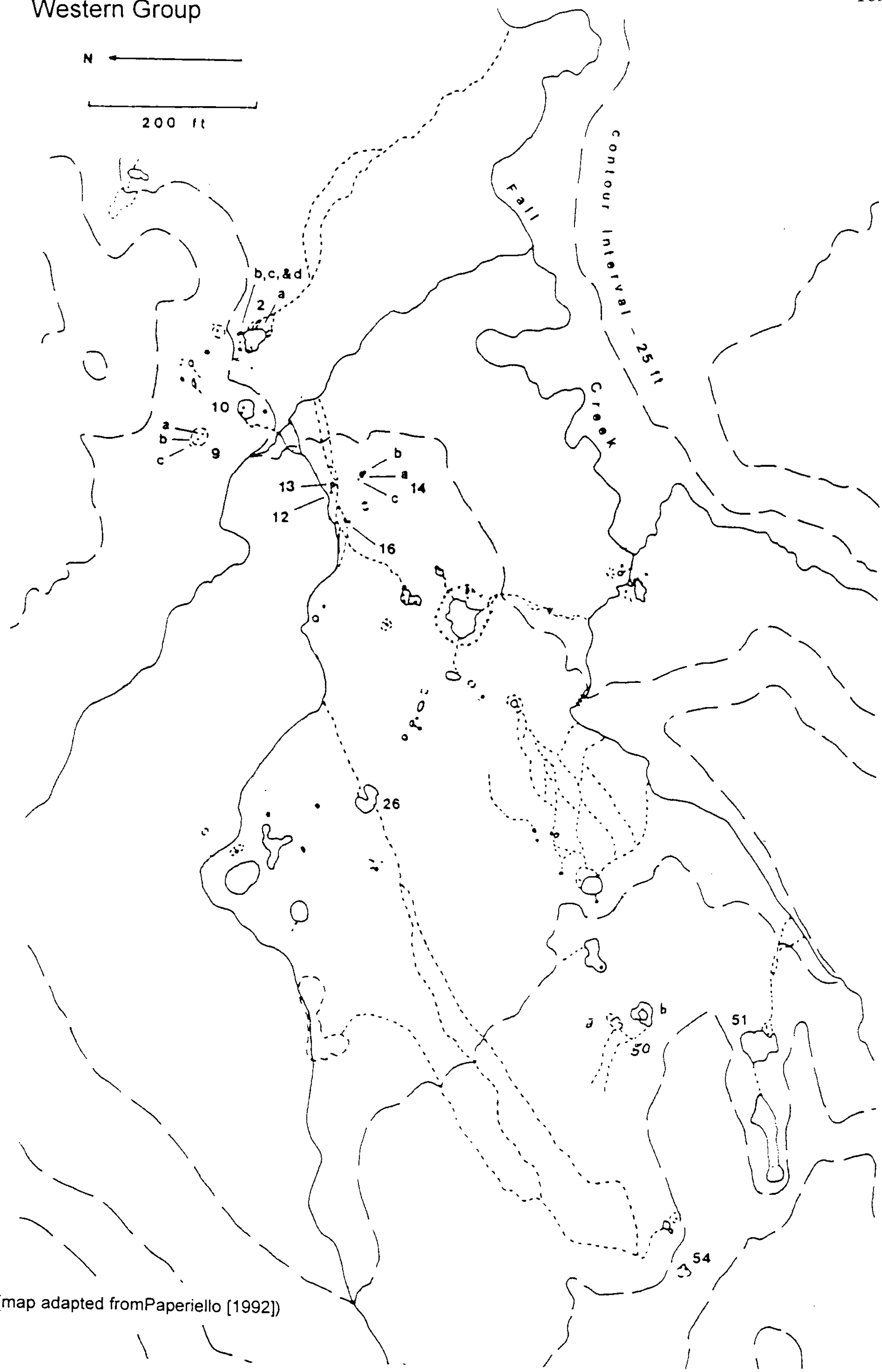
"Channel Spouters" #16(c & g)
August 1995: both active
August 1996: both active
August 1997: The south vent is a rather microscopic geyser erupting every few seconds to heights of several centimeters. It was active on both 7 July and 05 August 1997.

Note: A few of these vents (see below) have been periodic in the past. Only c & g have been seen active over the past two years. [Paperiello]



Western Group #16

Shoshone Geyser Basin
Western Group



(map adapted fromPaperiello [1992])

"Tunnel Geyser" #54
August 1994: audible splashing was periodic
August 1995: active
August 1996: a truly "buried geyser," its eruptions could only be heard
August 1997: Audible splashing was periodic; this vent is in a cave at the bottom of a deep pit at the upper end of the Western Group. Audible splashing was periodic; this vent is in a cave at the bottom of a deep pit at the upper end of the Western Group.

Notes: This spring has an interesting history. It was spouting from a new opening in the soft hillside in 1988. This coincided with a dramatic drop in the activity of Boiling Spring (#51), and the outbreak of two mud pots higher on the hill between them (#53 a and b). By 1991 it had became a bit more powerful, periodic, and its vent migrated deeper into the side of the hill. In 1992 you could still see it erupt through a small hole. By 1994 the vent was hidden deep in the hillside. I would suggest the informal name "Tunnel Geyser" for this feature.

SULPHUR HILLS GROUP

The new vent which opened up in 1994 was quite active in 1995 and was bubbling furiously. It has completely obliterated part of the old trail to the lake. In August 1996, this vent was flooded by a large acidic pond about 16 meters across.

"HORSE CAMP GROUP"

"Horse Camp Group" #2 (USGS #160):
July 1992: splashing
August 1994: geyser?
August 1996: acting more like a spouter than a geyser

"Horse camp Group" #15 (USGS #162):
August 1994: splashing to 50 cm
August 1995: active
August 1996: dormant

LAKE GROUP

Paperiello reported a small vent in this group near the lake was seen having small eruptions in August 1995 and in August 1996. (But without a map it is difficult to explain how to find it).

Unnamed Geyser (near isolated pine tree)
I = 43 and 44 minutes (2 intervals)
D = 50-60 seconds (3 approximate durations)
H = overflow and weak splashing

Note: This small geyser erupts from three vents: the north vent opens under a half-cone of sinter, while the south vents are about 1 meter away, 0.3 meters apart. A lone pine tree stands nearby. The cloudy grey water rose and fell periodically for most of the interval leading up to each of the three observed eruptions. Eruptions involved a brief overflow, waves, and minor splashing to heights of a few centimeters.

SHORE GROUP

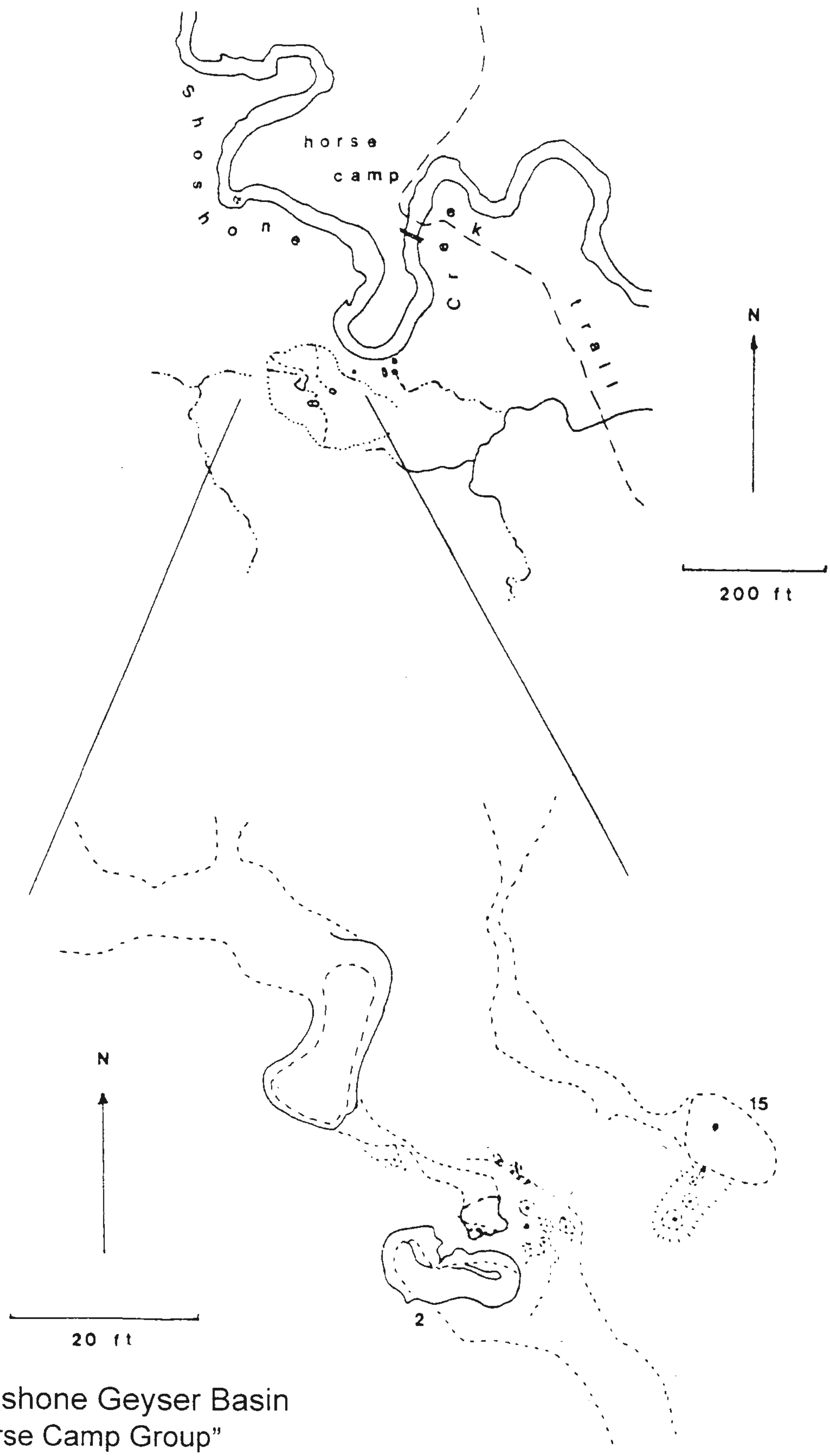
"Burning Eyes" & Unnamed Geyser

This geyser erupts from a small 5 by 7.5 cm hole on the north edge of a colorful orange/red formation containing two other spouting vents spaced 1.8 meters apart. This spouter has been was called "Burning Eyes" by Sam Martinez [1976].
August 1996: Three intervals (between "majors") of 29, 24, and 19 minutes were recorded. Durations were between 3½ and 4 minutes. This was its first known geyser activity since 1982.
August 1997:
I = 14 minutes (1 interval)
D = 2½-3 minutes (2 durations)
H = 1½ meters

Note: In 1996 and 1997, this geyser was having both major eruptions and minor eruptions, the majors reaching 1 to 1 ½ meters with loud sputtering and spraying. The minors began 6-10 minutes after the major and continued with occasional pauses until the next major. The water level in the northern spouter dropped during major eruption in the small geyser. The water from the geyser was clear but acidic.

Acknowledgments:

Many thanks to my sister, Tara Cross, my father, C.E. Cross, and Adam Johns, David Goldberg, and Michael Goldberg who helped me gather much of this data.



Shoshone Geyser Basin
"Horse Camp Group"

(map adapted fromPaperiello [1992])

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The following are a few excerpts from "A VAGABOND IN THE YELLOWSTONE," The Diary of Pat Quayle, Sept 4 - Oct 14, 1915, (handwritten, 288 pp.) YNP Archives:

Monday Oct 11, 1915

This summer past, having spent about forty days fishing upon this lake and keeping my eyes open for peculiarities I found several surprising phenomena at the west end of the Geyser Bay. . . which extends from the narrows to the swamps and sloughs at the base of the low miniture[sic] volcanoes beyond which on the banks of the Shoshone Creek are the geysers and hot springs. . .

Curiosity one day led me to pole and paddle around in the shallow estuary that we called Sulphur Bay because the water was too strongly impregnated with that mineral to taste good. I said pole and paddle because at times the bottom of the boat wud[sic] be scraping the fine clay mud, requiring poling across it. Suddenly it wud[sic] slip over the mud bar and be above the vast crater like hole in which the bottom and not be seen, hence paddling was necessary. Often many bubbles wud[sic] be rising from such places, and several times water was boiling up out of them, decidedly hot. Several mounds of (silicious ?) formation are to be found in Sulphur Bay, whence bubbles are continually rising.

This led to more discoveries made out beyond the sand bar cutting off the turbid shallow waters of Sulphur Bay from the main body of the lake. About half a mile out from the beach stretching clear across the lake is what we termed The Shelf. Along this shelf we wud[sic] make our best catches, so we trolled back and forth across the lake several times each day we were fishing. Beyond the shelf is deep blue water where the bottom cud[sic] not be seen under the most favorable conditions. On the shelf the depth is about fifteen to twenty feet getting more shallow as the beach is approached.

Just out from Sulphur Bay there are several irregular hot springs craters deep and black, some being a rod or two in diameter. Farther out towards the Shelf are formations like the Punch Bowl; several cones resembling those built up by active geysers were discovered on calm mornings when the bottom can be plainly seen.

One morning while traveling along with the Evinrude Motor we saw a crater of no insignificant size around which was set a triangular cordon of logs, on stakes driven into the surrounding soil, and this fully fifteen feet beneath the surface of the water. Who placed those logs around that crater? How long ago? Has Shoshone Lake risen about twenty feet? Here are some hieroglyphics [misleading facts] for the geologist to work upon. This might also throw some light upon that cordon of logs thickly encrusted with silicates that surrounds the Rustic Geyser in the Heart Lake Basin.

Splendid Geyser in 1985 and 1986

T. Scott Bryan

Abstract

During the unprecedented eruptive activity by Splendid Geyser during 1985 and 1986, it proved impossible to predict when an active series would begin or how long it would last. Within a series, however, there were some clear patterns. This paper summarizes a number of aspects of this activity, and relates the findings to Splendid's activity of 1996.

Introduction

Following its dormancy induced by the 1959 earthquake, Daisy Geyser rejuvenated in July 1971 [Wolf, 1979]. With it, Splendid Geyser was also active, and in fact most of Daisy's active episodes were initiated by eruptions of Splendid. Perhaps the only times in recorded history when Splendid had been more active were in the early 1800s and 1951-1952. However, as had been the case during the dormancy, Bonita Pool was the dominant member of the complex into 1978, and Daisy and Splendid had brief active periods only every 3 to 10 days.

In March 1978, an earthquake swarm struck Yellowstone. Bonita Pool essentially shut down, and the remainder of that year was a very good one for both Daisy and Splendid. Early in the year, Splendid's eruptions commonly occurred in series -- the initial (apparently) always triggered by falling barometric pressure. The next two years were not so good for Splendid. An series on November 2, 1980 ended that active phase [Strasser,1985]. Aside from a single play after the Borah Peak earthquake, Splendid became dormant for a few years, and Daisy became the dominant member of the group.

This changed in 1985. Early during that year Splendid had a few eruptions which occurred in series. Some concerted activity with Daisy also occurred. Then in July 1985, Splendid entered cyclic activity in which eruptive series consisting of 1 to 8 eruptions, recurred every few days. These series declined in frequency and vigor during October, and apparently ended with a short series on October 16-17. At least 57 eruptions took place during 1985. (See Table I).

The use of runoff channel markers indicated only one eruption (series) of Splendid took place between October 1985 and July 1986 (a lot of interpretation here -- the marker was in place in mid-March but was discovered missing in early May 1986). Then, after just three solo eruptions, Splendid entered another cycle of eruptive series. Similar to the activity of 1985 in most respects, these at first tended to be erratic, but they quickly settled down and included more eruptions per series. As with 1985, the action became less frequent and with fewer eruptions toward the end of the year. At least 107 eruptions took place during 1986.

Splendid continued to be active during 1987. It did not enter a winter dormancy as it had the previous year, but it also did not undergo extended eruptive series. It stopped playing in mid-summer after erupting just 26 times.

Splendid Geyser August, 1973 photo by T.Scott Bryan

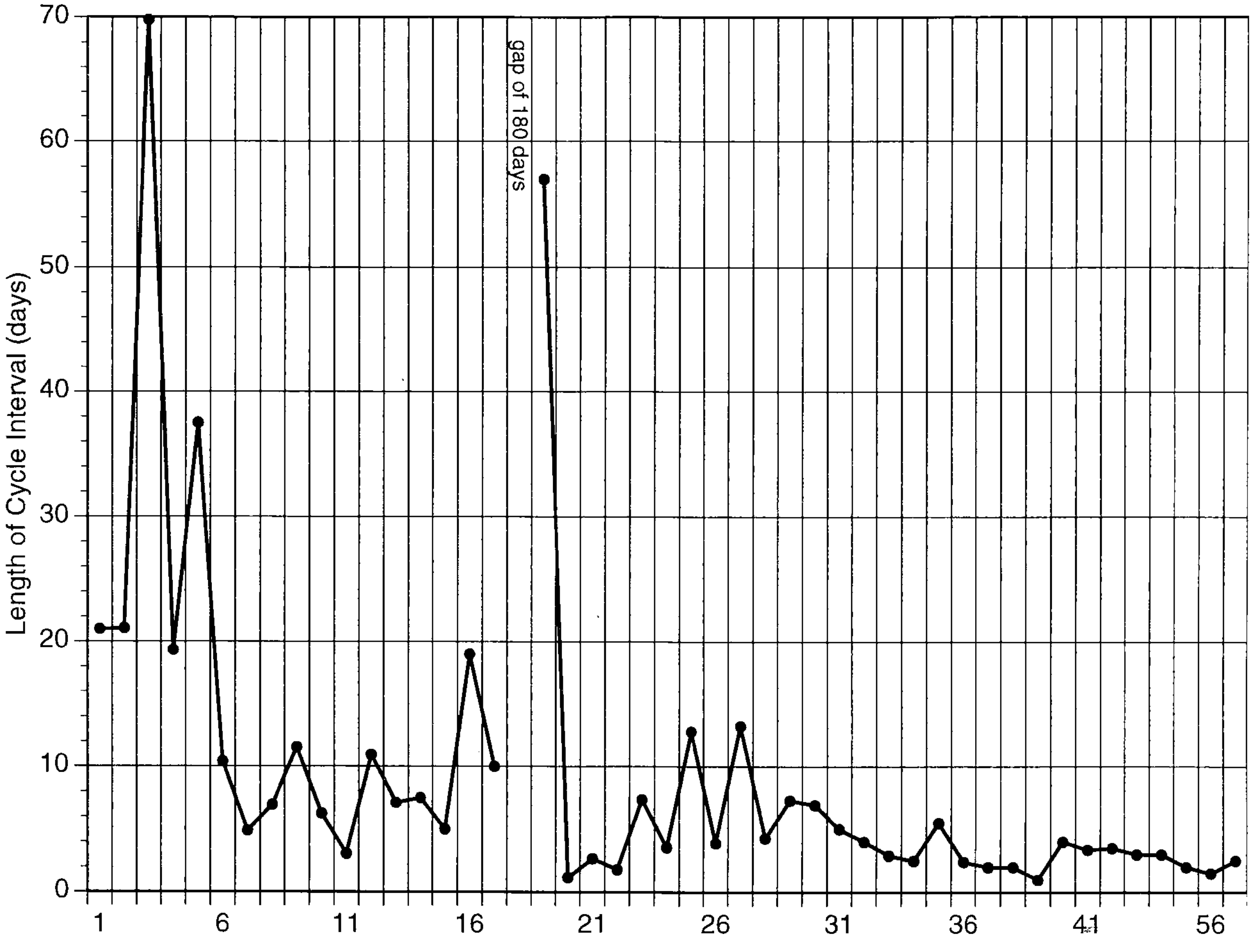

Figure 1. Sequential interval plot for Splendid Geyser cycle intervals. Rather than being a time–line chart, this simply gives the interval length versus each successive interval in order, thus showing the interval length trends through time. Note that the ±180 day interval of the 1985–1986 winter dormancy is not plotted.

General Activity Pattern

The detailed activity log for Splendid in 1985 and 1986 is presented here as Table I [Bryan, 1985 and 1986; Koenig 1990]. The comments column notes occasions when one or more eruptions went unseen. That such eruptions took place was clear both from the use of runoff markers and the fact that observers quickly became adept at judging the Daisy Group's activity status on the basis of water levels, degrees of boiling and surging, rates of crater infill, and the action of "Comet's Sputs." Note, however, that the analyses that follow in this paper are based entirely on observed eruptions and closed intervals.

Although Splendid tended toward shorter intervals between active episodes (herein called 'cycle intervals') as each season progressed, there was no clear pattern. As shown in Figure 1, the timing of Splendid's initial eruptions was not predictable. As will be pointed out later in this paper, it was not predictable in any respect— not even just a few minutes in advance.

Seasonal Control

Splendid underwent a few short eruptive series during the winter months of early 1985, then grew gradually more active as the summer progressed; 44 of the entire year's 57 eruptions (77.2%) took place in just ten weeks. Splendid was temporarily dormant from mid–October 1985 until July 1986 (there was probably a single eruption in April 1986). The renewed activity quickly built into vigorous series so that 77 of the year's 107 eruptions (72.0%) happened during August and September alone. These are only so many numbers, but a glance at Figure 2 shows that there was an extremely strong seasonal control to the activity.

The question, of course, is what was there about that time of the year that provided the con-

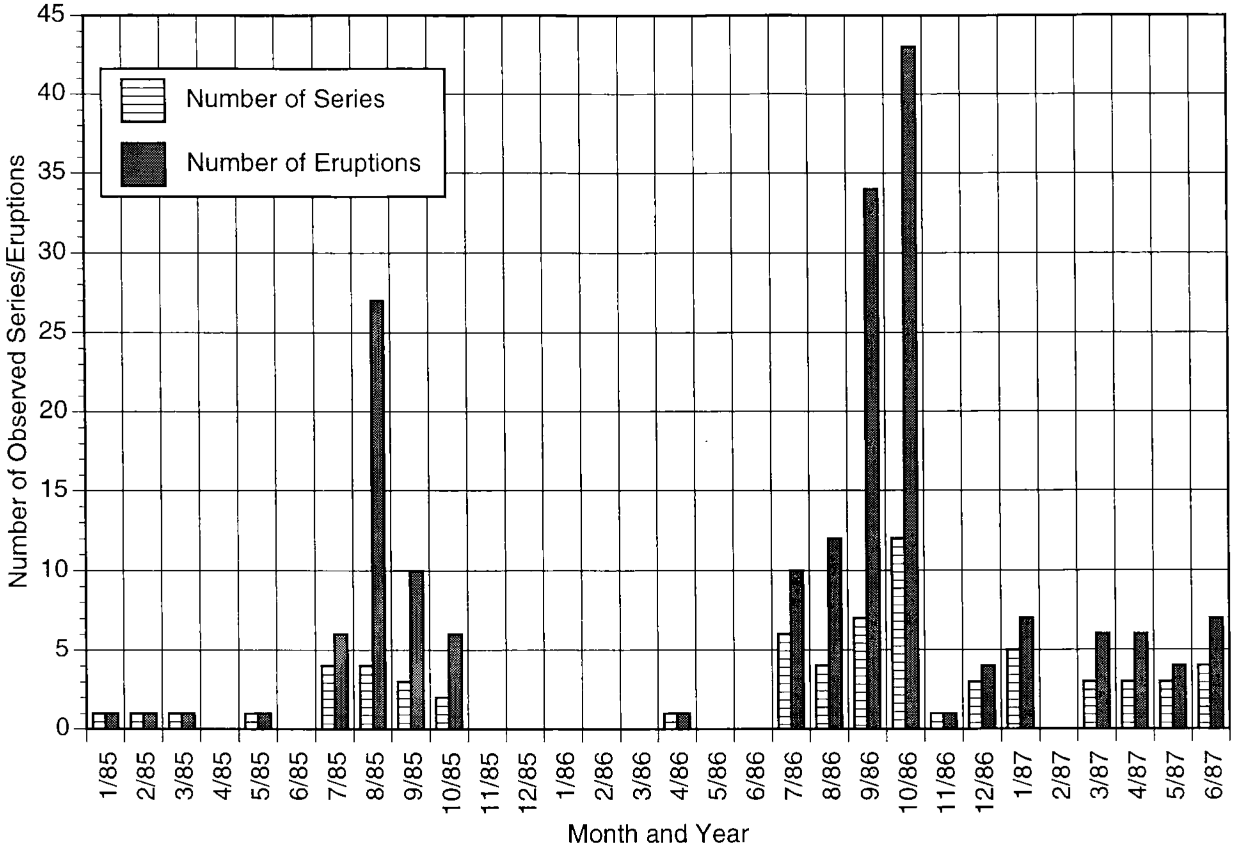

Figure 2. The eruption distribution given both by number of active cycles and by total number of eruptions, Splendid Geyser during 1985, 1986 and early 1987.

trol? The answer is probably barometric (atmospheric) pressure. It is known that Splendid is most likely to erupt during stormy weather, at about the time a storm front generated by a low pressure system passes over the park [Marler, 1973; Wolf, 1978]. On most occasions these pressure changes cause Splendid to surge more violently than usual following an eruption by Daisy, but they seldom yield eruptions. It is easy enough to see that if some sort of subsurface exchange of function channels more energy toward Splendid, then even slight pressure changes might trigger eruptions. That seemed to be the case in 1985 and 1986.

I have no barometric pressure data for 1986, but during 1985 a barograph recorder was maintained by J. Randolph Railey and Gerry Davies in the Old Faithful Visitor Center. I made it a regular practice to check the pressure, and how it was changing, on a daily basis. Whenever Splendid had an eruption, I noted the value of barometric pressure and its trend at the time. The results are shown in Table II. This data, which ends with my August departure from the park, made clear a number of points:

• With only the one certain exception of July 28, the barometric pressure *always* was falling at the time of the initial eruption of a series.

• On that July 28 exception, the pressure was rising at the time of the eruption but it had begun to rise following a sharp barometric low only two hours earlier.

• Although the pressure was dropping when the initial eruption took place, it usually began rising, if only briefly, a short time later. The effect was that Splendid somehow knew that the pressure would not drop further so that the time for an eruption was "now or never."

• The barograph, crudely corrected to equivalent sea level pressure, indicated that the readings were not particularly low. While Splendid did require that the pressure drop by some amount, it did not have to be either a large scale or a precipitous drop. On two occasions the total change was only 0.02 inch.

• Once Splendid had its initial eruption, subsequent eruptions of a series could take place regardless of what the barometric pressure was doing. Often, though, the general trend was for the pressure to continue dropping throughout an active period until the last eruption of a series. With no observed exception, the barometric pressure was *always* rising at the time of the last eruption in a series.

These points illustrate the barometric pressure control on Splendid, but they do not directly answer the question as to the seasonal control. I believe the two are tied together. During much of the summer season, Yellowstone is under the influence of the huge "Great Basin High," a broad high pressure air mass centered over Nevada and Utah. In the later summer this air mass grows weaker and allows more pressure variability. The result is an increase in late–summer eruptive activity. But then, why did the activity decline before the end of October? I do not know.

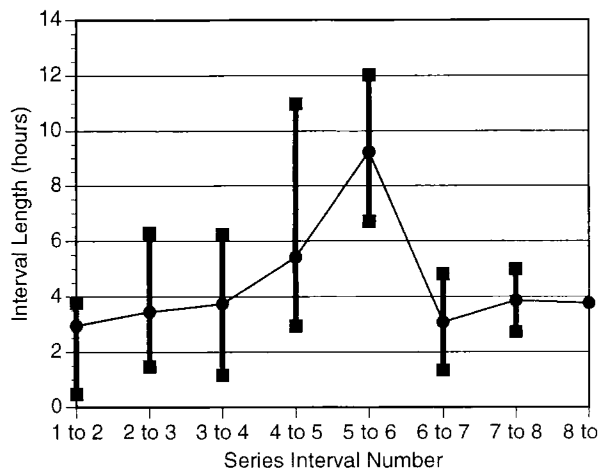

Figure 4. High–mean–low range chart for Splendid Geyser intervals, in–series 1985–1986. The ranges are actually overly large due to outlier intervals; in reality, each successive eruption in a series could be predicted with better–than–usual accuracy.

Eruptive Series

Splendid seldom had solo eruptions during its late–summer active episodes. Instead, there were series of individual eruptions; the number of plays per series ranged from two to twelve but usually was in the range of three to eight (Figure 3). While the timing of eruptive series themselves could not be predicted, both the intervals and durations of eruptions within a series tended to be quite regular.

Intervals Within A Series

In every case, the data for in–series intervals shows a wide range (Figure 4). In part this is because of outliers in the data; they are included, even though they are not representative. Nevertheless, it is clear that subsequent intervals generally, and quite regularly, increased in length through the first five series intervals (that is, up to series eruption #6). The intervals then dropped sharply so that further eruptions in a series took place on intervals as short as the first. In this case, the effect was almost as if the longer series were two separate series back–to–back. (This was not really the case, as shown by the water levels that did not recover to non–Splendid heights between the eruptions.)

Because of this pattern, it was possible to quite accurately predict the time of the next Splendid eruption in a series— or perhaps more accurately stated, when the next would take place *if* it took place. It was impossible to predict the length of a series; it was impossible to know whether or not an eruption #6 would follow #5.

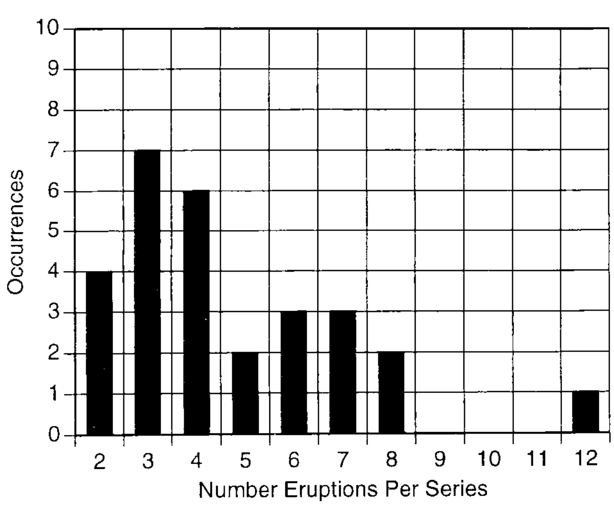

Figure 3. Column chart showing the number of occurrences versus number of eruptions per active series, Splendid Geyser 1985–1986.

Durations Within A Series

Splendid's durations also showed a clear pattern. The data set contains outliers, but the initial eruption of a series was uniformly shorter (average about 3.5 minutes) in duration than the others (average greater than 5 minutes), as shown in Figure 5.

Last Daisy Before Splendid

As noted earlier in this paper, it proved impossible to predict when an active period of Splendid would begin; it was not possible to do so even moments before the initial eruption. Some gazers held "Comet's Sputs"— a number

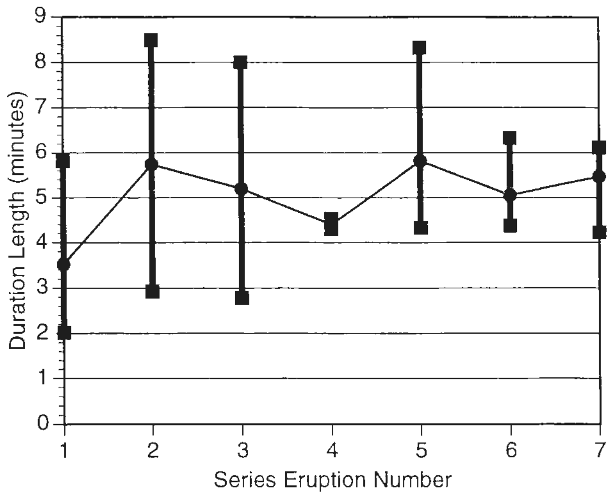

Figure 5. Relationship of eruption duration to in–series eruption, Splendid Geyser 1985–1986.

of small spouters near the west base of Comet's cone— to be reliable indicators. It is true that they are normally active only when Splendid is active, and it is possible that they respond to barometric change more readily than does Splendid, but evidence for this is far from conclusive.

Recent observers have often equated potential activity in Splendid with exceptionally long intervals in Daisy, apparently feeling that the lack of action in Daisy must surely force an eruption to occur elsewhere in the complex. Although this idea generally is not supported by history, the earthquake of June 30, 1975 did produce this relationship for about a month [Marler, 1978]; it was, however, both earthquake–induced and very short–lived. The 1985–1986 data does not support such a hypothesis. In fact, the last Daisy interval prior to an initial Splendid was entirely normal in both years. In 1985, the last Daisys averaged 89.5 minutes when the total yearly average was 85.6 minutes. In 1986, the last Daisys averaged 90.5 minutes in a year with an overall average of 91.8 minutes. The differences are insignificant and fall well within the normal interval ranges shown by Daisy in those years. Simply put, Daisy gave absolutely no indication of an impending Splendid.

It can be argued that a long Daisy interval is apt to be as bad for Splendid as it is for Daisy. Whether it is a wind–caused surface energy loss or a more deeply seated energy lack would make little difference in a system of geysers as intimitely related as these.

Last Daisy To First Splendid

In recent years, observers have mostly looked for Splendid to erupt within a few minutes of a Daisy eruption. Such was not the case in 1985–1986. The data for this was quite sparse, but it showed that Splendid began its initial eruption at about the time when Daisy filled and began its first preplay activity. The average lag time for the two years combined was 66.2 minutes, 20 to 25 minutes shorter than a normal Daisy–to–Daisy interval.

(The eruptions of Splendid during 1996 also initiated about 70 minutes after Daisy, but with much longer average Daisy intervals this was some 15 to 20 minutes prior to rather than at the onset of Daisy's preplay. Some observers expressed that this equated to significant functional differences within the plumbing systems. I disagree. During the early 1970s, eruptions by Splendid could be related to increased activity in Bonita Pool, and there were fairly clear indications that Bonita, like nearby Radiator Geyser, was more closely related to Splendid than to Daisy [Wolf, 1978]. In my speculative opinion, the 1996 pattern might be due to a comparitive lack of action in Bonita Pool, now a very different hot spring which no longer splashes or overflows as it did during the 1970s and 1980s. Certainly there are additional plumbing system considerations, but I believe that the 1996 eruptions were happening at the proper time with respect to Daisy, and that the Daisy Group was operating in the same fashion on both occasions.)

During the 1990s we have occasionally witnessed a "new" type of eruption, sometimes called a "post–Daisy minor." These eruptions, which typically last only about 1 minute and reach 50 to 70 feet high, have taken place within the first few minutes after Daisy. This is a very different form of activity, and probably should not be related to true major eruptions and eruptive series by Splendid.

Not Predicting The End Of A Series

During an active series by Splendid, Daisy continued to erupt. Many of these eruptions were in concert with Splendid (see next section). Daisy's intervals showed very wide ranges and sometimes approached the yearly normal during long Splendid intervals. It seemed likely that Daisy's in–series versus after–series interval might be different so as to show the end of Splendid's activity. Not so. For 1985 and 1986 combined, the average of all recorded in–series Daisy intervals was 188.8 minutes. The average

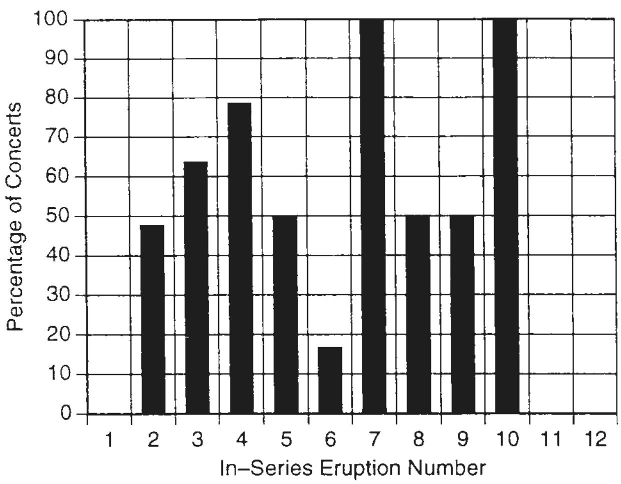

Figure 6. Percentage of observed eruptions that were Splendid–Daisy concerts, 1985–1986.

of all recorded first after–series intervals was 189.3 minutes. Daisy showed no immediate response to the end of Splendid's activity, and in fact required 6 to 8 hours to return to its non–Splendid seasonal norms.

Concerted Eruptions

Concerted eruptions, that is, simultaneous eruptions by both Splendid and Daisy, became an ordinary part of the eruptive series of 1985 and 1986. Among multi–eruption series, only one in 1985 and four in 1986 failed to include at least one concert, and during the remarkable series on September 23–25, 1986 seven of the twelve eruptions were in concert.

Concerted eruptions were amazing sights. Splendid usually began the show; only 2 of 47 concerts were induced by Daisy. The usual Splendid–to–Daisy lead time was between 1 and 2.5 minutes. Daisy showed little action until its own eruption actually started from a lowered water level. Splendid in concert was seldom less than 150 feet high, and it commonly approached 200 feet; although it was several years prior to this study, Splendid in 1973 was accurately triangulated during a concert at 218 feet tall [Paperiello, 1985]. Daisy was often triangulated by hand–held inclinometer in excess of 100 feet, and it exceeded 150 feet several times. Daisy during the concerted play ordinarily lasted more than 4 minutes, and some durations were greater than 5 minutes.

The frequency of concerted action during a Splendid series varied with eruption number (Figure 6), and it is believed that the differences were real even though the data was quite sparse. Two points can especially be made:

- The initial eruption by Splendid was never in concert.
- The sixth eruption by Splendid, which is the same that was preceeded by the longest in–series intervals, was seldom in concert.

"Jam Sessions"

A brief note should be made of the so–called "jam sessions" that occurred during Splendid's eruption series. In essence, these were system attempts to undergo concerted eruptions. Daisy started to play a minute or two after Splendid had started, but then quit after a relatively brief and weak duration. For some reason, jam sessions were considered at the time as outright failures, and they often went unrecorded.

During a jam session, the eruption by Daisy usually reached between 20 and 30 feet

Splendid Geyser August, 1973 photo by T.Scott Bryan high for a duration of 40 to 90 seconds. At the same time, Splendid tended to be weak, sometimes reaching less than 100 feet high until Daisy quit, when the sudden, massive jetting to redoubled heights was among the most amazing of all geyser spectacles.

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Author's Note: This paper is a revised and abridged version of a report I produced in late 1986. It is based entirely on personal notes and recollections, plus a few late–season observations supplied to the author by Ranger–Naturalist Dan Ng in October 1986.

Thanks to Heinrich Koenig for producing the GOSA Archives Data Logs, which allowed me to double check and fill out my tattered original records, and to Paul Strasser and Gordon Bower who refereed this manuscript and, with their very different perspectives, corrected numerous awkward and unclear statements, and some historical stumbles.

Dual eruption by Daisy (left) and Splendid Geysers
August, 29,1985 photo by T. Scott Bryan

Table I
Splendid Geyser Activity, 1985–1986

Date	Time Splendid	Duration Splendid	Interval In–Series	Interval Cycle	Concert Daisy Time	Comments
1/18/85	1435					
2/08/85	1520			21d 00h 45m	1520	v.r.; concert indicates not initial eruption of series
3/01/85	1818			21d 02h 58m	1820	v.r.; concert indicates not initial eruption of series
5/10/85	1355			69d 19h 37m		no intervening activity per markers
5/29/85	2200			≈19d 08h		v.r.
7/06/85	0940			≈37d 12h	0935	rare concert initiated by Daisy
7/16/85	1934			10d 09h 54m		
7/21/85	1700			4d 21h 26m		Splendid time accurate
7/28/85	1615	≈2m		6d 23h 15m		
	1732	5m 37s	1h 17m			
	2024	8m 00s	2h 52m			
8/08/85	0530			11d 13h 15m		
	0918	2m 56s	3h 48m			
	1112	2m 47s	1h 54m			
	1237	4m 21s	1h 25m		1239	concert
	1734	4m 20s	4h 57m			
8/09/85	0100		7h 26m			Splendid time accurate
8/14/85	1134	4m 18s		6d 06h 04m		
	1316	6m 21s	1h 42m		1318	concert
	1751	4m 43s	4h 35m			
	2151	4m 24s	4h 00m			

8/15/85	0850	4m 50s	10h 59m			
	1830	4m 27s	9h 40m			
	1951	4m 14s	1h 21m		1952	concert
8/17/85	1333	2m 05s		3d 01h 59m		
	1645	5m 42s	3h 12m			
	2045	4m 44s	4h 00m			
8/18/85	0300		6h 15m			Splendid time accurate within minutes
	0741	8m 20s	4h 41m		0743	concert
	1943	≈3m	12h 02m			
8/19/85	0000	6m 03s	4h 17m		0002	concert; time accurate
	0500		5h 00m			Splendid time accurate
8/28/85	1210	2m 01s		10d 22h 37m		
	1351	6m 32s	1h 41m			
	1657	4m 25s	3h 06m		1659	concert
	1936	≈4m	2h 39m		1937	concert
8/29/85	0103	6m 34s	5h 27m		0105	concert
	0746	6m 20s	6h 43m		0748	concert
9/04/85	1542	2m 30s		7d 03h 32m		
	1611	4m 09s	0h 29m			
	1857	4m 37s	2h 46m			
	2007	4m 32s	1h 10m		2009	concert
9/05/85	0211	4m 23s	6h 04m			
	1301	4m 23s	10h 50m			
	1452	6m 07s	1h 51m		1453	concert
9/12/85	early am			≈7.5d		believed a solo eruption
9/17/85	early am			≈5d		
	1618	8m 05s	>12h?			
10/06/85	early am			≈19d		
	1358	8m 30s			1358	concert
	1926	≈5m	5h 28m			
10/07/85	0938	≈5m			0939	concert; overnight unknown
10/16/85	active			≈10d		
10/17/85	active					

end of 1985 data; evidence from on–site observations and markers is that no further eruptions occurred until after mid-March 1986

May/86	-----					marker found gone in early May (date uncertain)
7/05/86	2124	4m 57s		>57d		solo eruption
7/07/85	early am			≈1d 04h		solo eruption?
7/09/86	1705			≈2d 16h		solo eruption
7/11/86	1157	≈5m		1d 18h 52m		
	1310	5m 17s	1h 13m		1311	concert; end of series
7/18/86	1828	5m 49s		7d 06h 31m		
	2056	6m 27s	2h 28m		2058	concert; end of series
7/22/86	0759			3d 13h 31m		
	1442		6h 43m			
	1637	6m 07s	1h 55m			
8/04/86	0300			≈12d 19h		Splendid time estimated
	0511	≈6m	≈2h		0512	concert
	1040	6m 20s	5h 29m		1042	concert; end of series
8/08/86	0000			≈3d 21h		v.r., estimated time
	0230		≈2h 30m			v.r., estimated time
	0848	6m 19s	≈6h 18m		0850	concert; end of series
8/21/86	0530			≈13d 05h 30m		estimated time; ?not first of series
	0758	3m 44s	1h 28m		0759	concert
	1103	5m 11s	3h 05m			
	1339	4m 18s	2h 36m		1340	concert; end of series
8/25/86	1207			≈4d 06h 37m?		
	1416		2h 09m		1419	concert; end of series
9/01/86	1917	2m 15s		7d 07h 10m		
	2059	6m 31s	1h 42m			
9/02/86	night					at least 1 eruption overnight
	0825					
	0954	6m 30s	1h 29m		0957	concert; end of series

9/08/86	1752	4m 14s		6d 22h 35m		
	1902	4m 44s	1h 10m			
	2153	3m 56s	2h 51m		2154	concert
9/09/86	night					believed single eruption to end series
9/13/86	1825			5d 00h 33m		solo eruption
9/17/86	missed?			≈4d		initial eruption probably missed
	2054				2054	concert
	night					
9/20/86	1623			≈2d 22h		
	night					at least 1 eruption overnight
	0934				0935	concert
9/23/86	night			≈2d 12h		probably 2 or more eruptions overnight
	0927	≈7m			0929	concert
	1349	≈4m	4h 22m		1351	concert
	1650	≈5m	3h 01m		1652	concert
	1915		2h 25m		1915	concert
9/24/86	0400		≈8h 45m			estimated time
	0850		≈4h 50m		0852	concert
	1133	≈4m	2h 43m		1135	concert
	1519	≈4m	3h 46m		1520	concert
9/25/86	night		>7h			at least 1 eruption overnight
	1024	≈4m				end of series
9/28/86	1545			≈5d 12h		
	1731	≈4m	1h 46m			
9/29/86	night					probably 1 eruption overnight
	0616				0618	concert
	1006	≈5m	3h 50m		1005	rare concert initiated by Daisy
	1345	≈4m	3h 39m		1346	concert
	1830	≈5m	4h 45m			end of series
10/01/86	0200			≈2d 10h		estimated time
	0721	≈4m	≈5h			
	1047	≈4m	3h 26m		1048	concert
	1513		4h 26m		1514	concert
10/02/86	night		>10h			end of series

10/03/86	night			≈2d		
	1022	≈6m				eruptions probably missed
10/05/86	night			≈2d		solo eruption?
10/06/86	night			≈1d		
	0945					
	late eve		≈12h			
10/07/86	night					probably single eruption missed
	1149		>5h			
	1409		2h 20m		1410	concert
	1817		4h 08m		1817	concert
10/08/86	night		>6h			
10/10/86	night			≈4d		
	0836				0836	concert
	1515		6h 39m			
10/13/86	1246			≈3d 09h		
	evening		>9h			
10/14/86	1016					intervening eruptions probably missed
	1338		3h 22m		1340	concert; end of series
10/17/86	night			≈3d 12h		probably 2 or more eruptions missed
	1606		>9h			
10/18/86	night					
	1116				1117	concert
	1641		5h 25m		1642	concert
	night					
10/20/86	morning			≈3d		eruption probably 0600-0700
	1318		>6h		1320	concert
	1616		2h 58m		1618	concert
10/21/86	night					
10/24/86	night			≈3d		
	0937					
	1315		3h 38m		1316	concert
	1829		5h 14m		1831	concert; end of series
10/26/86	night			≈2d		solo eruption?

10/27/86	1710		≈1d 12h		
10/28/86	night	>5h			
10/30/86	night		≈2d 12h		probably 2 or more eruptions missed
	1329	>5.5h		1331	concert
10/31/86	night	>9h			
11/05/86	active				
12/02/86	1126				
12/23/86	1058			1100	concert; not initial
	1408	3h 10m		1408	concert
12/25/86	1230				v.r.

end 1986 data

Table II
Splendid Geyser, 1985 Barometric Pressure Data

Date	Time	Barometer *	R, F, S **	Barometric Trend, Previous 24–Hour Period
1/18/85	1435	30.08	F	nearly steady, total drop <0.10 inch
2/08/85	1520	29.60	R	not initial eruption; pressure dropping shortly before
3/01/85	1818	29.85	F	steady storm system fall from 30.13
5/10/85	1355	no data		logbook reported snow this date
5/29/85	2200	29.95	S	pressure wavering, essentially steady
7/06/85	0940	30.36	F	slight pressure drop just after high for 24 hours; highest pressure ever recorded for initial eruption
7/16/85	1934	30.22	F	lowest pressure in 24 hour decline
7/21/85	1700	30.13	F	low point of sharp drop followed by rapid rise
7/28/85	1615	30.25	R	low of 30.21 recorded at 1400
	1732	30.27	R	
	2024	30.28	S	end of series
8/08/85	0530	30.09	F	24 hour low, down from 30.28
	0918	30.12	R	
	1112	30.13	R	
	1237	30.14	R	
	1734	30.16	S	
8/09/85	0100	30.24	R	rising rapidly; end of series
8/14/85	1134	30.24	F	steady drop began 0000, continued for 42 hours
	1316	30.20	S	
	1751	30.17	F	
	2151	30.17	S	
8/15/85	0850	30.10	F	
	1830	30.03	F	
	1951	29.99	S	lowest pressure in over one week; end of series
8/17/85	1333	30.22	F	slight drop (0.02 inch) from 30.24 at about 0800
	1645	30.21	F	
	2045	30.22	R	
8/18/85	0300	30.23	S	
	0741	30.26	R	
	1943	30.24	F	low point of brief pressure dip
8/19/85	0000	30.28	R	
	0500	30.31	R	end of series
8/28/85	1210	30.32	F	drop less than 0.02 inch
	1351	30.32	S	
	1657	30.28	F	
	1936	30.26	F	
8/29/85	0103	30.28	R	
	0746	30.33	R	rising rapidly; end of series

* — Barometric pressure in inches of mercury, read from electric barograph corrected for altitude.
** — R = rising pressure; F = falling pressure; S = steady or irregularly wavering pressure.

Hillside Geyser at West Thumb

by

David Monteith

ABSTRACT: Hillside Geyser at West Thumb Geyser Basin was active in the Fall on 1995. The following report describes the results of three days of observation of this geyser during late September 1995.

Hillside Geyser at West Thumb Geyser Basin had its first verified major eruption since 1948 on August 24, 1995 [1]. Most knowledgeable geyser observers who saw subsequent eruptions gauged the height to be 12-15 meters (40-45 feet). Some visitor reports, however, estimated heights to be as much as 20-30 meters (70-100 feet) [2]. Whatever its height, Hillside was still an impressive geyser.

Little systematic observation of Hillside Geyser was undertaken during its active periods in 1995 or 1996. The following is a report of observations taken over a three day period, September 22-24, 1995. Little is known about the activity prior to this period except that Hillside was active with eruptions occurring sporadically.

Hillside erupted three times over the three days of observation. (See Table 1). There is not enough data to determine if this activity was exceptional. During the period of observation, Hillside was seen to overflow gently for many hours prior to an eruption. During this time of overflow, there was nearly constant sizzling around the edges of the pool and an arc shaped area of light boiling along the edge of the pool nearest Yellowstone lake. It was often possible to see convection currents over the geyser's vent. In addition, every few minutes there were also very small upwellings and surges accompanied by light boiling .

Hillside Geyser appeared to go through three to four hour cycles. During most of this period it looked as described above. Then it appeared to heat up. The size of the surges and the amount of bubbling over the vent increased slightly. After 30 minutes to an hour, the geyser appeared to cool down and the cycle repeated. After the stronger of these periods, the pool dropped about one to two inches below overflow. Only at this time did the overflow completely stop. The water level then quickly rebounded. After a few minutes the overflow started again, but the activity appeared to subside.

The September 24 eruption was the only one that this observer saw from the beginning and at close range. The recorded times for this eruption are shown in Table 2. It started with little warning. The geyser looked as though it may have been heating up and entering one of its warmer periods, but the differences were so slight that it was hard to tell. The first indication that something unusual was happening was a sudden half meter splash from the geyser. This was the only splash seen over more than 13 hours of continuous observation. The geyser then boiled vigorously for about 15 seconds, and the eruption started. The early stages of the eruption emptied the geyser's pool. It was characterized by vigorous bursting play of 3 to 4 meters (10-12 feet). About 40 to 60 seconds into the eruption, as the pool was emptied, the play slowly changed into a vertical column. The maximum height of the column, 12 to 14 meters (40-45 feet), was reached about 90 seconds into the eruption and was sustained until just before the water gave out. The nearly vertical column was about the diameter of the pool, about 2 meters (6 feet), and was possibly angled at about 5 to10 degrees towards Yellowstone Lake. The column had a very feathery appearance; it was possible to see through it. The eruption was ended by a quiet forced steam phase lasting about 1½ minutes. The total duration of the eruption was 6 minutes 25 seconds.

After the eruption, the crater steamed quietly and no water could be seen. It took 4 hours, 45 minutes for the crater to refill and for the geyser to start overflowing again.

Hillside Geyser David Monteith Photo

Table 1. Eruptions of Hillside Geyser September 22-24, 1995

Date	Time	Approximate Interval
Sept. 21	7:36*	
Sept. 23	13:37**	20 hours
Sept. 24	17:59	28.5 hours

* Observation started only after the eruption began. The eruption looked similar to that seen on September 24. The duration was greater than 5 minutes.

** This eruption was seen and reported by one of the naturalist staff from Grant Village.

Table 2. September 24th Eruption of Hillside Geyser

Time	Activity
17:59:05	2 foot splash followed by heavy boiling
17:59:20	Eruption Starts
18:00:54	Maximum Height Reached, 12-14 meters
18:04:24	Water turns to steam. Duration of water 5min 4sec.
18:05:45	End of forceful steam. Duration of steam 1min 20 sec.
22:50	Start of overflow. Time for overflow to restart 4.75 hours.

References:

[1] *The GOSA Sput*, October 1995, Vol 9, No 5, pg 1.
[2] *The GOSA Sput*, August 1996, Vol 10, No 4, pg 4.

Hillside Geyser David Monteith Photo

Giant Geyser

by

David Monteith

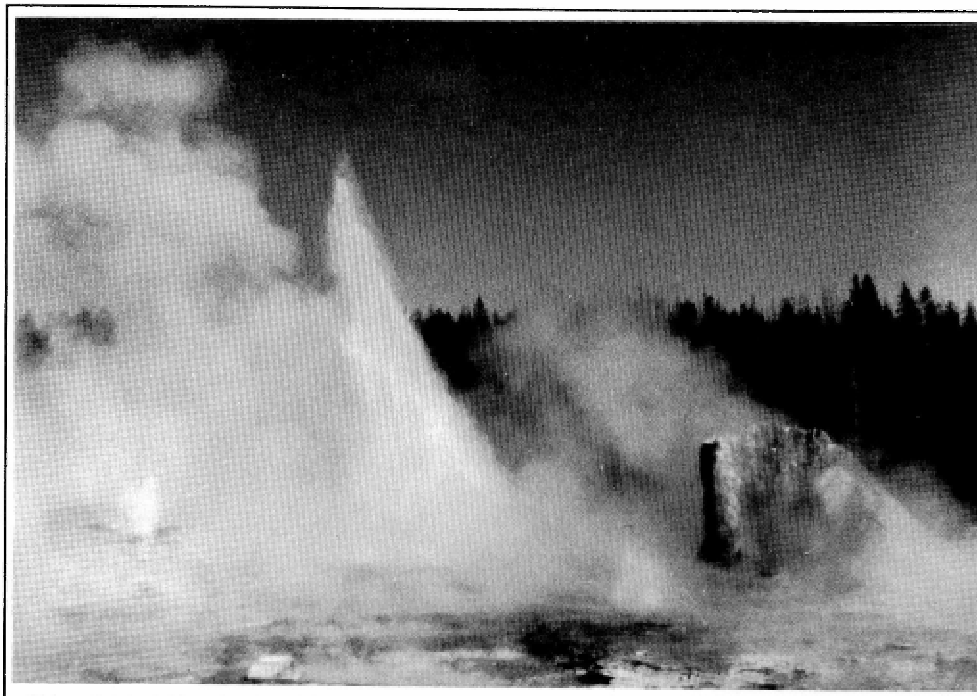
The Giant eruption of September 25, 1995:

Giant Geyser Monteith photo

Giant Geyser at about midway into the eruption.

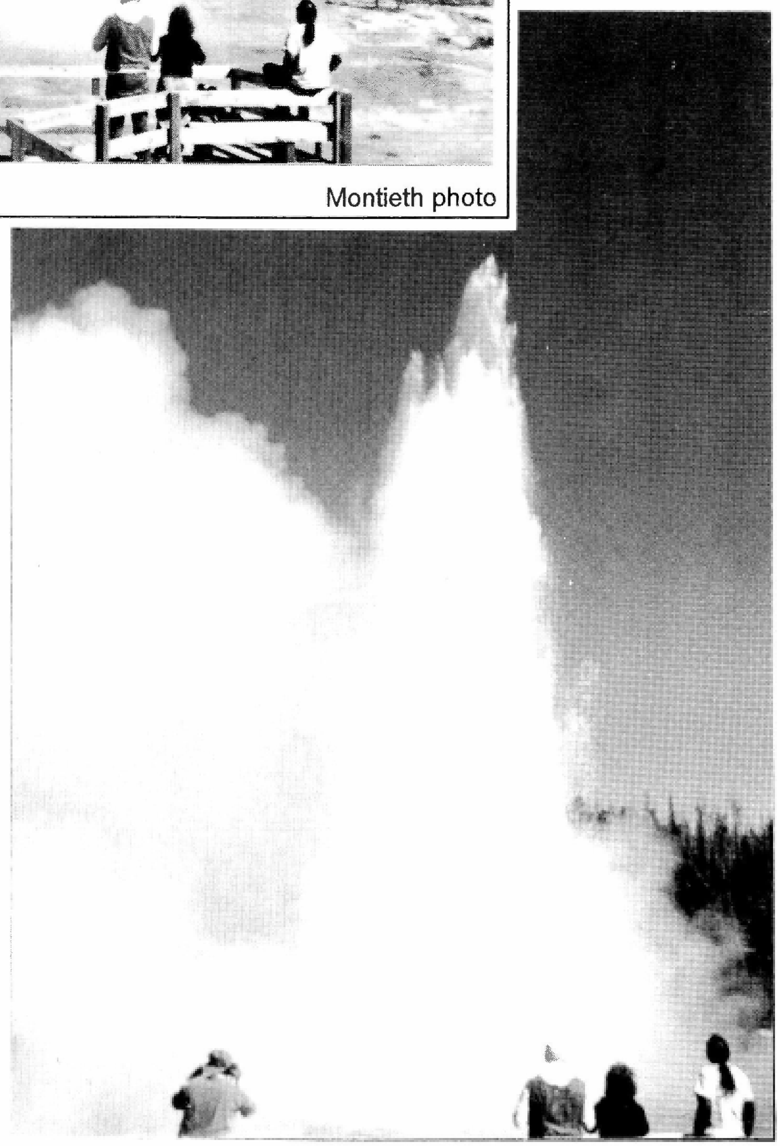
Giant Hot Period Montieth photo

In the photo above, at least eight platform vents are in eruption. Below, the "Feather Vent" can be seen to the right of Mastiff, and Catfish to the left.



Giant Hot Period with Mastiff Montieth photo

Giant Erupts! Montieth photo



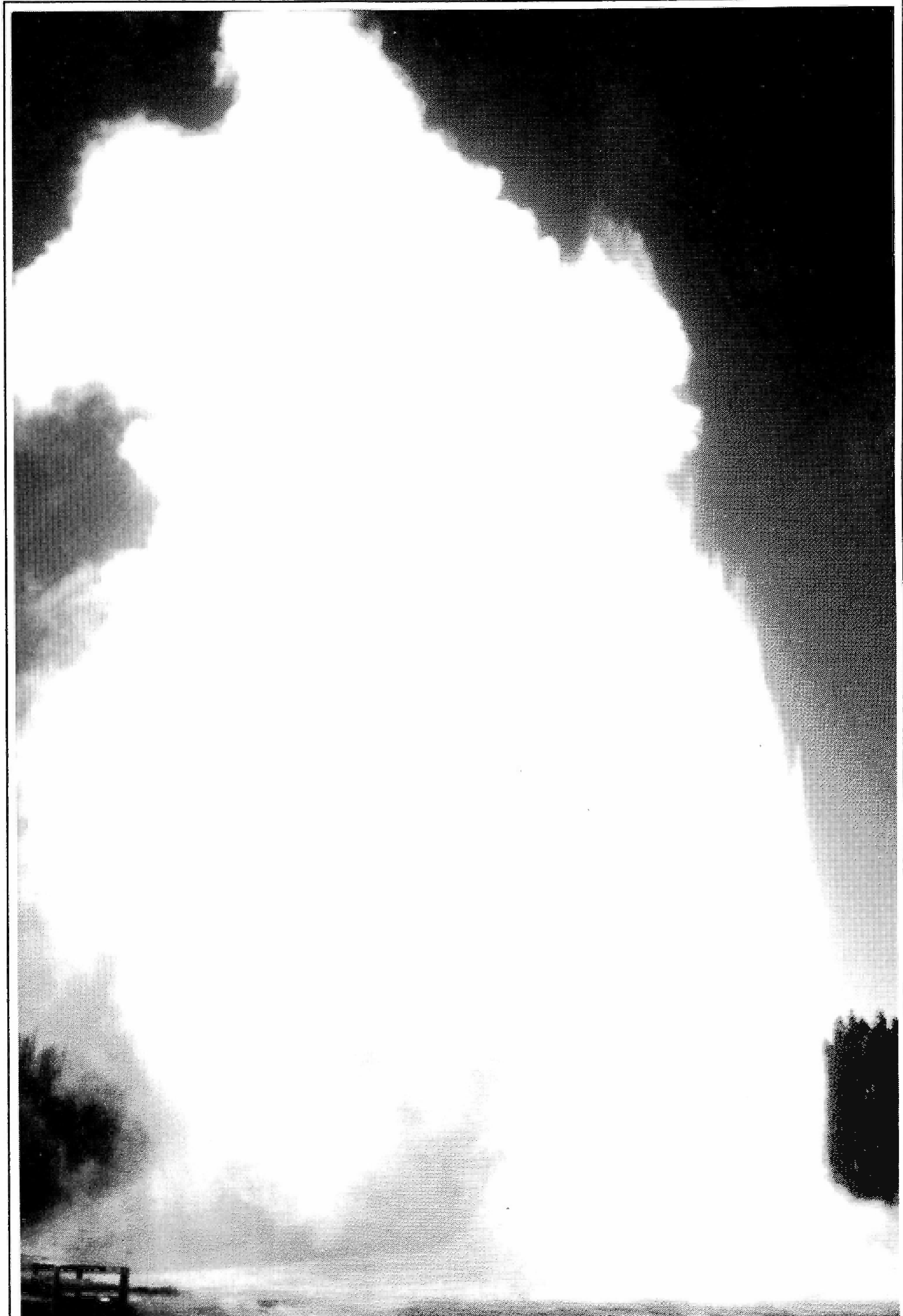
Giant builds height Montieth photo

After its initial surge, Giant Geyser lifts very quickly. It will reach its final height in one uninterrupted movement.

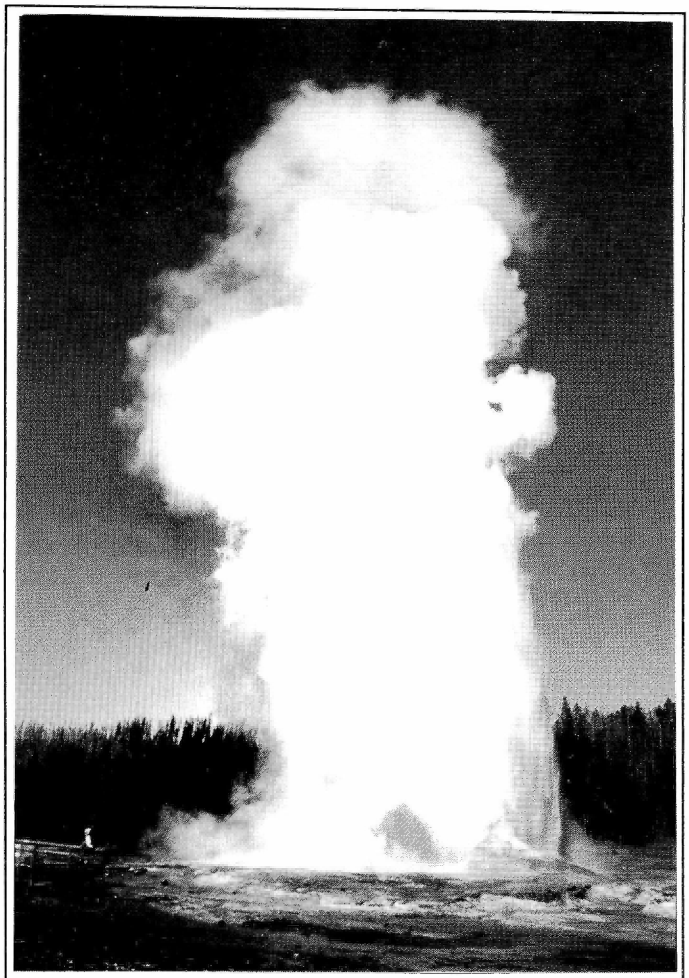
Giant at maximum height Monteith photo

Giant Geyser rose to a maximum height of over 200 feet. The eruption then gradually declined over the next 60 minutes.

The eruption of Giant has been underway for about 10 minutes.



Giant Geyser Monteith photo



Giant as it gradually lowers Monteith photo

The eruption of Giant gradually comes to an end. Shortly afterwards onlookers note that the Purple Pools have lowered about a foot. Two of the pools had been overflowing before Giant's eruption.

North Purple Pool & Giant's steaming cone in back Montieth photo

Observations of Flood Geyser in 1983 and 1984

H.Koenig and Tomáš Vachuda

Abstract: During 1983 and 1984 eruption data was collected at Flood Geyser which showed a linear correlation between the duration of an eruption and the length of the following interval. There was also a possible tri-modal distribution of intervals and durations.

Introduction

Flood Geyser is located in the Midway Geyser Basin, on the east bank of the Firehole River about 900 meters upstream (south-east) from Excelsior Geyser. The location is easily accessible, located below a small terrace with a turnout of the Grand Loop Road between Madison Jct. and Old Faithful. Despite the ease of access, Flood has rarely been carefully observed [Whittlesey 1988]. General information on Flood can be found in [Bryan 1986] and [Marler 1973].

Discussion

At first glance, this geyser seems to have a very irregular interval and duration. Durations range from a single splash to many minutes. The table in [Marler 1978] shows that Flood was considered to have two types of eruptions: the major eruption lasting 12 to 17 minutes, and minor eruptions lasting 1/2 to three minutes. The same table shows intervals ranging from two to four hours for major eruptions, and three to twelve minutes for the minor eruptions. In the observations for this report, the intervals range from 30 seconds to nearly 47 minutes. Data collected on several dates in 1983 and in 1984 also show that there is a strong relationship between the duration and interval.

Eruptions of Flood Geyser consist of large splashes, two to four meters high, very similar to the eruptions of Turban Geyser. The durations varied from a quick splash, to over eight minutes. The longer eruptions seemed to have the larger bursts. Most eruptions began with the water level in the pool about one-half to one meter below overflow. The water would rise with the start of the eruption, although the shortest eruptions could have little or no overflow.

Neither the statistics for the intervals nor the durations for either year fit a normal distribution. A simple linear regression, however, shows a good correlation (r2=0.973 and 0.978) in both years between the duration of an eruption and the interval that followed. The prediction equation for 1983 was:

*interval= (5.595 * duration) + 1m24.84s*

while that for 1984 was:

*interval = (5.432 * duration) + 1m44.86s.*

The major difference between the two years was that the eruptions consisting of a single splash were only recorded during the 1983 eruptions.

Conclusions

Flood has been characterized as having major and minor eruptions. As the graphs show, there is definitely a tendency toward two or three distinct classes of eruptions. The data of 1984 definitely shows a tri-modal tendency. There was, however, no evidence during the observations of any sort of tendency for the eruptions to build from a series of minor eruptions into a major eruption.

	Duration	Interval After
n=	39	38
Ave=	1m17s	11m23s
SDev=	2m31s	13m14s
Min=	1s	30s
Max=	8m 21s	46m38s

Table 1
Flood Geyser Statistics - 1983

	Duration	Interval After
n=	39	36
Ave=	3m27s	19m52s
SDev=	2m52s	16m01s
Min=	10s	1m35s
Max=	8m09s	43m49s

Table 2
Flood Geyser Statistics - 1984

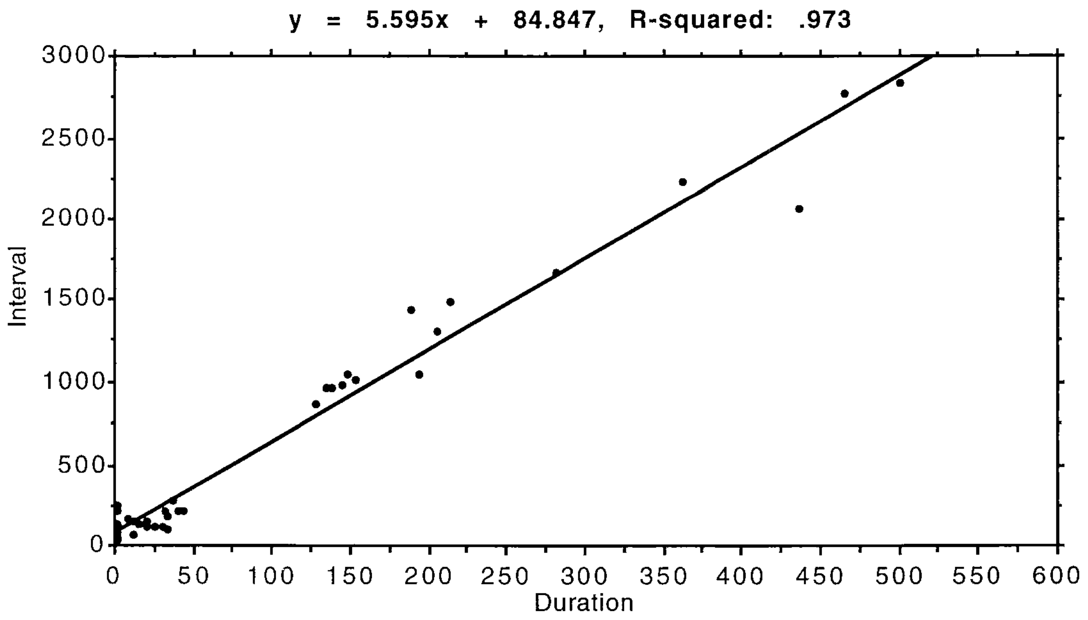


Figure 1
Duration vs. Interval — 1983 (in seconds)

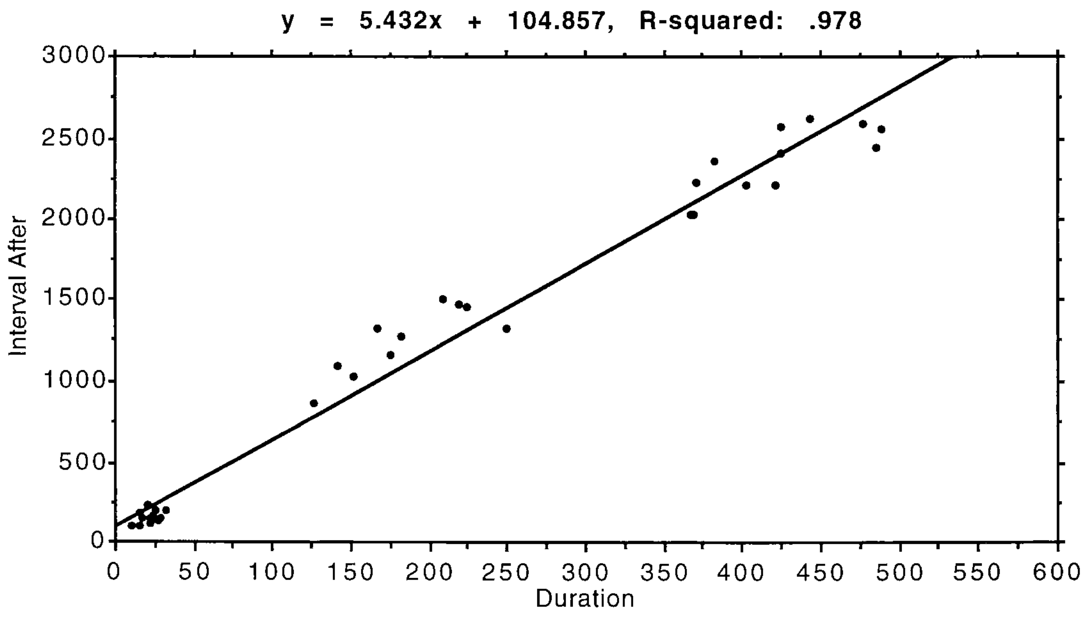


Figure 2
Duration vs. Interval — 1984 (in seconds)

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Flood Geyser, October, 1981 Paperiello photo

A Nonlinear Perspective on the Dynamics of Yellowstone's Plume Geyser

by

Kevin M. Short
Julie Knowles Raye

ABSTRACT: In this paper we apply ideas of nonlinear dynamics to the time series of Plume eruption data collected by heinrich Koenig in 1993 [Koenig, 1996]. We note several well-known characteristic features of Plume's eruption behavior: intermittency effects, indicated by a tendency to cease erupting, or "sleep", for several hours each night; evidence of hysteresis, since eruptions "turn on" and "turn off" at different temperatures; and the "Giantess Effect" where eruption frequency increases and sleep periods disappear during eruptions of nearby Giantess Geyser. We provide an introduction to nonlinear analysis techniques and show how they can be useful in the anaylsis of the Plume time series. We then model the refill-reheat-erupt cycle of Plume with a non linear limit cycle which undergoes a subcritical Hopf bifurcation and develope a mechanism where the limit cycle is driven by a diurnal variation in temperature and the Geyser Hill Wave proposed by T. S. Bryan [1993]. Finally, we show that this model can reproduce the characteristic intermittency and hysteresis exhibited by Plume, as well as the Giantess Effect. We also include a non-mathematical summary of our results in the Appendix.

1. INTRODUCTION

Old Faithful Geyser in Yellowstone National Park, earns its name and reputation because of its predictability; the duration of one eruoption of Old Faithful faithfully determines the time of the next eruption. Other geysers in the park, Plume Geyser for example, are not so predictable. The interval between Plume eruptions on a given day can range from less than forty minutes to more than ten hours. This unpredictability, coupled with the interdependence of geysers in the same basin, leads us to suspect that nonlinear dynamics underlie Plume's behavior. This paper outlines distinctive characteristics of Plume's eruption pattern, briefly explains some features of nonlinear systems, discusses evidence of their presence in Plume's dynamics, and presents a basin approach to creating a model for the system which duplicates many of the unique characteristics of Plume's behavior.

We adopt an approach to the modeling where we attempt to develop a simple model

Plume Geyser 1972 T. Scott Bryan Photo

FIGURE 1 Time Series of Plume Data

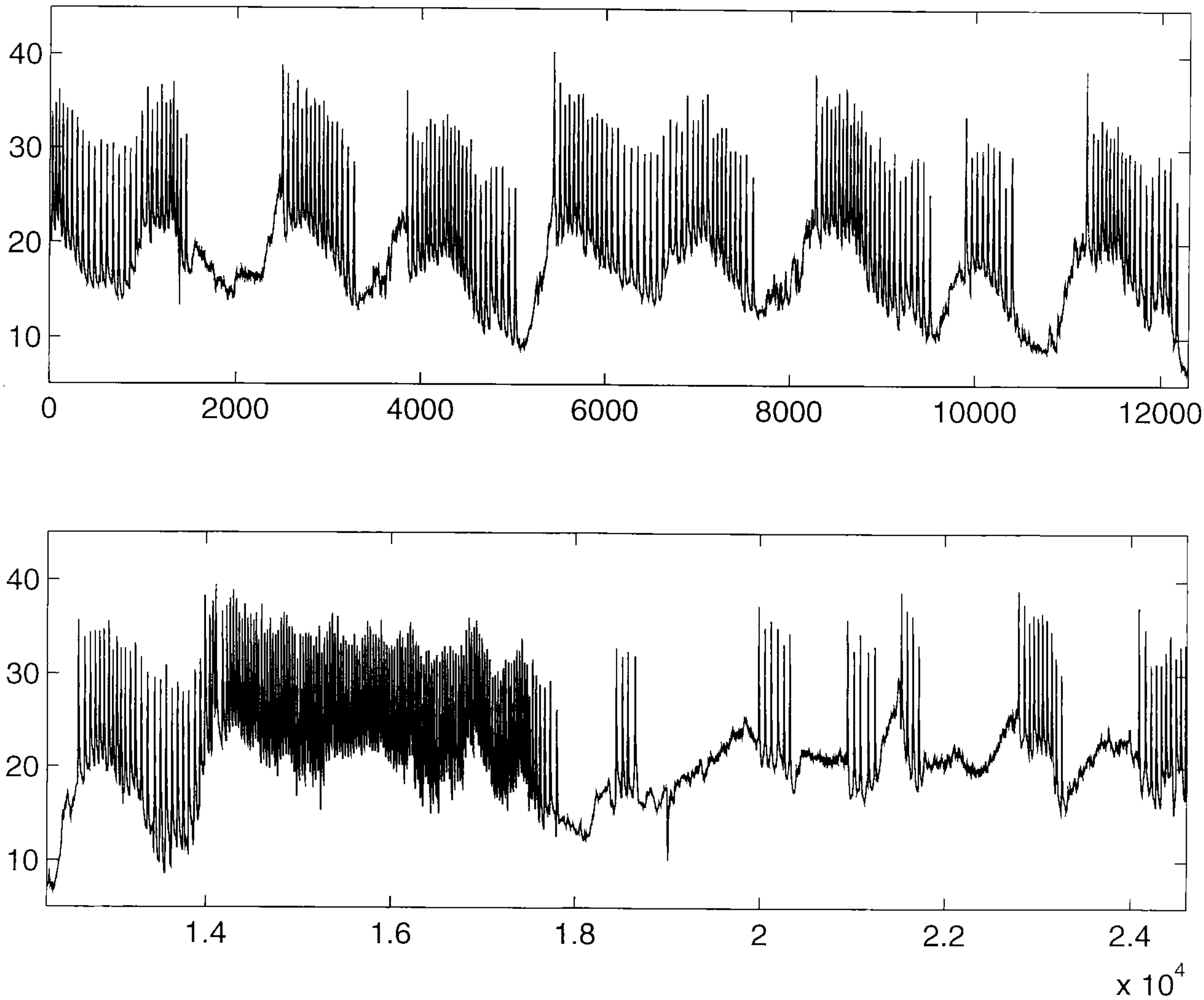
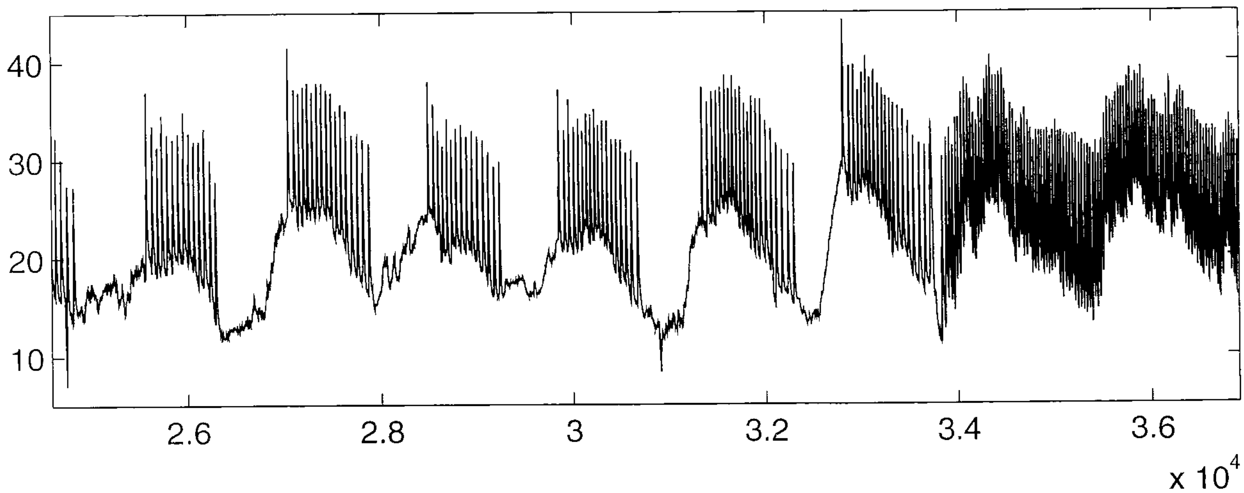
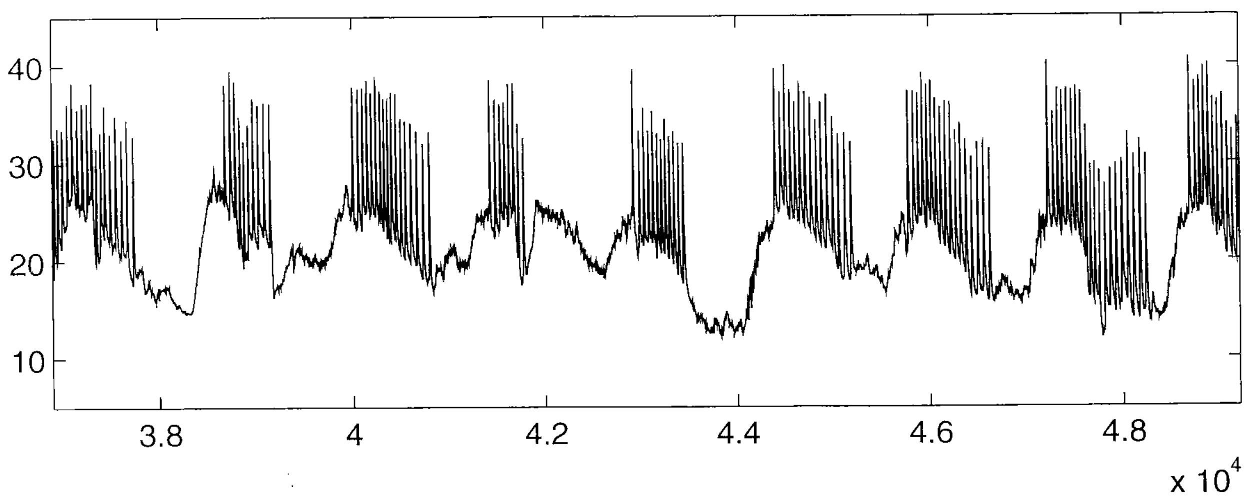


FIGURE 1 Time Series of Plume Data





which exhibits the characteristics of Plume's eruptions, without trying to model the hydrodynamic effects which occur in Plume's basin. In the paper *Dynamics of a Geyser Eruption*, Dowden, Kapadia, Brown, and Rymer[1991] point out that there are two distinct elements of geyser eruptions that can be considered when developing a model. One approach is to model the process underlying an individual eruption, and the other approach is to develop a model which reproduces the eruption pattern. They choose to concentrate on the former; here we discuss the latter. As they note in the paper, the factors that determine the eruption intervals occur on a relatively long time scale. Consequently, we make many simplifying assumptions on the short term which should not affect results considerably, while any long term assumptions are unavoidable due to lack of data. We hope that the work presented here provides the motivation to consider potential nonlinearity in the dynamics of geyser behavior when collecting and analyzing data in future field experiments.

In the summer of 1993, while developing a technique for detecting geyser eruptions from the temperature of the runoff water, Heinrich Koenig measured the temperature of the water in the runoff stream flowing from Plume using a temperature recorder. The water in the stream consists of a mixture of runoff from Plume as well as Giantess Geyser and smaller thermal features nearby. A boardwalk passing over the stream shielded the temperature recorder from direct sunlight. The recorder sampled the water temperature each minute, to the nearest tenth of a degree Celcius [Taylor, 1994]. Temperature data collected from July 9, 1993 to August 8, 1993, shown in Fig. 1, provides the basis for the nonlinear analysis of Plume's dynamics presented here [Koenig, 1993]. Eight gaps occur in the data as a result of changing the tape in the temperature recorder; although the longest gap is almost thirty minutes long, the remaining gaps are close to ten. The figure showing the entire time series incorporates a straight line interpolation fit connecting the data points on either side of the gaps.

The temperature data obtained from Plume reveal several distinctive behavioral characteristics of the geyser:

1. Plume has a tendency to "fall asleep," causing eruptions to cease for several hours during the early morning hours. A sleep period usually lasts between six and twelve hours, so the eruptions generally resume by midday.

2. Plume's eruption intervals are affected by the diurnal variation in temperature. Intervals between eruptions tend to shorten in the afternoon and lengthen towards late evening, eventually leading to the sleep periods.

3. There is evidence of hysteresis in the Plume temperature time series, as observed in its eruption behavior before and after a sleep period. This means that although Plume may go to sleep today when the surface temperatures are at a certain temperature, tomorrow morning Plume may not wake up until the temperatures are well above that temperature. So, eruptions are neither "turned on" nor "turned off" by specific trigger temperatures of the runoff water; this morning the geyser might be inactive at one temperature, but it might erupt at the same temperature this afternoon.

4. Finally, Plume is significantly affected by one of its neighbors, Giantess Geyser. Although an eruption of Giantess is a relatively

infrequent occurence, it causes Plume to erupt quite regularly, approximately every half hour, for a couple of days without any sleep periods. This "Giantess Effect" is a clear indication of geyser interdependence. In fact, all four of these characteristic features of Plume's behavior are evidence of nonlinearity in the dynamics of the geyser, since sporadic behavior, hysteresis, and interaction between systems are elements commonly found in nonlinear systems.

The remainder of the paper begins with a tutorial section on the analysis of nonlinear systems in Section 2. Then in Section 3 we explain how some techniques of nonlinear analysis can be applied to the data collected from Plume. In Section 4, we illustrate an approach to creating a simple model that exhibits much of the characteristic behavior of Plume. Finally, in Section 5, we give results obtained by our model and show that the time series produced by our model is similiar to the Plume eruption time series, and in Section 6, we discuss these results and make suggestions for further research. We also provide a non-mathematical summary of our results in the Appendix.

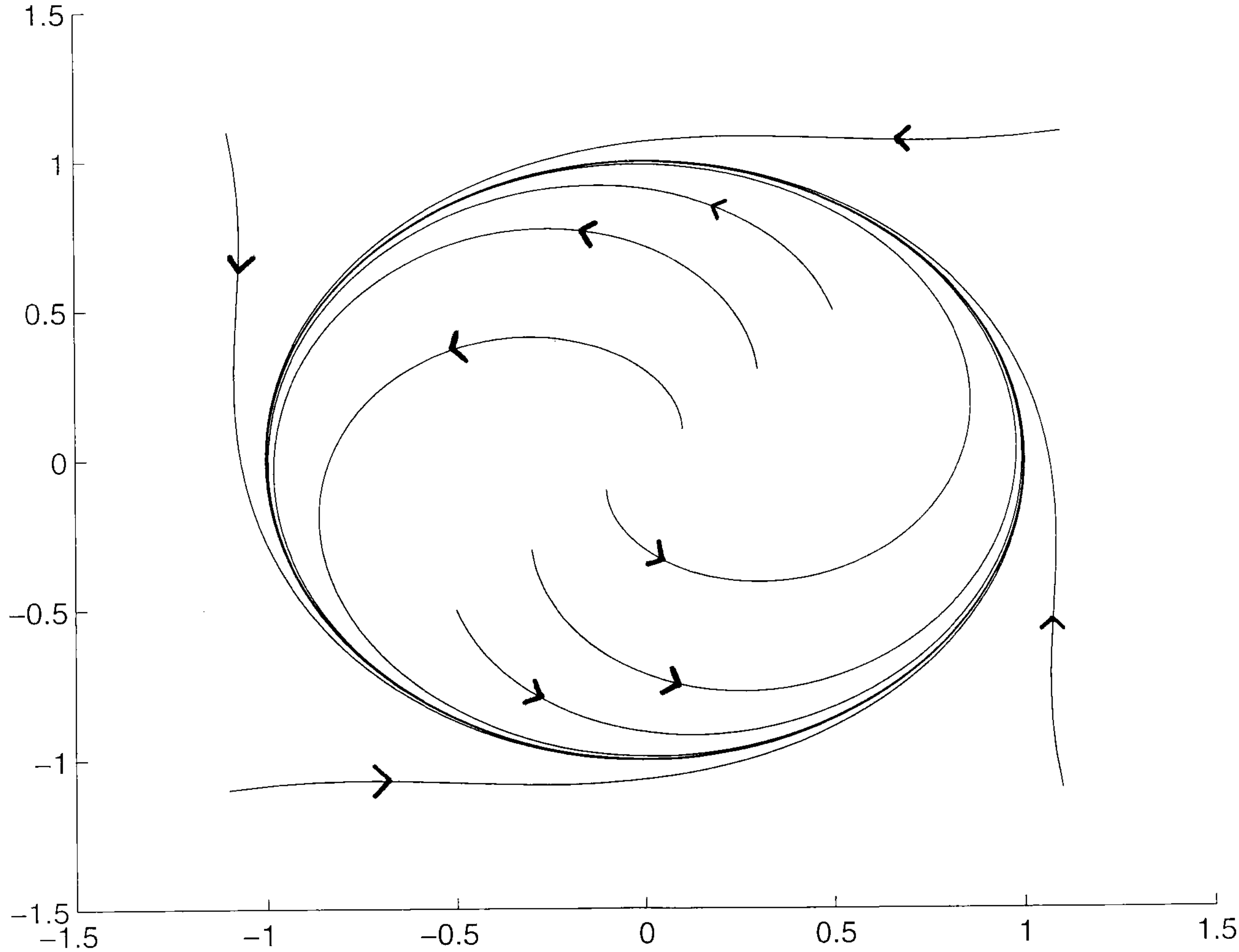
2. NONLINEAR SYSTEMS

Before discussing the analysis of the Plume Geyser data, it might be useful to present a brief primer on the analysis of nonlinear systems in general for those who are unfamiliar with these tools. For those who are familiar with them, we hope this is a useful review. Here we discuss such concepts as phase space, limit cycles, intermittency, hysteresis, time delay reconstructions, and Lorenz maps, and in following sections we show how these tools can be used in the analysis of the Plume Geyser data.

To begin with, what is a nonlinear dynamical system, and how do we analyze it? A *dynamical system* changes in time. In mathematical terms, many dynamical systems can be represented as a differential equation or as a system of differential equations. The equations that express the behavior of a *nonlinear system* contain one or more nonlinear terms, which could be products of variables, variables raised to a power, and/or terms involving trigonometric functions as well as others. The key difference between linear and nonlinear dynamical systems is that linear systems generally have solutions that can be written down in terms of simple functions, whereas nonlinear systems rarely have solutions which can be written down. The existence and uniqueness theorems guarantee that solutions still exist, but the solutions can usually only be found numerically using a computer. Examples of nonlinear dynamical systems in our daily life include columns of smoke swirling from a smokestack, a wildly waving flag in the wind, and a dripping water faucet [Gleick, 1987].

The variables that are necessary to describe the state of a dynamical system are known as the *dynamical variables*. We are accustomed to looking at the time series of these variables, e. g., the plot of the temperatures in the Plume runoff channel in Fig. 1, to observe the behavior of an individual variable over time. These variables, however, can be expressed as the coordinates of vectors which can be plotted, independent of time, in what is referred to as *phase space*. We describe the state of a dynamical system by a vector of its variables, for example $\mathbf{v}= (x, y, z, t)$. In contrast, we describe the phase space of the system by a vector that supresses the time variable, $\mathbf{w}= (x, y, z)$. For

FIGURE 2 Phase Portrait of Stable Limit Cycle at r=1



any given *initial condition*, i.e. the initial values for the dynamical variables, a dynamical system evolves along a solution curve, which we call a *trajectory*. The *phase portrait* of a system is a picture of the trajectories for many initial conditions. Looking at the *phase space* of a nonlinear dynamical system of equations is one of the simplest techniques to study the system because it allows us to find information about the solutions of the system even though they cannot be written down.

Consider the example of the dynamical system describing the behavior of a flag waving in the wind. The dynamical variables of the system tell us where the flag is in relation to the flagpole at a given time. The phase space, however, would give us different positions of the flag without any indication of the time when the flag was in any one place. Furthermore, the waving pattern of the flag around the pole can depend on where the flag was in relation to the pole when the wind picked up. By looking at the trajectory in phase space of the flag's behavior, however, we can trace the flag's range of motion from its initial position to those that follow. This can give us more information about its waving patterns than simply watching it flap back and forth in the breeze, since the trace in phase space may show us recurring patterns or repeated sequences of flapping.

A *limit cycle* is a special type of trajectory in phase space, one only obtained from certain nonlinear dynamical systems. A limit cycle is a trajectory that forms a circle or some other closed loop in phase space. Furthermore, it must not have any other closed trajectories nearby; all neighboring trajectories must spiral in to the limit cycle or away from it. Here we focus on *stable* limit cycles, ones that attract all nearby trajectories. Thus, any trajectory that starts near the stable limit cycle spirals toward it until it reaches it; then it loops around it forever. If the trajectory is bumped slightly from its path, or perturbed, it resumes spiraling toward it. A limit cycle which repels nearby trajectories is called *unstable*; in the case of an unstable limit cycle, trajectories that start near the limit cycle spiral away from it.

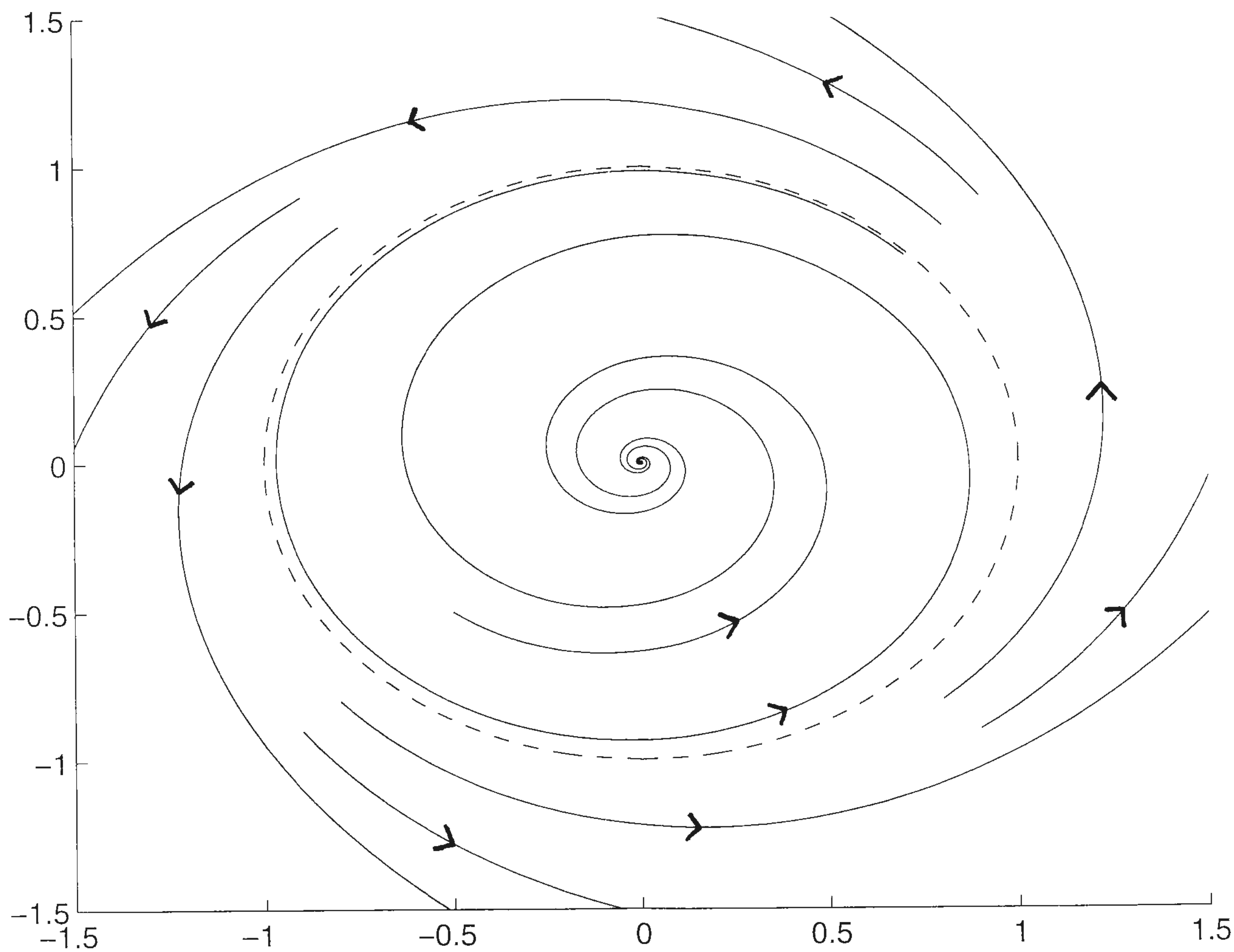
A simple example of a limit cycle in polar coordinates is

$$\begin{aligned}\dot{r} &= r(1-r)\\ \dot{\theta} &= \omega\end{aligned}$$

where ω is constant. Here $\dot{\theta}$ represents the rotational speed, so the trajectories must all have the same period of rotation since ω is constant. The phase portrait of the limit cycle is shown in Fig. 2. Since we are working in polar coordinates and r represents the radius, we can consider only $r \geq 0$. For this example, if r is less than one, we know that r^2 is less than r, so $\dot{r} = r - r^2$ is greater than zero, which means that the radius increases. However, if r is greater than one, we know that r^2 is greater than r, so $\dot{r} = r - r^2$ is less than zero, and the radius shrinks. The stable state occurs when $r = 1$, giving $\dot{r} = 0$. Once this stable state is reached, the system remains at $r = 1$, and its rotation is maintained since $\dot{\theta} = \omega$ is constant. If the system is somehow perturbed from this stable state, it spirals back with a constant rotational speed toward the limit cycle at $r = 1$ until it eventually reaches it.

Stable limit cycle behavior probably provides a good model for the dynamics of a well-behaved, predictable geyser such as Old Faith-

FIGURE 3 Phase Portrait of Unstable Limit Cycle at r=1



ful. The rotation around the limit cycle represents the refilling and reheating that occurs within a geyser between eruptions. We are assuming that the geyser erupts once during a rotation, causing a direct relationship between the eruption interval and the period of the limit cycle. A slight disturbance of the periodicity of the geyser eruptions can be related to the perturbation of a stable limit cycle. If a trajectory is perturbed from its limit cycle, it spirals back to the cycle, though it may take a few rotations before it is back on it again. In the previous example, $\dot{\theta}$ is held constant, fixing the period of a rotation regardless of the radius, so the period is constant even when the trajectory is not on the limit cycle. However, if $\dot{\theta}$ depends on the radius, the period changes until the system is back on the cycle. This could account for slight variation in the eruption intervals of a highly predictable geyser, and an awareness of such variation is already incorporated in the prediction algorithm for Old Faithful.

In many instances, dynamical systems are influenced by *control parameters* which are not considered to be dynamical variables of the system but can affect the behavior of the system. These parameters are constants or functions in the system that are fixed or independent of the dynamical variables of the system and can be thought of as external influences. For example, in a chemical reaction, temperature can serve as a control parameter, and the rate of a reaction can often be controlled by adjusting the temperature. The state of a reaction is described by the concentrations of the chemicals at a given time; these are the system's dynamical variables. In some cases, however, temperature is critical to the occurence of a reaction, because some reactions only take place within certain temperature ranges. For these reactions, temperature is a control parameter, but it is external to the interacting chemicals.

Limit cycles and other special classes of phase portraits sometimes occur only when the control parameters in a system are set at specific values. If a parameter change results in a drastic change in the structure of the phase portrait, this change is called a *bifurcation*. For an example of a bifurcation, let's look at the previous limit cycle example, with one minor adjustment:

$$\begin{aligned}\dot{r} &= \mu r(1-r)\\ \dot{\theta} &= \omega\end{aligned}$$

where ω is again constant, and μ is our control parameter. This time we have multiplied $r(r-1)$ by μ in our equation for $\dot{r}$. Now, the behavior of the radius is not dependent only on r, but on μ as well. If μ is positive, the behavior of the system is the same as that described above, although μ affects the growth rate of r. If μ is negative, however, the behavior changes. If r is less than one, then $\dot{r}$ is less than zero, and the radius shrinks until the trajectory reaches the fixed point at the origin. If r is greater than one, then $\dot{r}$ is greater than zero, and the radius grows without bound as the trajectory spirals out to infinity. This is illustrated in Fig. 3. The dashed line shows the unstable limit cycle at $r = 1$. Thus, the shift from positive values of μ to negative, or from negative to positive, changes the behavior of the system, resulting in a bifurcation which changes the stability of the limit cycle. The study of bifurcations is an active research area, but a good introduction to the topic can be found in Strogatz [1994] or Drazin [1992].

Bifurcations produce many of the interesting aspects of nonlinear dynamics. Two such behaviors are *intermittency* and *hysteresis*. Intermittency, as the name suggests, occurs when a particular type of nonlinear behavior occurs sporadically. For example, in the system described previously, imagine that we vary μ very slowly. For positive μ, trajectories starting from initial conditions inside the limit cycle spiral out to the cycle and continue looping around it as long as μ remains positive. When μ becomes negative, the origin becomes stable and even a slight perturbation toward the origin will cause the solution curves spiral in to the origin and remain there as long as μ is negative. Allowing μ to become positive again forces the solutions to spiral out to the limit cycle once more. Thus, we have intermittent limit cycle behavior. Returning to the example of chemical reactions, let μ correspond to the temperature around some critical temperature T_o. Then for $T < T_o$, no reactions occur and the reactants maintain their concentrations. When $T > T_o$, reactions begin and changes in the levels of concentration occur, but if T happens to drop below T_o again, reactions can turn off. We should note that for some systems, switching the parameters back to the original values that they had before the bifurcation does not exactly reverse the behavior of the system. This is evidence of hysteresis in the system. We discuss hysteresis in more detail in Section 4, so we defer further explanation until then.

Finally, we consider the Rossler system, a system which exhibits chaos for certain parameter values [Rossler, 1976]. It presents a simple, yet interesting example of two additional concepts in nonlinear analysis, time delay reconstructions and the Lorenz map. This nonlinear system is composed of three differential equations in three dynamical variables, x, y, and z, with three parameters, a, b, and c:

$$\begin{aligned}\dot{x} &= -y - z\\ \dot{y} &= x + ay\\ \dot{z} &= b + z(x - c)\end{aligned}$$

To obtain a times series of x, y, and z values from this system, we let the system evolve numerically using a fourth-order Runge-Kutta algorithm with a step size of 0.005. Plotting three-vectors $(x(t_i), y(t_i), z(t_i))$ for $i = 1, 2, 3, \ldots$ in phase space with $a = b = 0.2$ and $c = 5.7$ reveals a geometric structure known as an *attractor*. The attractor, shown in Fig. 4a, is generated by a stretching and folding behavior, so trajectories sometimes fold over and reinsert themselves elsewhere in the attractor, with no periodicity in their behavior. These folds and reinsertions allow all trajectories to remain in the finite space of the attractor for all time without intersecting. Because the trajectories never leave the attractor and the attractor has a well-aligned geometric structure, it is possible to predict the future evolution of a trajectory.

For chaotic systems such as the Rossler system, obtaining data for all of the dynamical variables in the system is unnecessary. The dynamics of the system are encoded in just one of the variables. A remarkable fact for many chaotic nonlinear systems is that simply by taking the time series of one dynamical variable, for example just the x variable from our numerical solution of the Rossler system, we can reconstruct essentially the same attractor seen when plotting vectors containing all three variables. One method of reconstructing the attractor using the time series of only one variable is to use a *time delay reconstruction* [Packard et.al., 1980] [Takens, 1981]. Time delay reconstruction in-

FIGURE 4a Rossler Attractor

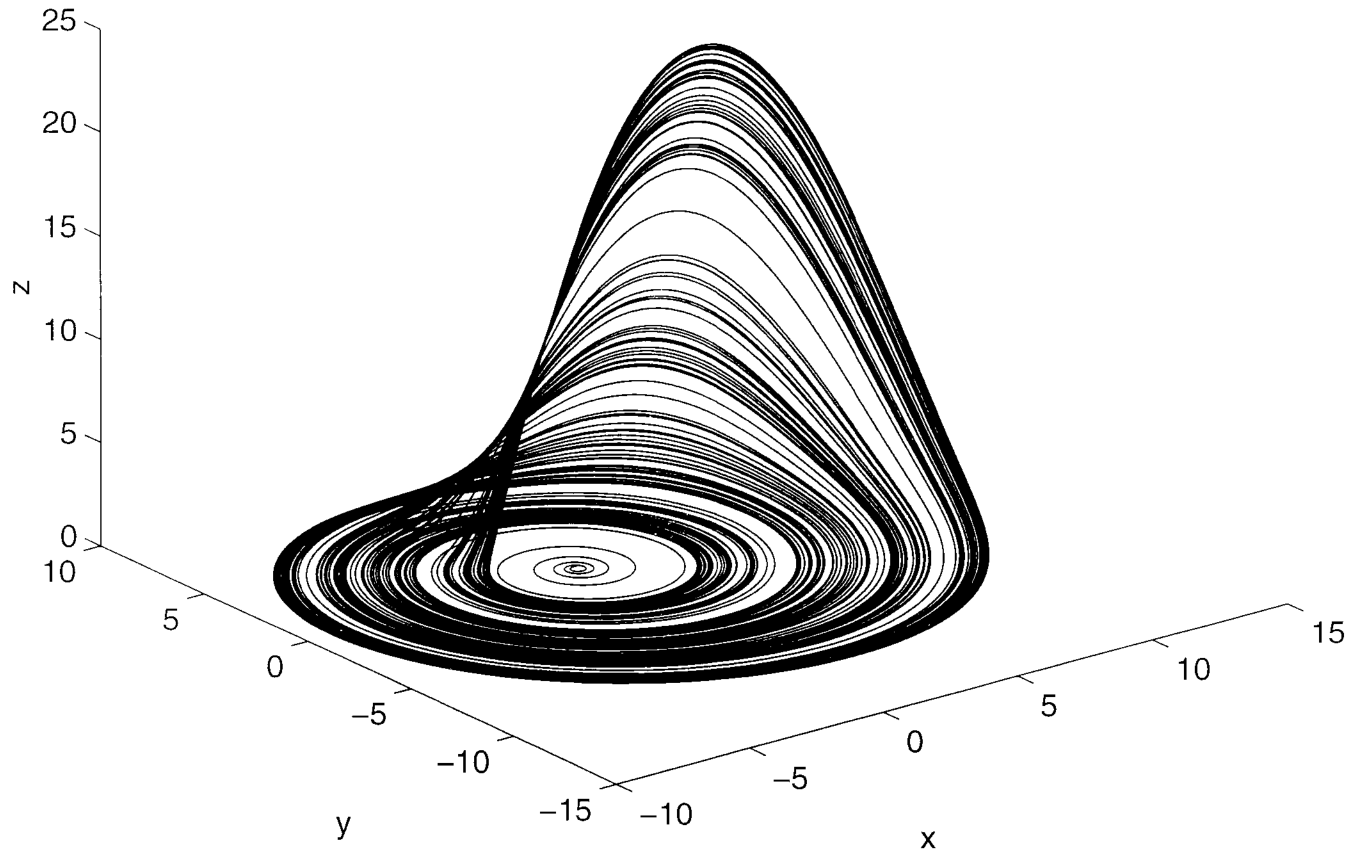


FIGURE 4b Time Series of the x Variable of the Rossler System

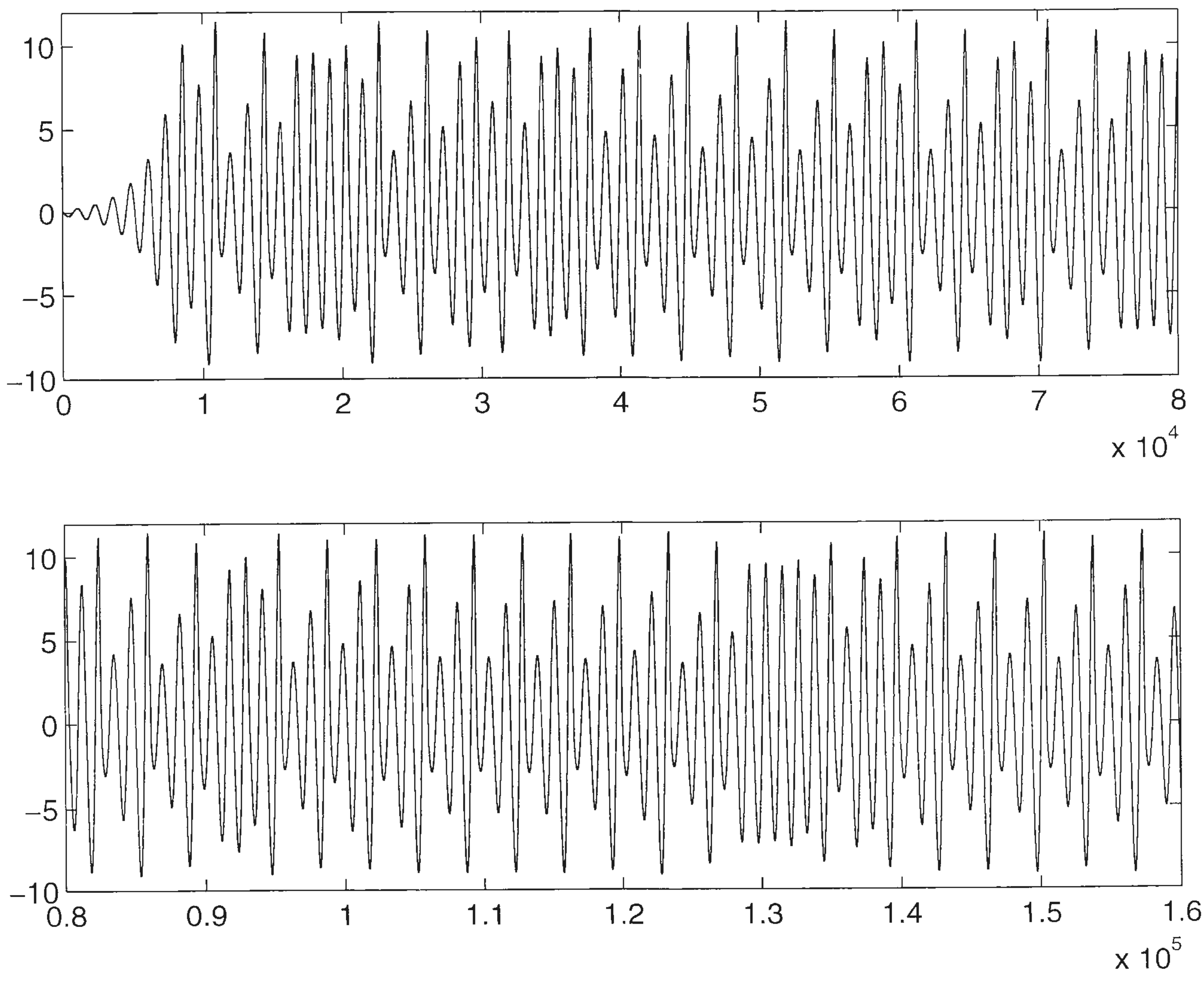


FIGURE 4c   Time Delay Reconstruction of Rossler Attractor

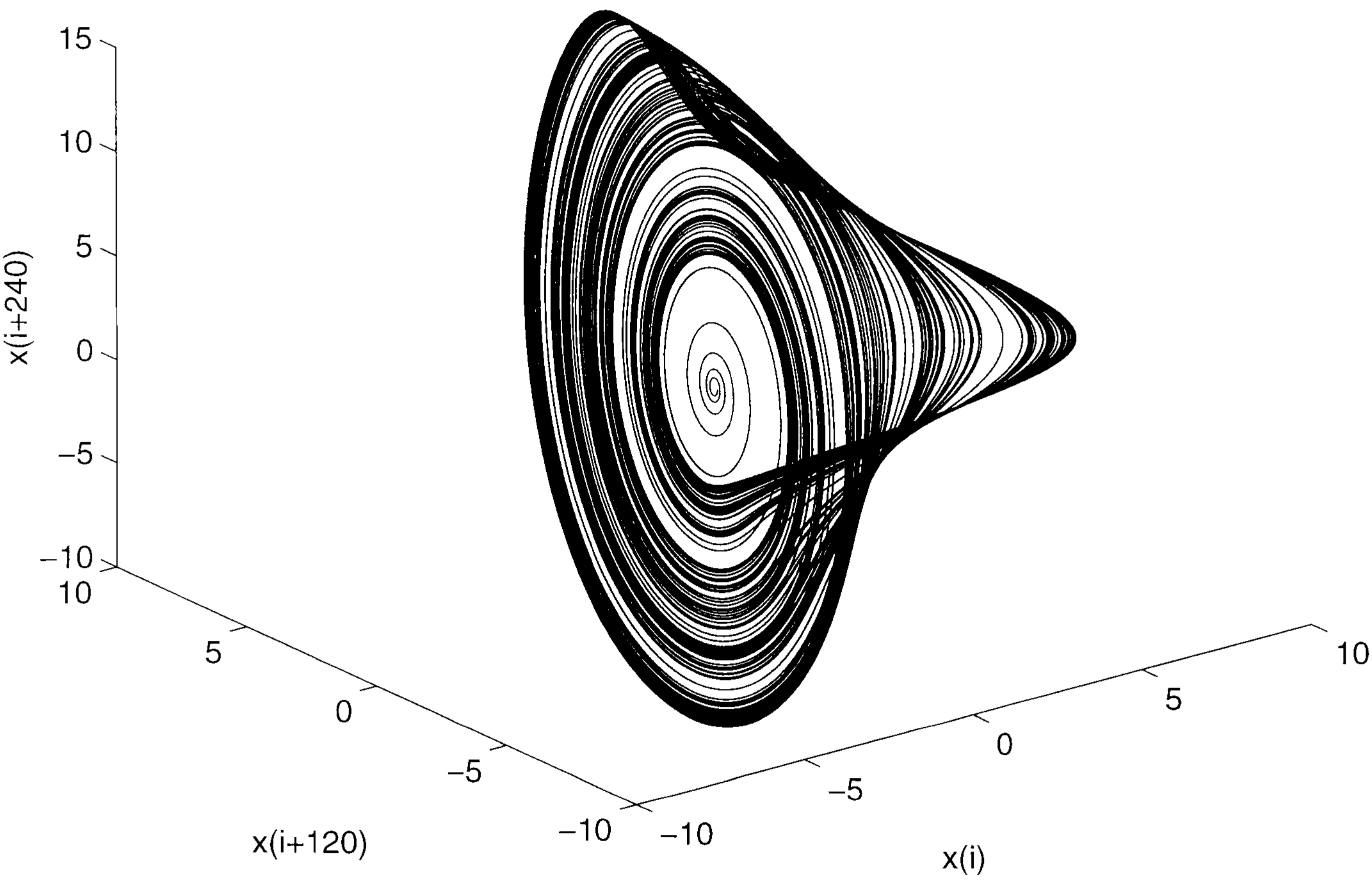


FIGURE 5 Lorenz Map of Rossler System

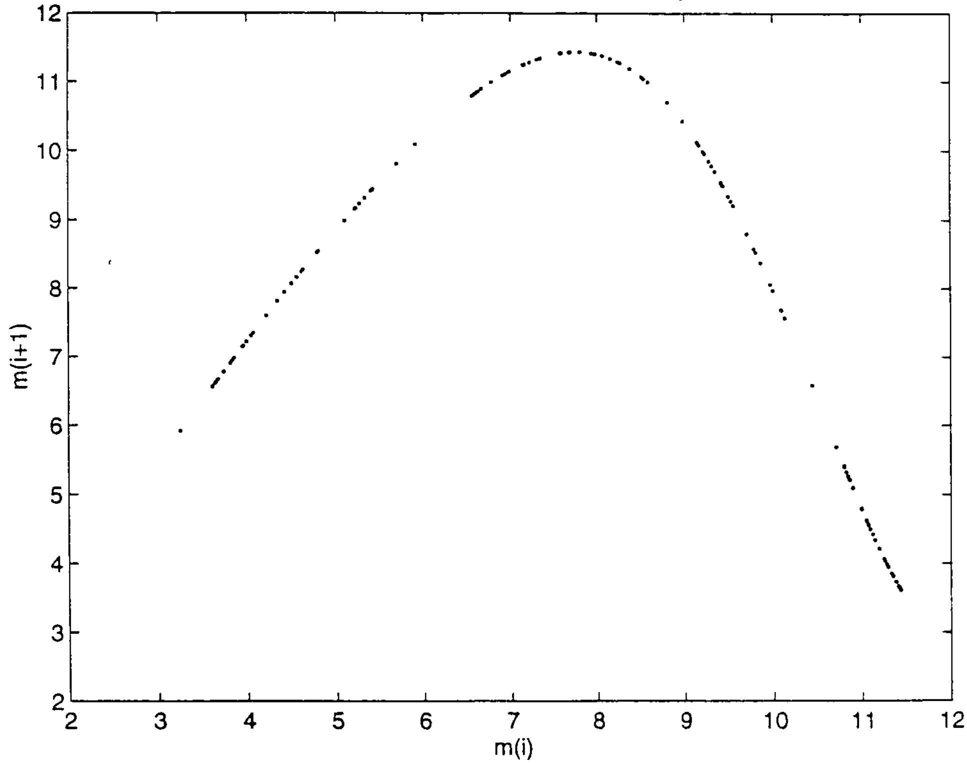
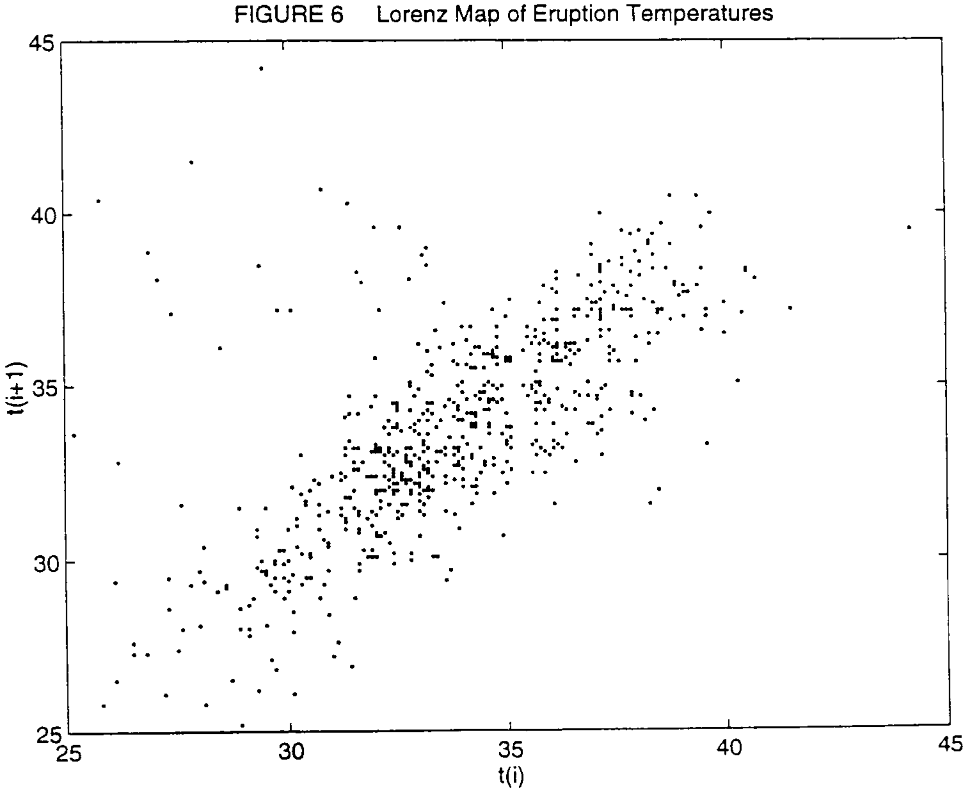


FIGURE 6 Lorenz Map of Eruption Temperatures



volves taking the original one-dimensional time series and selecting data points separated by a given interval, or time delay, and placing them in higher dimensional vectors. For example, if the data from the x variable of the Rossler system is $\{x_1, x_2, x_3, \ldots, x_n\}$ and we want to produce a three-dimensional reconstruction with a time delay of three, we create higher dimensional vectors $\mathbf{v_1} = (x_1, x_4, x_7)$, and in general $\mathbf{v_i} = (x_i, x_{i+3}, x_{i+6})$. Plotting all possible reconstructed vectors in $\mathbf{R^3}$, or 3-space, reveals a smooth deformation of the original Rossler attractor seen in Fig. 4a. The process of creating a time delay reconstruction is shown in Figs. 4b and 4c, where Fig. 4b shows the time series for the x variable, and Fig. 4c shows the attractor created by plotting the vectors reconstructed from the x variable using a time delay of 120 time steps. Notice that the reconstructed attractor is a smooth deformation of the original, which in this case means that it is oriented differently along the axes and it appears curved inward slightly where the trajectories fold over and reinsert themselves.

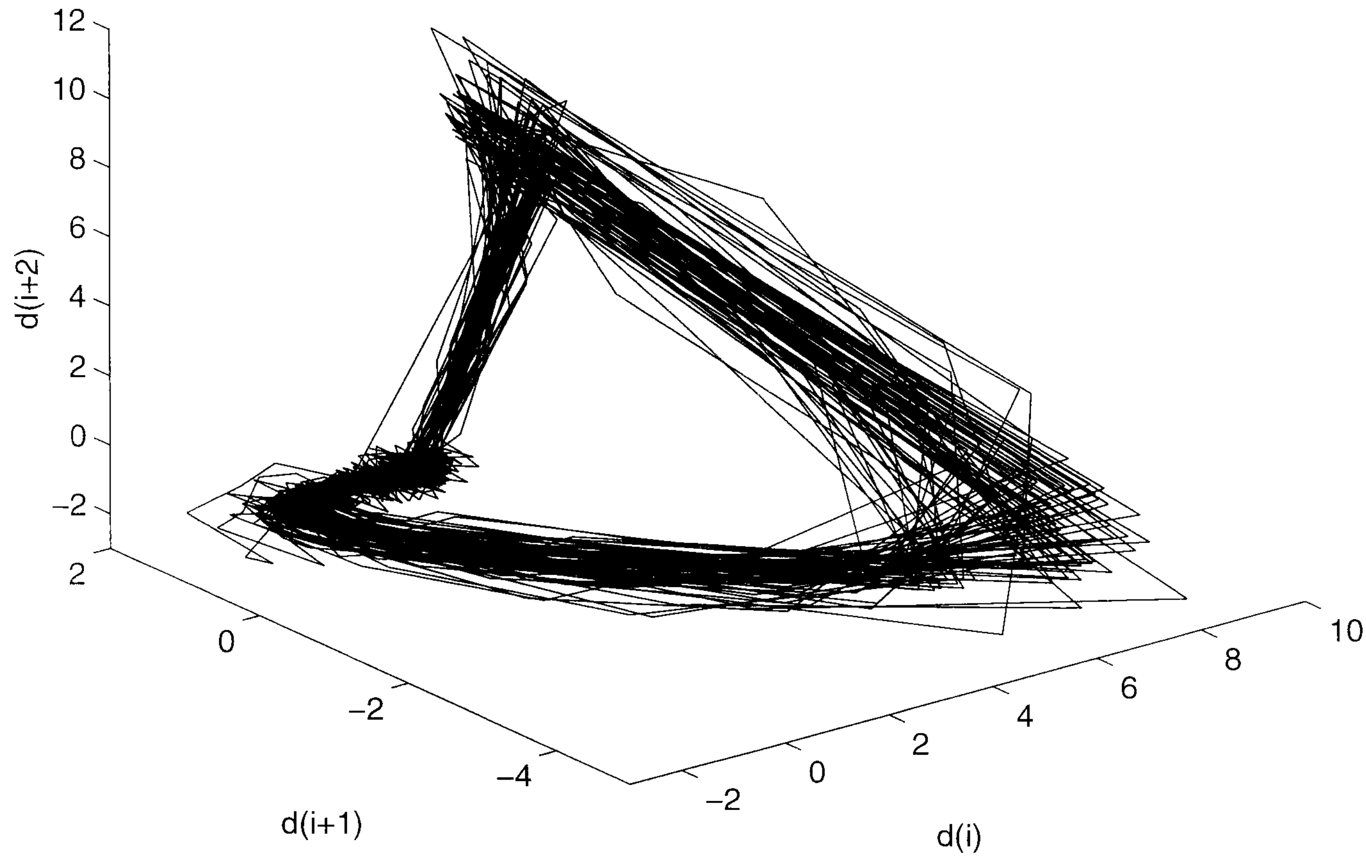
In addition to looking at the reconstructions of a nonlinear system, there are other methods of analyzing the data contained in a variable which may be equally informative, simpler, or more appropriate. One such method is the *Lorenz map* [Lorenz, 1963]. Assume we have a time series of x-coordinate values for the Rossler system. A *local maximum* of the time series is the highest value over a short period of time, with the further requirement that on either side of the maximum, the values must decrease. If these local maxima are recorded in order $\{m_1, m_2, m_3, \ldots\}$, and each one is plotted against the next to form two-vectors (m_i, m_{i+1}) for all values of i, the plot produced is known as a Lorenz map. The Lorenz map for the Rossler system, shown in Fig. 5, resembles an arch; near the crest of the arch trajectories fold and reinsert themselves into the attractor and then they continue to loop around the attractor. This is evidence of determinism; in a random system, the plot of the two-vectors would be a scattering of points, but here the geometric structure indicates predictive capability. Given a current local maximum, we find it on the horizontal axis of our map and determine the height of the arch at that point. This value becomes the predicted value for the next maximum. In the next section, we look at a similiar map plotted for the local maximum temperatures in the runoff channel (the eruption temperatures) which is somewhat revealing about Plume's dynamics, but is still deficient in its predictive capability.

The ability to recreate the attractor from just one dimension implies that for some systems one variable can encode the dynamics of the entire system. The implication is that a data set like the temperature of the runoff water might provide us with enough information to predict the behavior of a geyser, although the data set must be sufficiently long enough to capture all of the variability in the geyser's dynamics. If reconstructing the temperature data in this way is not possible, we might need a longer time series or a time series from another variable in the Plume system, or perhaps nonlinear analysis might not apply.

3. EVIDENCE OF NONLINEARITY IN PLUME DATA

Now that we have discussed some aspects of nonlinear systems, we are ready to talk about evidence of their presence in the Plume temperature data. So far, we have only looked

FIGURE 7 Time Delay Reconstruction of Changes in Temperature



at the time series of the data, Fig. 1. This time series can show us when individual eruptions and sleep periods take place and when the Giantess Effect is present, but it fails to show us anything about the underlying dynamics of the system. In the previous section, however, we mention alternative ways of studying the data, including Lorenz maps and reconstructions in phase space, that help us to analyze the behavior of dynamical systems. In this section, we apply these techniques to the data from Plume.

Although the original data set contains only the temperatures from the runoff channel, several other sets of data can be derived from it. The first one to consider is a time series of the temperatures in the runoff channel at the times of eruption; these are just the peaks of the original time series. Along with this time series of peaks, we can look at the lengths of the time intervals between eruptions and the changes in temperature between each sample. Each of these new data sets can be analyzed individually or in combination with the others. Here we examine the Lorenz maps and reconstructions created from the data and discuss what they illustrate about the dynamics of Plume.

Although Lorenz maps have the potential to point out a mechanism that "triggers" eruptions or sleep periods, the results obtained from the data subsets are inconclusive. In general, most of the points plotted on the maps fall close to the line $y = x$. This indicates that the values may vary considerably throughout the data sets, but the change between successive data points is small. For example, refer to Fig. 6, a map of the eruption temperatures which is a plot of the points (T_i, T_{i+1}) where T_i represents an individual temperature peak during an eruption. We see that the temperature at the time of eruption ranges from twenty-five to forty-one degrees, approximately. However, the clustering of the points along the line $y = x$ shows that the temperature does not change significantly from one eruption to the next. After comparing these results with the original time series in Fig. 1, it appears that the outliers of the map, the points that are not close to the $y = x$ line, occur just after a sleep period. This agrees with the concept of hysteresis in the system; the last eruption before the sleep period tends to occur at a relatively low temperature, while the first eruption after a sleep period tends to occur at a relatively high one, causing T_i to be much less than T_{i+1}, so (T_i, T_{i+1}) does not lie along $y = x$.

As is the case with the Rossler system, the time delay reconstructions of the Plume data tell more about the dynamics of the system than the Lorenz maps. The most illustrative reconstruction is created from the data subset of the changes in temperature between samples. A regular geometric structure appears in a three-dimensional plot with a time delay of one, of the form (d_i, d_{i+1}, d_{i+2}), where $d_i = T_{i+1} - T_i$ represents an individual change in temperature. This can be seen in Fig. 7. The geometric structure seen in the figure appears to be part of a limit cycle, and we draw an analogy between the behavior of a trajectory in the limit cycle and the eruption cycle dynamics of Plume. (We must, however, keep in mind that Fig. 7 only represents the behavior of the temperature in Plume's runoff channel; we have no record of the dynamics occurring beneath the surface.) A trajectory makes one clockwise loop around the limit cycle for every eruption of the geyser. At the time of an eruption, the trajectory is at the bottom of the attractor. It then moves clockwise around the attractor, completing the loop at the time of the next eruption. The "knot" at the back of the cycle just before the trajectories shoot upward is a result of the sleep periods. The knot occurs just after the location in phase space where eruptions occur, and a trajectory that corresponds to an eruption followed by a sleep period gets "tangled up" in that area of the cycle, instead of following the more direct paths of the other trajectories. This results in a longer time for the trajectory to complete the cycle, producing the sleep period. During a sleep period, the trajectory enters the region of the knot and zig-zags back and forth, causing the intermittency in Plume's dynamics. Ideally, we would be able to look at the paths of the trajectories in the knot and know when a sleep period will occur. Unfortunately, this is not the case. There is no way to tell which trajectories correspond to sleep periods simply by observing their behavior when they first enter the region of the knot. The sleep period trajectories only become evident once the other trajectories have already left the knot

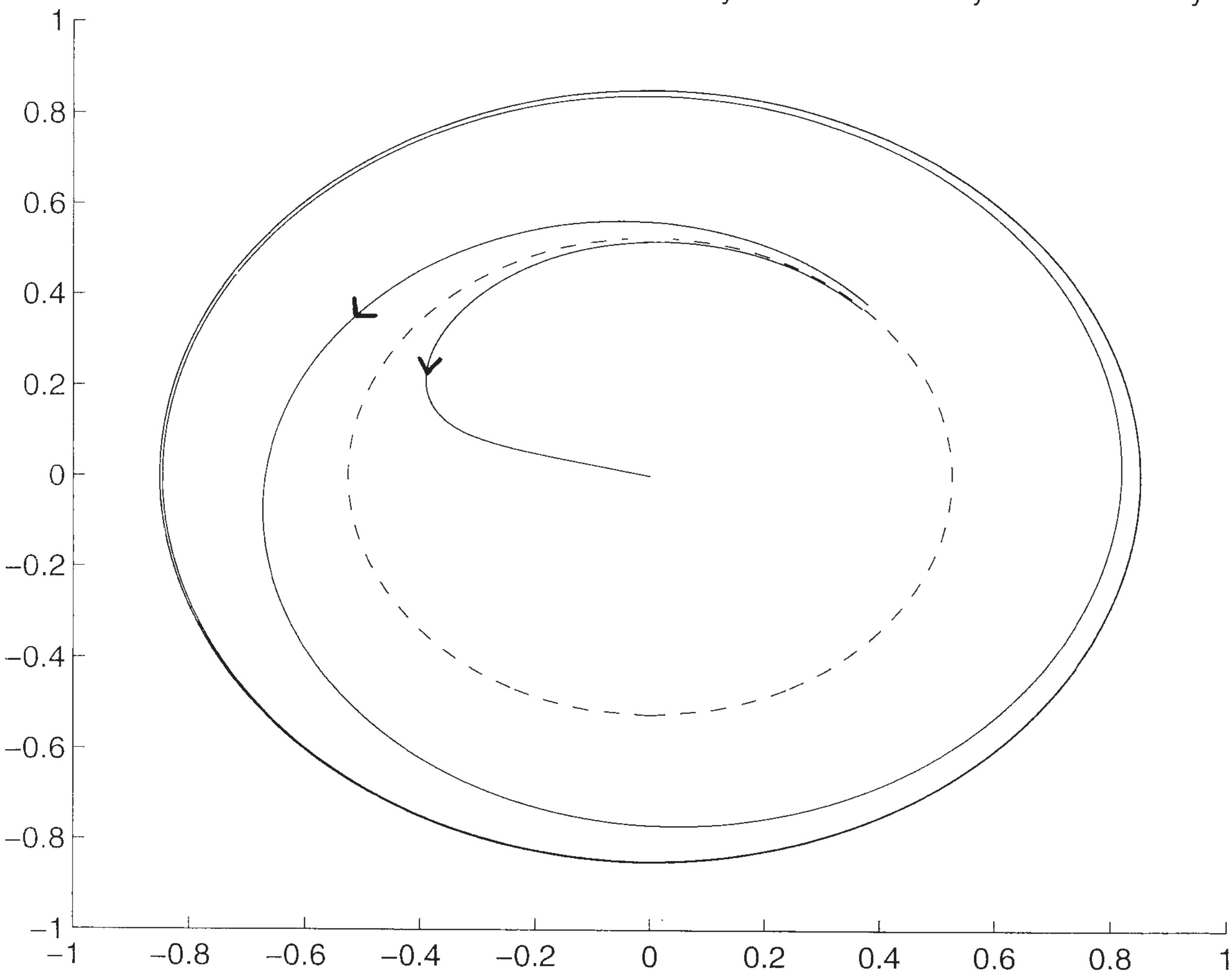
As we mentioned earlier, in order to make predictions based on the attractor reconstruction, the time series must include all of the system's dynamical variation. One problem with the Plume data is that we only see surface temperatures, so we don't see what is happening within the system during the sleep periods. In addition, if there is some slowly varying component to the system, our time series may be too short. Perhaps if the time series were longer, or it were possible to adjust the data to correct for any slow variation in the system, our attractor reconstruction would be more predictive. Because of these limitations, we must find other ways of looking at the system, such as creating a mathematical model that mimics its behavior. This is our task in the next section.

4. MODELING

Although we are unable to predict the onset of a sleep period using maps and reconstructions, we have learned several things about the dynamics of Plume. We know that it is affected by a diurnal variation in temperature. We know that the eruption intervals lengthen before sleep periods and that there are no specific trigger temperatures that affect the sleep periods [Taylor, 1994]. Moreover, it appears that it exhibits intermittent limit cycle behavior. There is, nonetheless, one final element we must consider before building a basic model for Plume's dynamics. If the diurnal variation is the only cause of irregularity in Plume's behavior, then the dynamics should be nearly identical from one twenty-four hour period to the next if the daily temperatures are nearly the same. This is not the case, so we need to include some other factor influencing Plume's behavior.

The Geyser Hill Wave, discussed by T. S. Bryan in his article *Cyclic Hot Spring Activity on Geyser Hill* [1993], offers a plausible explanation for the additional variation in Plume's dynamics. The Geyser Hill Wave (GHW) is postulated to be a regular, cyclic event that seems to affect all of Geyser Hill, including Plume [Taylor, 1994]. The GHW influences water levels in some geysers and boiling action in others, causing eruptions and changes in eruption intervals. At the peak of the GHW, known as S_{max}, Plume seems to have shorter intervals between eruptions. As the GHW progresses, the intervals lengthen by as much as eight to ten minutes. The period of the GHW ranges from three to

FIGURE 8 Phase Portrait of Unstable Limit Cycle Surrounded by Stable Limit Cycle



nine days, but in 1992 most were between five and seven days [Bryan, 1993]. Thus, the GHW might provide an "independent force" which affects geyser behavior. In this section, we try to use the diurnal temperature variation and the Geyser Hill Wave to drive the geyser eruption cycle, which we model as a limit cycle.

We start with the limit cycle to form the base of our model, as it corresponds to the refill-reheat-erupt cycle of a geyser. Then we adjust its parameters as necessary. Because of the intermittent nature of Plume, we need a limit cycle that undergoes a bifurcation between two distinct states. In the first state, the origin is stable and is surrounded by an unstable limit cycle. This state corresponds to a sleep period where no eruptions occur because trajectories are drawn to the origin instead of looping around the limit cycle. As the bifurcation parameter crosses a critical value, the origin loses stability and the trajectories move out to the stable limit cycle surrounding the origin. This state produces the oscillations, or loops around the limit cycle, that correspond to the geyser eruption cycle. This type of bifurcation is known as a *subcritical Hopf bifurcation*. Consider the following equations in polar form:

$$\dot{r} = \mu r + r^3 - r^5 \qquad (1)$$

$$\dot{\theta} = \omega \qquad (2)$$

This exhibits limit cycle behavior when $\dot{r} = 0$. The period of the limit cycle ω is constant and μ is the control parameter that affects the bifurcation. When μ is less than zero, there are two attractors, the stable origin and a stable limit cycle. An unstable limit cycle lies between them. Figure 8 shows that two nearby initial conditions can be drawn to different attractors if they are on opposite sides of the unstable limit cycle (indicated by the dotted line). Increasing μ from a negative value shrinks the smaller unstable limit cycle until μ is equal to zero, at which point the unstable limit cycle has zero radius and so is just the fixed point at the origin. The result is that when $\mu = 0$, the origin becomes unstable. Thus, a bifurcation occurs when μ crosses zero, since the origin changes stability. The stable limit cycle farther out remains stable as μ crosses zero. Hence, for μ greater than zero, trajectories move out to the stable limit cycle since it is the only attractor around. To summarize, for μ less than zero, trajectories inside the unstable limit cycle are drawn to the fixed point at the origin, which we take as corresponding to the sleep periods of Plume, but for μ greater than zero, trajectories loop around a stable limit cycle, corresponding to the eruption cycles. Thus, our limit cycle undergoes a bifurcation causing the dynamics to exhibit both the inactivity of Plume during a sleep period and the eruption behavior during its periods of activity.

Now that we have the type of bifurcation that we want, there are two additional aspects of this system that we must note. First, the radii of both limit cycles, not just the unstable one, depend on μ. In the system of equations, $\dot{r}$ determines the rate of change of the radius. When $\dot{r}$ is equal to zero, the radius becomes fixed, and we have a limit cycle. So, to find the length of the radius of the limit cycle, we let $\dot{r}$ be zero, and we solve for r. We can factor out an r, leaving us with $\dot{r} = r(\mu + r^2 - r^4) = 0$. It is clear that $r = 0$ is the solution which represents the fixed point at the origin. Using the quadratic formula to solve $\mu + r^2 - r^4 = 0$, we find that $r^2 = \frac{1}{2} \pm \frac{1}{2}\sqrt{1+4\mu}$. When μ is greater than or equal to zero, we have one positive real solution, $r = \sqrt{\frac{1}{2} + \frac{1}{2}\sqrt{1+4\mu}}$, the radius of the single stable limit cycle, and there is no unstable limit cycle. (There is a negative real solution as well but it is just the negative equivalent of the positive one, and the remaining solutions are imaginary.) For μ less than zero but greater than $-\frac{1}{4}$, we get two positive real solutions and two negative. Since the negative solutions are again the equivalents of the positives, we can ignore the negative solutions, and we have $r = \sqrt{\frac{1}{2} - \frac{1}{2}\sqrt{1+4\mu}}$ for the radius of the unstable limit cycle and $r = \sqrt{\frac{1}{2} + \frac{1}{2}\sqrt{1+4\mu}}$ for the stable limit cycle, which is the same form of the radius we get when μ is positive. When μ is less than $-\frac{1}{4}$, there are no real roots, and the only attractor is the fixed point at the origin. Thus, μ controls not only the stability of the limit cycles, but their size as well.

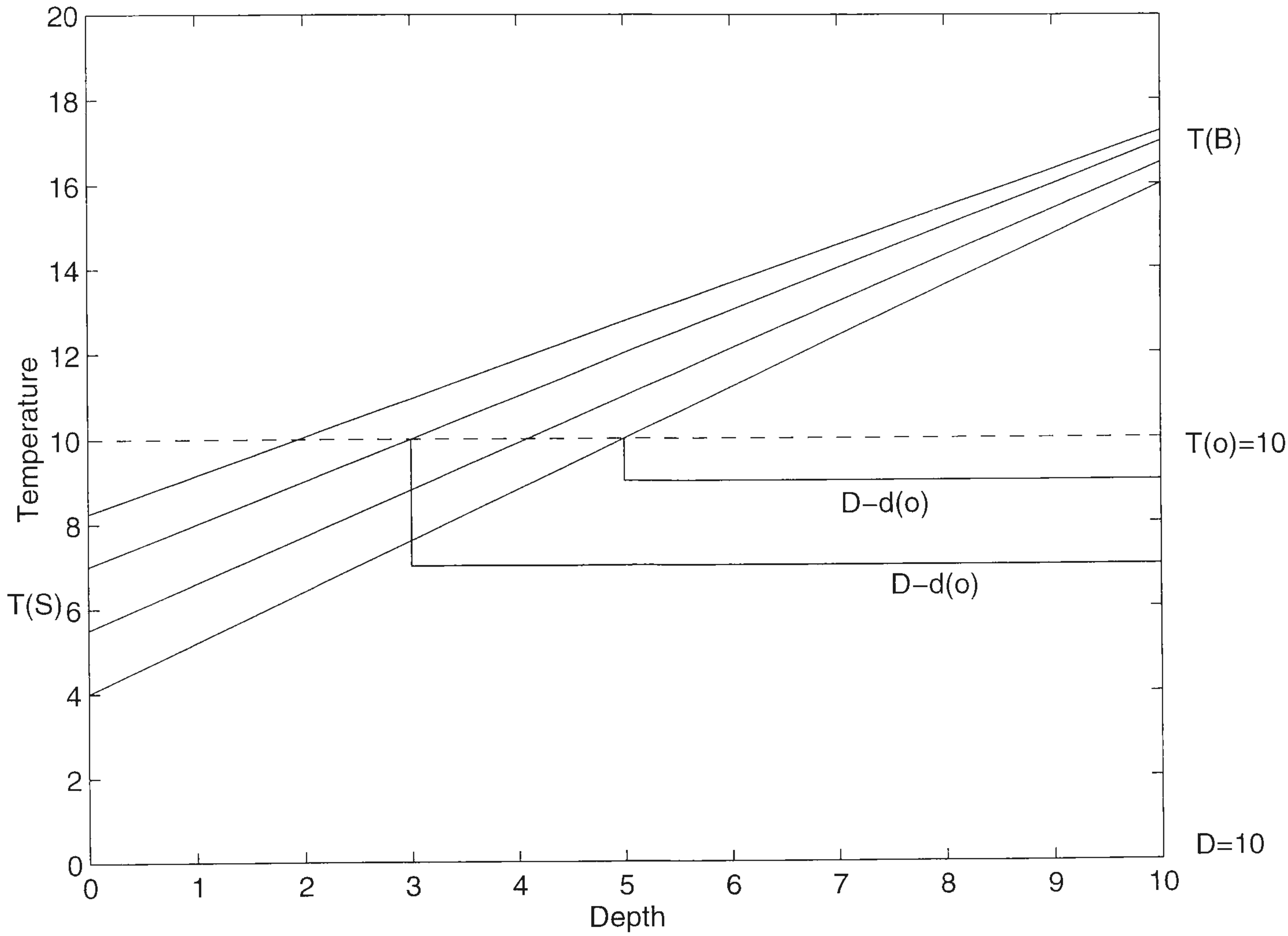
In addition, it is important to realize that in this system the period of the limit cycle, controlled by $\dot{\theta}$, is constant and is independent of the radius of the trajectory. So, since $\dot{\theta}$ gives the angular velocity, all trajectories rotate counterclockwise around the limit cycle at the same rate, no matter what radius or value for μ. This means that a trajectory rotates around a limit cycle of radius one in the same amount of time that it would take to rotate around a limit cycle of radius $\frac{1}{4}$, even though it travels a greater distance when the radius is one. The equation for $\dot{\theta}$, as well as the effect of μ on the size of the limit cycle, is adjusted later when we take further steps to tune the system to model Plume's dynamics.

The next step in building the model is to produce intermittent limit cycle behavior from our limit cycle. With this intermittent behavior, we want trajectories to be drawn to a stable limit cycle and rotate around it a number of times. Then we want to destabilize the limit cycle and cause trajectories to be attracted to the newly stable origin. After some time, we want to reverse the stabilty again and force trajectories to spiral back to the stable limit cycle. This intermittency is analogous to the daily cycle of eruptions and sleep periods of the Plume Geyser. Looking at the limit cycle defined by the equations above, we have seen that for most negative values of μ, trajectories are drawn to the fixed point at the origin and that for positive μ, they are attracted to the stable limit cycle. In order to produce the intermittency that we desire from our equations, we need to redesign our system so that μ varies from positive to negative and negative to positive.

To accomplish this, we use an approach similiar to the one described in Platt, Spiegel, and Tresser [1993]. They propose that on-off intermittency can be obtained by coupling together two systems of differential equations. One of these systems must be a system like ours, where the type of behavior exhibited depends on a parameter value, in our case μ. The other system, the one we need to add, controls the values of that parameter. In other words, we couple our existing system of equations with a new one that we design. We then define our μ to be some function of the dynamical variables in the new system. This enables us to guarantee that the range of the function is both positive and negative and thus ensure intermittency in the limit cycle.

Because the intermittent behavior of the limit cycle is analogous to the sleep periods of Plume, the system controlling the intermittency must be analogous to the forces that influence the sleep periods. We postulate these forces to

FIGURE 9 Linear Temperature Profile (not to scale)



be the diurnal variation in temperature and the Geyser Hill Wave, although we admit that this may be a simplification. In our first modeling effort, we base our models of the diurnal temperature variation and the Geyser Hill Wave on simple harmonic oscillators. We have converted the typical second order differential equation for a simple harmonic oscillator to an equivalent first order system

$$\begin{aligned}\dot{x} &= y\\ \dot{y} &= -\omega_o^2 x\end{aligned}$$

where ω_o is the period of the oscillator. Note that this system is in Cartesian coordinates. In this model, we let the period of the GHW oscillator be approximately five and a half times that of the diurnal variation in an attempt to produce the effect of the usual five to seven day period of the Geyser Hill Wave. In a second effort, we take a different approach to modeling the Geyser Hill Wave, where we use MATLAB cubic spline interpolation to fit a curve to the S_{max} intervals observed by T. S. Bryan [1993]. Using a spline curve, we are able to vary the amplitude of the S_{max} in order to simulate the effects that would be produced if the Geyser Hill Wave had a non-constant amplitude.

As we state earlier in the paper, we are only concerned with developing a model for the eruption intervals of Plume, not with modeling the hydrodynamical process that controls the eruptions. We assume that the Geyser Hill Wave has the effect of producing varying subsurface temperatures, and we assume a linear cooling between the subsurface temperature and the air temperature. We also assume that the underground column beneath Plume has a total depth D. We want to set a threshhold temperature T_o at which boiling occurs underground and find the depth d_o where the threshhold temperature is reached, based on our assumption of a linear temperature profile. The distance between depth of the base of the column D and d_o corresponds to the zone of superheating in the column. We use this value to determine μ, the parameter that controls our limit cycle. Figure 9 illustrates the idea. If we let T_B denote the subsurface water temperature at the base of the column and T_S denote the air temperature at the surface, then the slope of the line connecting the two temperatures can be expressed as

$$m = \frac{T_B - T_S}{D}$$

Using the point-slope formula for a line, we can now solve for d_o

$$d_o = \frac{D(T_o - T_S)}{T_B - T_S}$$

Then, we have

$$|D - d_o| = \left|D - \frac{D(T_o - T_S)}{T_B - T_S}\right|$$

Since this value corresponds to the zone of superheating in the column, it is always positive. The geyser, however, only erupts when the superheated zone is thick enough, so by defining c to be the critical thickness necessary for any eruptions, we can ensure that μ has both positive and negative values by subtracting c from $|D - d_o|$. So the final definition of our control parameter is

$$\mu = \left|D - \frac{D(T_o - T_S)}{T_B - T_S}\right| - c = \left|D\left(\frac{T_B - T_o}{T_B - T_S}\right)\right| - c$$

Now that we have a form for μ that should produce the intermittent limit cycle behavior we desire, we can look at the period of the limit cycle more closely. The time series of Plume data shows that the eruption intervals are shortest during the afternoon and have the largest amplitude, so we want the period of the limit cycle to decrease with an increase in the length of its radius to mimic the effect of the diurnal variation. In our original system, $\dot{\theta} = \omega$ is constant, and the period of the limit cycle is $T = \frac{\pi}{\omega}$. So, if $\dot{\theta}$ is constant, the period doesn't change, regardless of the radius of the limit cycle. Since Plume exhibits shorter eruption intervals during the afternoon when the diurnal temperature is hottest, we want the period of the limit cycle to decrease when the diurnal temperature is at a maximum. Our function for μ increases as the diurnal temperature T_S increases, and since r is dependent on μ, the radius of the limit cycle changes as well. (Here we ignore the influence of T_B on μ and r because the Geyser Hill Wave varies little over the course of an afternoon.) So, if we represent $\dot{\theta}$ as an increasing function of r, we see an increase in angular velocity as the radius of the limit cycle increases, corresponding to the shorter eruption intervals during the hottest part of the day. For our system, we set

$$\dot{\theta} = 2r^4 \tag{3}$$

We now have the three components that we need for our model. Once again, they are a limit cycle which exhibits both intermittent behavior and a period that is dependent on the size of the radius, a simple harmonic oscillator that represents the diurnal variation in temperature, and a model for the Geyser Hill Wave, either another oscillator or a spline curve representation. Now we couple together our components to get the following system of coupled differential equations

(System I)

$$\begin{aligned}
\dot{x_1} &= (\mu + R - R^2)x_1 - 2x_2R^2 \\
\dot{x_2} &= (\mu + R - R^2)x_2 + 2x_1R^2 \\
\dot{x_3} &= x_4 \\
\dot{x_4} &= -\omega_S^2 x_3 \\
\dot{x_5} &= x_6 \\
\dot{x_6} &= -\omega_B^2 x_5
\end{aligned}$$

where $R = x_1^2 + x_2^2$ in order to simplify the appearance of the system, and ω_S and ω_B control the periods of the diurnal variation and the Geyser Hill Wave, respectively.

While this system may look strange and unfamiliar, it is really just the three components we mention above coupled together. The equations for $\dot{x_1}$ and $\dot{x_2}$ are just the equations for our limit cycle defined by Eq. (1) and Eq. (3) written in Cartesian coordinate form instead of polar form. The $\dot{x_3}$ and $\dot{x_4}$ equations give the dynamics of the diurnal variation represented by a simple harmonic oscillator. Finally, the $\dot{x_5}$ and $\dot{x_6}$ equations give the oscillation of the Geyser Hill Wave. Notice that the system for the diurnal variation and the system for the Geyser Hill Wave evolve independently and only serve to drive the limit cycle.

Finally, we need to express the control parameter μ in terms of the coordinates of $\mathbf{x}$, i.e. $(x_1, x_2, x_3, x_4, x_5, x_6)$. In our definition for μ

$$\mu = \left| D - \frac{D(T_o - T_S)}{T_B - T_S} \right| - c$$

T_S is given by x_4, representing the diurnal variation in air temperature. T_B is given by $k(T_{B_o} + x_6)$, where x_6 is the oscillation around T_{B_o}, some base subsurface temperature, produced by the Geyser Hill Wave and k is a scaling factor to adjust the amplitude of the oscillations.

FIGURE 10 Spline Curve Representation of GHW – p(t)+T(B(o))

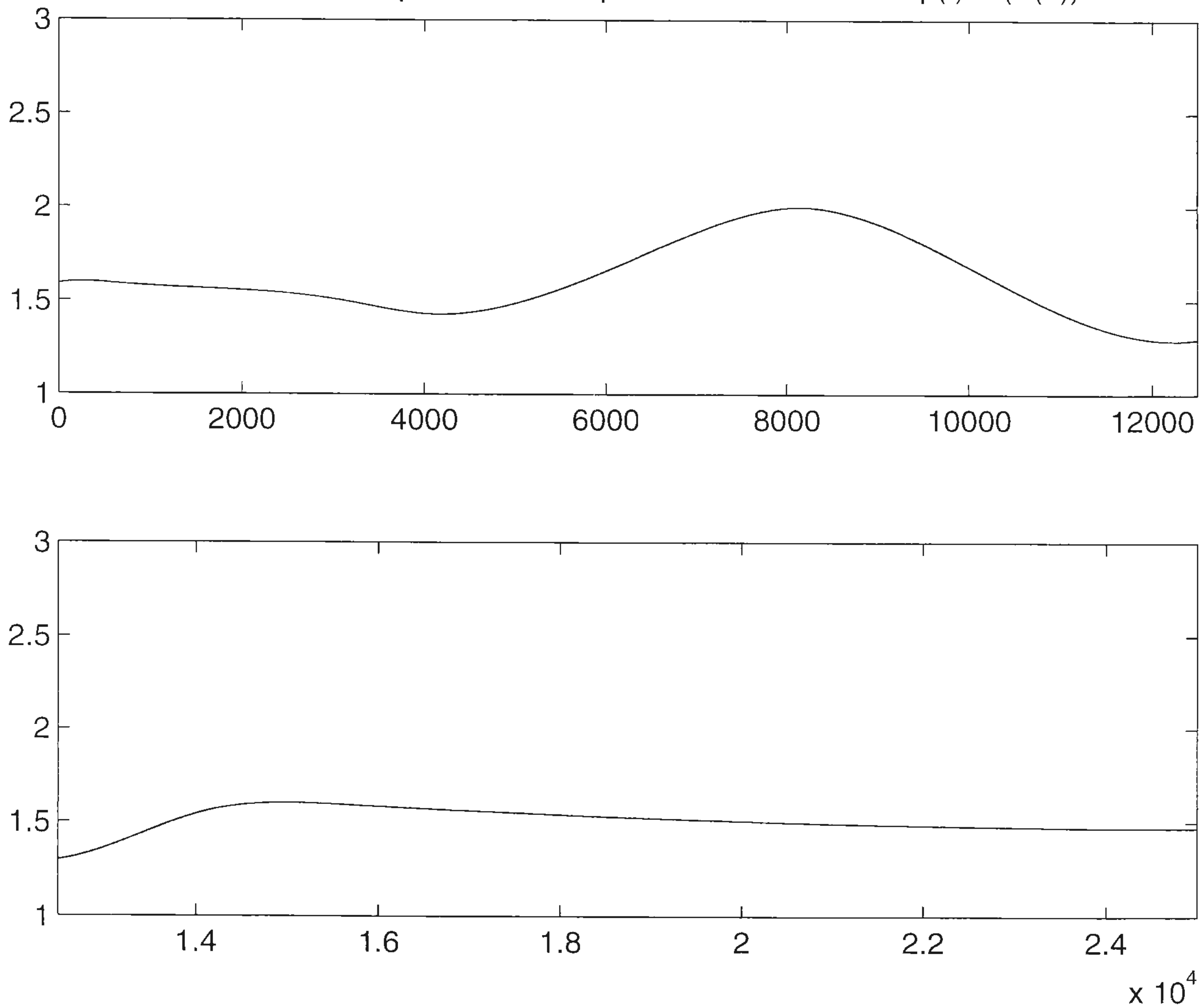


FIGURE 11 Time Series of x1

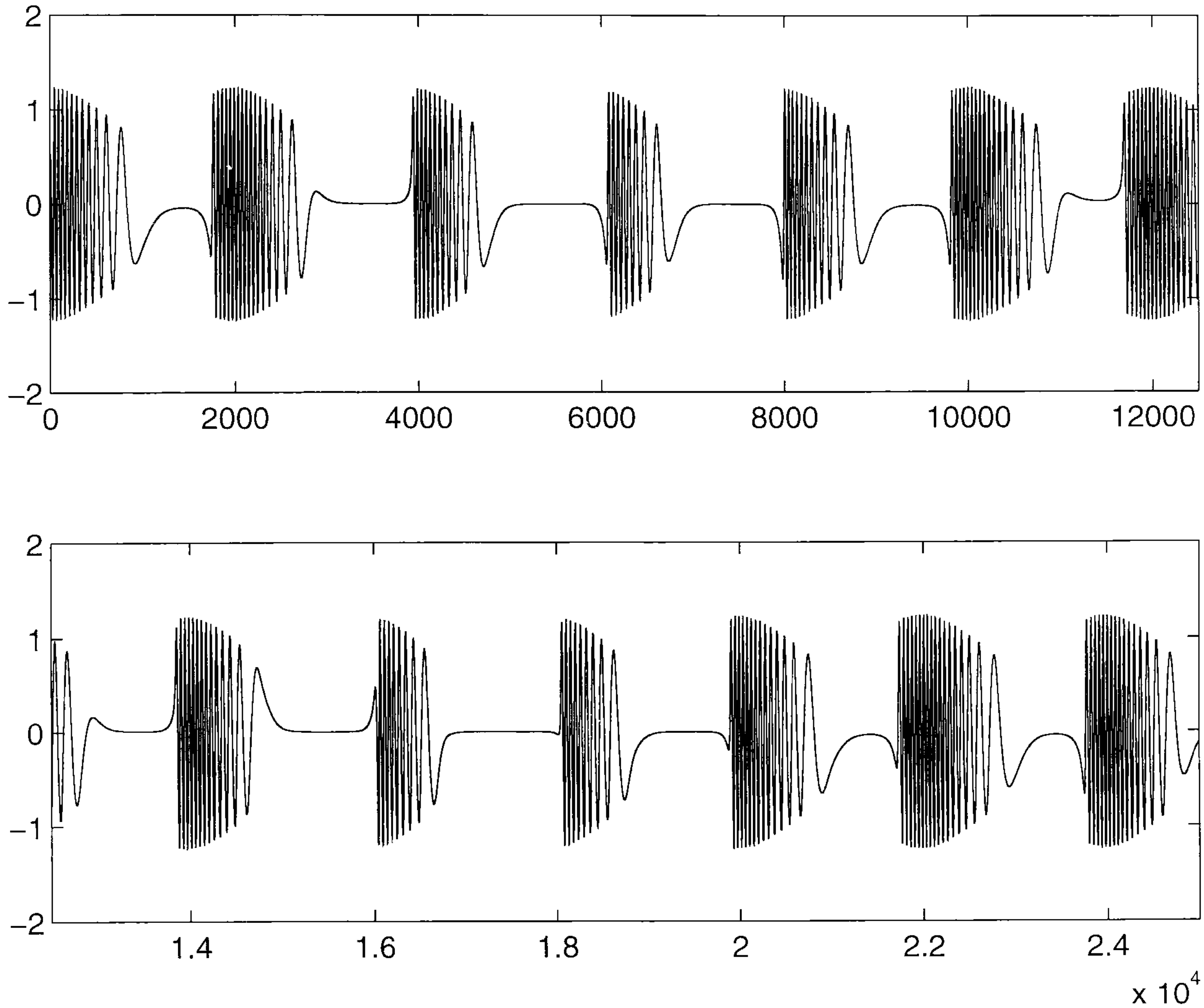
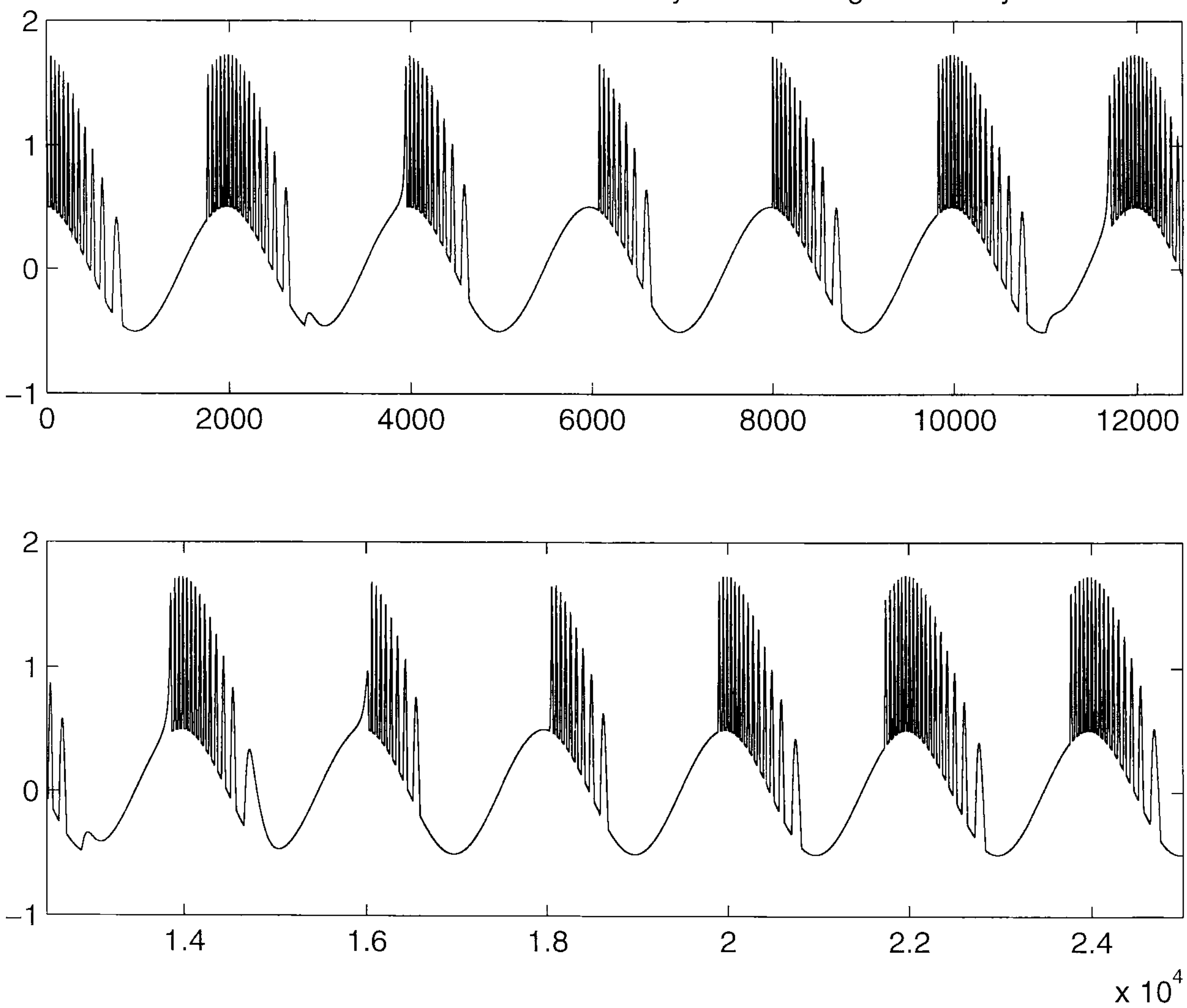


FIGURE 12 Time Series Generated by Model Using Oscillatory GHW



So we have

$$\mu = \left| D - \frac{D(T_o - x_4)}{k(T_{B_o} + x_6) - x_4} \right| - c$$

where $k = 0.2$, $c = 1.515$, $D = 3$, $T_o = .75$, and $T_{B_o} = 7.5$. The parameter $\omega_S = \frac{\pi}{32}$ and the parameter $\omega_B = \frac{\pi}{175}$; we define ω_S to be close to five times ω_B to indicate their relative time scales.

Now we want to look at the system of equations produced when we use the spline curve to model the Geyser Hill Wave. The observations of Bryan [1993] indicate variation in the period of the Geyser Hill Wave, although the relative strengths of the S_{max}, which would correspond to the amplitude, are presently unknown. We use the observed times of $Smax$ to help us determine the period of our spline curve and we have chosen different amplitudes, so that both the amplitude and the period of the Geyser Hill Wave vary. We assume the variation is around the base temperature T_{B_o}, and the corresponding curve is shown in Fig. 10. The dynamical system incorporating this model is the following:

(System II)

$$\begin{aligned} \dot{x_1} &= (\mu + R - R^2)x_1 - 2x_2R^2 \\ \dot{x_2} &= (\mu + R - R^2)x_2 + 2x_1R^2 \\ \dot{x_3} &= x_4 \\ \dot{x_4} &= -\omega_S^2 x_3 \end{aligned}$$

where R, and ω_S are defined as they are in the previous system. Again we have

$$\mu = \left| D - \frac{D(T_o - T_S)}{T_B - T_S} \right| - c$$

but this time the base temperature T_B is represented by $p(t) + T_{B_o}$, where $p(t)$ is the oscillation given by the spline curve at time t around a base temperature T_{B_o}. So we have

$$\mu = \left| D - \frac{D(T_o - x_4)}{p(t) + T_{B_o} - x_4} \right| - c$$

where $c = 0.505$, $D = 3$, $T_o = .75$, and $T_{B_o} = 1.5$. As in System I, the parameter $\omega_S = \frac{\pi}{32}$.

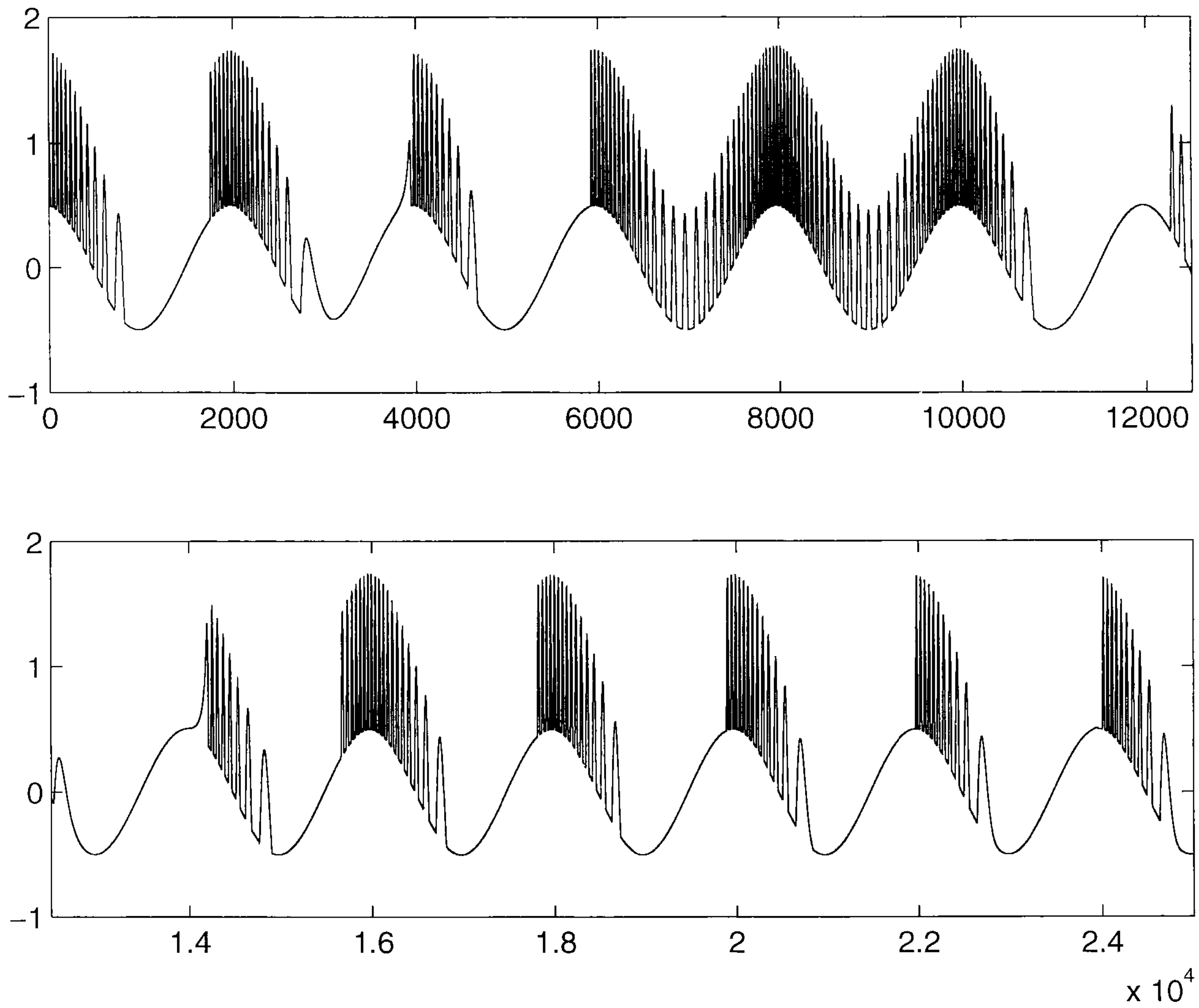
5. RESULTS

We let our first system of six differential equations in six dynamical variables evolve numerically, using a fourth-order Runge-Kutta algorithm with a step size of 0.005. We then consider the time series for the variable x_1, shown in Fig. 11, which represents the temperature of the subsurface water. Since the eruptions only occur when a sufficiently large volume of the subsurface waters are at or above boiling, we arbitrarily set this threshhold at $x_1 = 0$ for our time series.[1] So, we assume that when x_1 is greater than zero, an eruption is occurring and water is being ejected to the surface, and when x_1 is less than zero, no eruptions are occurring. When water is ejected, we simply make the assumption that its temperature is being added to the temperature at the surface, so we then add this to the time series for x_4, which models the diurnal temperature variation. The resultant time series is shown in Fig. 12.

In studying the time series given by our models, we hope to find those characteristics that are apparent in the time series of Plume temperature data. At the risk of being redundant, these include sleep periods, diurnal varia-

[1] We recognize that this is an oversimplification, since higher runoff temperatures at the surface can be produced by larger volumes of hot water and/or steam or by the ejection of higher temperature water and/or steam. Since our data does not allow us to distinguish between the cases, we speak of the temperature of the ejected water, although it would be equivalent to say that x_1 represents the volume of superheated water.

FIGURE 13 Time Series Generated by Model Using Spline Curve GHW



tion in temperature, hysteresis, and the Giantess Effect. In the System I time series in Fig. 12, we see that the sleep periods are obvious; they are indicated by the smooth curves, whereas the peaks indicate eruptions. We note the effect of the diurnal variation by the lengthening of the eruption intervals prior to a sleep period. This is evident from the larger spaces between the peaks just before the sleep periods and is especially noticeable in the time series when $t \approx 1.5 \times 10^4$. The hysteresis in the time series is apparent from the differences in the turn on and turn off temperatures for the individual sleep periods. The height of the graph at $t \approx 900$ is less than it is at $t \approx 6000$, yet the system erupts at $t \approx 900$ but is still asleep at $t \approx 6000$. There is, however, no Giantess Effect present in our time series, since there is a sleep period for every period of the diurnal variation. Because we suspect that the effect of Giantess on Plume is a result of the Geyser Hill Wave, it is likely that using a different model for the GHW could produce the Giantess Effect in the time series.

Now we want to evolve System II where the Geyser Hill Wave is represented by the spline curve shown previously in Fig. 10 to create our time series for x_1. The difference between this system and System I is that here our representation of the Geyser Hill Wave varies in both period and amplitude to better model the postulated behavior. As before, when x_1 is greater than zero we assume an eruption is occurring and water is being ejected to the surface. We add the temperature of the ejected water to the surface temperature to get the final time series shown in Fig. 13.

We compare this time series with the one obtained from our previous model. Again, the smooth curves are evidence of the sleep periods. We can see the lengthening of the eruption intervals before the sleep periods. In addition, we note the hysteresis by comparing the heights of the graph at $t \approx 15,000$ and $t \approx 14,000$. At $t \approx 15,000$ the height is less than it is at $t \approx 14,000$, yet eruptions occur at $t \approx 15,000$ but not at $t \approx 14,000$. Just before the sleep period begins at $t \approx 2900$, we can see a failed eruption, which occur frequently before and after sleep periods in the original time series. Moreover, we see the Giantess Effect indicated by the absence of sleep periods between $t \approx 5800$ and $t \approx 11,000$ and by the dark sections of the graph around $t \approx 8000$ and $t \approx 10,000$, where the intervals between eruptions are shorter, so the peaks are closer together, resulting in a darker plot. If we compare Fig. 10 with Fig. 13, we can see that the Giantess Effect corresponds to an S_{max}. Judging by the diurnal variation, the system should have gone to sleep at $t \approx 6900$ and again at $t \approx 8900$, yet the Giantess Effect maintains eruptions. It is also interesting to note that there are few eruptions during the day following a Giantess Effect, evident near $t \approx 12,500$, a feature that is present in our original time series and is perhaps a result of Giantess drawing heat from the Geyser Hill Wave. The presence of the Giantess Effect when we generate our time series using the spline curve, but not a simple harmonic oscillator, to model the Geyser Hill Wave is a good indication that amplitude variation of the GHW might account for the effects of Giantess. We mention this again in the next section, as we discuss our results.

6. DISCUSSION

After analyzing the dynamics behind Plume's eruptions, we have several final comments. To begin with, the dynamics appear to be generated by a nonlinear system, since we can see the intermittency and variation in periodicity. We believe that a limit cycle provides a good model for the behavior of Plume. In addition, we postulate that the cycle is controlled by a diurnal variation and by the Geyser Hill Wave, but we acknowledge that other factors may play a role as well. T. S. Bryan [1993] discusses some of these possible causes of the diurnal variation. The air temperature variation is certainly not sinusoidal and is only as predictable as the weather. One could easily replace the sinusoidal drive with actual daily temperature data, and this would probably produce more similarity between Fig. 1 and Figs. 11 and 12. If there is a chaotic component to the system, we suspect that the Geyser Hill Wave is a likely source. In order to study its behavior further and make a conclusive classification, more quantitative data needs to be collected for the Geyser Hill Wave, especially more exact times of S_{max} and S_{min}, their relative strengths, and their effects on the geysers in the basin. From the information that we have, however, the GHW does not appear to be periodic, at least not over a one month span, and we don't have enough oscillations to see quasiperiodicity. This is evident in our failed attempt to recreate the Giantess Effect with System I; if the Geyser Hill Wave were periodic over a short time span, we would have expected that the periodic Geyser Hill Wave model in System I would have been able to reproduce all of the dynamics seen in our original time series, including the Giantess Effect. However, the Giantess Effect did not appear until we varied the amplitudes of the Geyser Hill Wave in System II. In addition to improving our model, more conclusive information about the Geyser Hill Wave might allow us to create a better reconstruction from the time series. If we could adjust the data to correct for the effects of the Geyser Hill Wave, we might be left with just the effects caused by the diurnal variation. This might give us a more consistent pattern of behavior for Plume which could result in a better reconstruction. Alternatively, if we had an independent time series describing the state of the Geyser Hill Wave, we could attempt to create a multi-dimensional reconstruction that would include the subsurface dynamics.

There are additional factors that might influence Plume's reaction to an eruption of Giantess. We fail to include them in our model, but they could be easily added. Giantess is located on the hill above Plume, and when Giantess erupts, the runoff water from Giantess mixes with Plume's in the runoff stream below Plume. It is reasonable to expect that as the runoff water from Giantess flows down the hill toward the stream, some of the water enters Plume and thus speeds up the process of refilling Plume's subsurface column. Therefore, an eruption of Giantess could further decrease the period of Plume's eruption cycle, shortening the length of its eruption intervals. This effect can be reproduced in our model by coupling the Giantess Effect back into the surface temperature variation and the limit cycle system when Giantess erupts. In addition, in our model we treat the Geyser Hill Wave as if it is independent of the eruptions of the geysers in the basin. However, after a Giantess eruption there are very few eruptions of Plume, which could be indicative of a low GHW as a result of the eruption of Giantess. So, our model could be improved if we include this effect by allowing a Giantess eruption to remove heat from the system by coupling it back to the equations that govern the Geyser Hill Wave. Further adjustments to our model can be made to make some of the simplifying assumptions more realistic. For example, we implicitly assume that there is only one surface temperature that is the same for both water and air. Because Plume has a relatively small basin, this assumption seems reasonable, but it should be fairly easy to determine its accuracy and adjust the model accordingly.

As we mention in the introduction, our intent in this paper is to model the characteristic dynamics behind Plume's eruption intervals, not the hydrodynamics of the system. Consequently, we ignore the actual physical dynamics in the geyser channel as a result of changes in the temperature, pressure, and state of the subsurface water. In order to model the hydrodynamics, we would need to use a system of partial differential equations (PDE's), while our model is comprised simply of ordinary differential equations. Of course, the system of partial differential equations would consider the dynamics of the system at a very fine scale and, assuming the nontrivial problem of determining boundary conditions could be overcome, it would present a more accurate model of the behavior of the eruption time series. The model presented in this paper takes a broader view, where we only try to reproduce the dynamics of the eruption cycles. However, because both models try to reproduce the same system, if the PDE simulation could be run long enough, it ought to be possible to obtain equivalent solutions. This means that since the solution to our model using ordinary differential equations is an intermittent limit cycle, perhaps the solution to a model using partial differential equations might also be an intermittent limit cycle. This could prove to be an interesting result, because it would draw a connection between nonlinear dynamics and partial differential equations.

Finally, there is another approach to studying nonlinear systems which is generally called *nonlinear forecasting.* These techniques have been developed to predict the evolution of chaotic systems. In these forecasting approaches, a long time series of data is collected and a phase space reconstruction is created. The forecasting algorithm then uses only the data and the phase space geometry to determine a prediction. In these techniques, we might say that the data <u>is</u> the model, since no *a priori* equations of motion are used. However, the success of these approaches hinges largely on having enough data to include all of the variability of the system and fill out the phase space. The time series analyzed in this paper only contains between five and ten cycles of the Geyser Hill Wave, which inhibits the accuracy of the prediction algorithms. If a longer time series is ever collected in future field studies, it would be interesting to try to apply nonlinear forecasting to see if it is possible to make accurate predictions of Plume's dynamics.

We recognize that the work described in this paper ignores or oversimplifies many of the actual physical processes that underlie geyser eruptions. Although we may neglect many of the hydrodynamic effects that occur, we do not intend to minimize their importance in understanding Plume's behavior. Instead, we wish to offer a new perspective of the geyser's dynamics. In addition to looking at the eruption behavior from the usual physical perspective, as a system controlled by its temperature, pressure, and volume, we propose looking at it as a limit cycle that is driven by external influences, namely daily temperature variation and the Geyser Hill Wave. Furthermore, we provide a mathematical mechanism for the intermittency and hysteresis present in the Plume time series. We introduce this new perspective in the hope that it might be able to augment and enhance any research currently being conducted on Plume or other geysers that might behave similarly.

ACKNOWLEDGEMENTS

We would like to thank Heinrich Koenig for making the data available to us and for answering many of our questions. We also thank Ralph Taylor and T. S. Bryan for corresponding with us about our work, and Udo and Janet Freund for helping us to obtain journals from GOSA. This project was funded by a SURF grant through the Undergraduate Research Opportunities Program at the University of New Hampshire, in conjunction with the UNH Parents Association.

APPENDIX

NON-MATHEMATICAL SUMMARY

1) Our initial analysis of Plume convinced us that the intermittent eruption cycle, hysteresis (differing turn-on and turn-off temperatures), and the varying eruption periods required that a nonlinear model be used. We chose as the basis for our model a dynamical system which exhibits limit-cycle behavior. A limit cycle can be thought of as just a (nonlinear) periodic oscillation which exhibits some significant differences from typical periodic oscillations. (For example, if we compare a stable limit cycle to a frictionless pendulum, the pendulum would behave like the limit cycle if it always (eventually) oscillated back and forth with the same amplitude, no matter where we released it.)

2) Now, if we just used the stable limit cycle, then Plume would erupt on a regular schedule with no sleep periods. Consequently, we needed some mechanism to switch off the eruptions, which meant that mathematically we needed to add a control parameter to our system. The first obvious potential switch was a daily temperature variation. If we used only the daily temperature variation as our switch, we could produce sleep periods in the eruption cycle, but on any two days with similar temperature profiles, the eruption patterns would be identical, and we knew from the time series that Plume's behavior is much more irregular than that (e.g., some days exhibit no sleep periods).

3) In order to produce a time series that more accurately reflected the considerable variation exhibited by Plume, we realized that the triggering mechanism needed another influence, and by looking at the data and observing, e.g., the spacing between a day without a sleep period (near $t = 6000$ in Fig. 1) but no Giantess Effect, and the soon-to-follow Giantess event (at $t = 14,000$) and similar indicators, we felt that a slowly varying influence on a longer time scale would be appropriate. In the GOSA literature we found a discussion of the Geyser Hill Wave [Bryan, 1993], and it appeared to provide an appropriate mechanism that would provide the next piece of the puzzle. So, we took as our hypothesis that the GHW was real, and we attempted to see if it could be joined to the daily temperature variation to provide an appropriate triggering mechanism.

4) We modeled the GHW as a slowly varying

sine wave, and for purposes of discussion, we assumed that it represented an increased subsurface heating. The triggering mechanism was then related to the difference between the GHW subsurface temperatures and the surface temperatures. Using this simple model of the GHW, we could produce an eruption time series that exhibited sleep periods, varying turn-on and turn-off temperatures, and the daily eruption patterns showed the same kind of variability as that which was present in the Plume data. However, (as we expected) there was still no Giantess Effect.

5) In order to produce the Giantess Effect, we allowed the GHW to have varying strength and varying period, where we chose the spacing of the GHW maxima according to the observations of Bryan [1993], and we put in varying amplitudes for the maxima. The net effect was that the Giantess effect became present in the time series once the GHW was allowed to have varying strength.

6) The model of the Plume system as a limit cycle driven by both the daily temperature variation and the (varying) GHW can produce all of the observed intermittency, hysteresis, and variability in the Plume time series, except for one feature. That remaining feature is that during a Giantess event, there is observed in Plume an increased eruption frequency which occurs once Giantess is actually erupting. Since we are not modeling Giantess, we did not include any feedback from it into our model, so we do not account for this effect. We suspect that it may be caused by Giantess dumping water into Plume so that the recharging is done more rapidly, and we hope that this can be tested at some point.

In conclusion, we attempted to build a simple model, where each level of increased complexity was added to account for the observed behavior of Plume. All of the elements of the model are derived from mechanisms reported by researchers in the field, so we believe the model to provide a unifying mathematical framework for further research. Our hope is that this work will help researchers to plan their data gathering activities in such a way that such a model can be confirmed or discarded, although we would expect considerable modification even if the overall structure survives.

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Excursion to the Kamchatka Geysers

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Abstract: This paper serves as a brief introduction to the Kamchatka geyser basin. Included are explanations of geyser behavior, a description of significant features, and some results of recent studies related to the Kamchatka geysers.

Historical Background

The geysers in the valley of the river Geysernaya were first described by T.I. Ustinova, who discovered them in 1941. She also gave names to the most powerful or notable of these thermal springs. Because of the remoteness of the region, descriptions of the geysers were sporadic until 1972. As a rule, observations were limited to a few hours at a time. Systematic, lengthy observations of geyser activity were begun under the direction of V.M. Sugrobov, who carried out a complex study of Kamchatka's high-temperature hydrothermal system.

Research into the behavior of the geysers was carried out with the aid of flow meters that were placed in the overflow channels of the geysers almost annually during the period of fieldwork, *i.e.* for one to three months per year. During 1974 and 1975, with the aid of an automatic telemetric conductor system, V.N. Nechaev succeeded in capturing a series of observations for a period of over 13 months. Since 1990, data has been collected by means of a telemetric system.

The dynamic properties of the geysers (such as the velocity and force of the eruption, the height of the water column, and the volume of discharge) were determined by various means: devices that measured the discharge of water (V.M. Sugrobov); visual recording (O.P. Rulenko); hydrometrical devices (V.A. Droznin); and by a specially devised method of hydrometrical sounding (G.S. Steinberg). There are no studies of this region, which constitutes part of the Kronotsky Nature Preserve, which utilize the various methods of geophysical reconnaissance, except for geothermal surveys which were limited to determining the acoustic and seismic parameters of the noise generated by the geysers themselves.

In the over 50 year period of observation there have been no considerable changes in the function of the majority of the geysers. The general nature of activity is the same as that described by T.I. Ustinova. At the same time, quantitative changes in periodic activity have been determined for practically all principal (consistently observed) geysers. If one does not take into account the changes in function of several geysers (Pervenets, Shchel, Grot), which were due to observed exogenous breaches of the ground surface, changes in activity could be connected to the deepening of the bed of the river Geysernaya, to the tectonic life of a geologically young region, as well as perhaps to overall changes in volcano-tectonic conditions on the peninsula.

Distribution of the Geysers

About 300 springs have been identified and hydrochemically tested in the valley of the river Geysernaya. They all appear to be pulsating springs; that is, they do not have a constant discharge. About 90 springs are geysers, which is to say their activity is cyclical, and during that cycle there is a rest phase, during which neither water nor pressurized steam reach the surface. About 30 of the major springs have been named.

The overwhelming majority of the thermal springs and formations are found on the left bank of the river Geysernaya. This seems to be indisputable proof of the source and drainage of the thermal waters — they flow from the sides of the Kihpinych volcano. The general area containing manifestations of thermal activity,

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Translated by S.D. Maslakovic and T.J. Vachuda.

delimited by the 20^0 C isotherm at the depth of 1 meter, comprises 1.3 x 10 km^2. Geysers are found along the middle and lower portions of the river Geysernaya and along the central portion of the brook Vodopadnaya. The excursion path of the joint stock company Sogzhoi was lengthened along the central region of the Geysernaya Valley and from it only two of the most powerful geysers — Pervenets and Troynoi — are not visible. They are found a significant distance downstream from the helicopter landing area. Geyser Malyi is an analogous geyser to Pervenets in its strength and manner of eruption. Usually, excursions into the Valley of the Geysers begin with the observations of its periodic activity. Side by side with Malyi is the geyser Bolshoi.

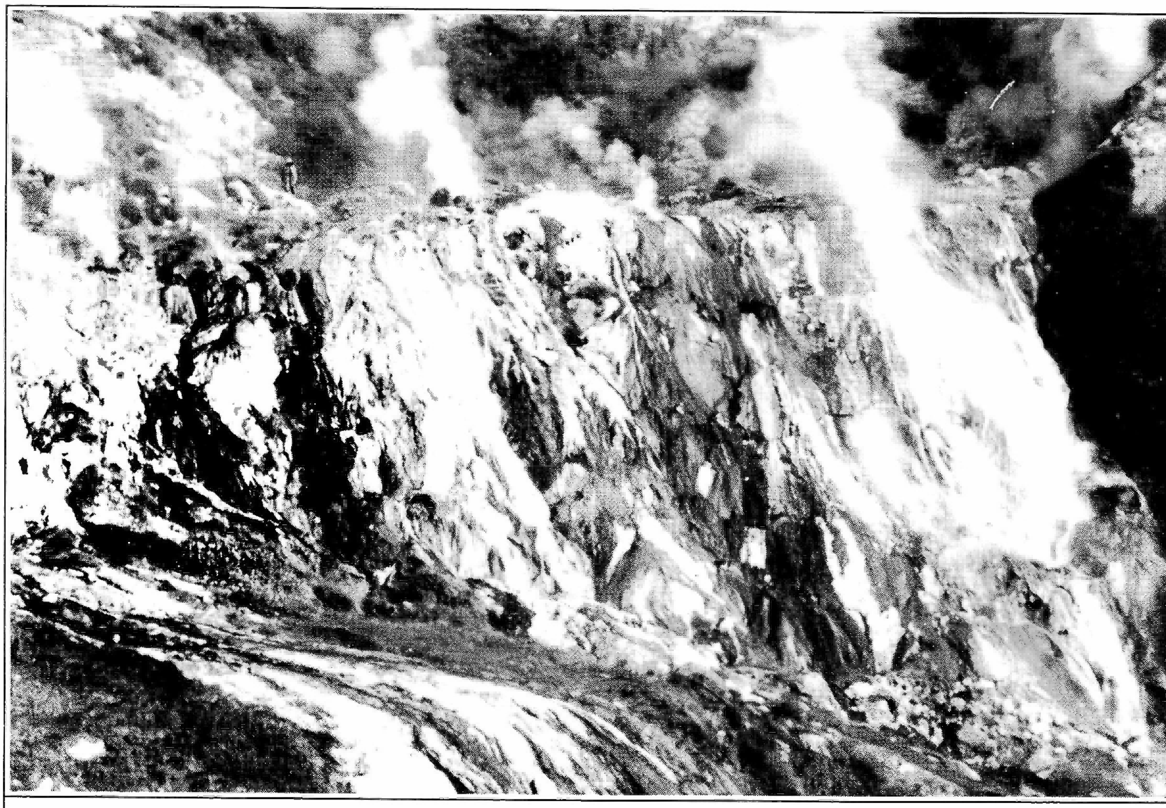

Figure 1. The Vitrazh. The vent of Grot is at the upper right of the picture. For scale, note the volcanologist on the upper left. (Vachuda photo).

After that, the path leads past the geyser Shchel and the pulsing spring Malachitovyi Grot, then across a small bridge to the central observation area. Here the broad view of the Vitrazh (Stained-Glass Panel) (Fig. 1) opens up (including the geysers Grot, Novyi Fontan, Nepostoyannyi, and Dvoynoi), along with a view of the boiling spring Averii, and geysers Paryashchii, Zhemchuzhnyi, and Velikan. The return path leads along the small multicolored lakes and mud pots, including Dantov Ad (Dante's Hell) and Bolshoi Kotel. During the course of the excursion, one can observe that in addition to the named springs there are many that have not been named.

Theory of Geyser Activity

Two identical geysers hardly exist. The activity of geysers differs fundamentally in their periodicity, regularity, height of water column, length of intervals and periods of rest, character of eruptions, et cetera. Such variety explains the absence of a single general theory to explain the mechanism by which all geysers function.

In the most general sense, one can separate the activity of a geyser into four phases: rest, overflow, eruption, and steam phase. For most geysers, including the majority of the large Kamchatka geysers, all of the four phases are very pronounced. However, for some geysers, for example Shchel, Dvoynoi, Nepostoyannyi and Sakharnyi, the overflow phase is not pronounced; and for the last three of these, the steam phase is also not obvious.

Formerly, the periodic activity of geysers was linked to the peculiarities of their underground structure. In a general survey work (Allen and Day, 1935), it was presumed that the presence of an underground cavity was necessary for the existence of geysers. The second main condition specified in that work is that two underground currents mix within this cavity: cold water, and hot water or steam. In a later, more specialized work (Rinehart 1980), it was argued that geyser activity could be explained using a combination of two primary models: the "pot" model and the "tube" model. In the first case, the conditions necessary for an eruption are reached within the area of a cavity that forms a part of an underground system of channels that feed the geyser. In the second case, these conditions occur within the long geyser channel itself. While there are many descriptions of the moment the boiling point is reached at some depth in the underground geyser system as the main precondition for the beginning of an eruption, there is no satisfactory explanation of why this process has a periodic character. Clearly, with the rise towards the surface of thermal waters greater than 100° C, at some depth the boiling point is reached and vaporization begins, but it is not necessary for this process to be periodic. Exploited geothermal wells, for instance, produce a stable discharge, the temperature distribution within in the well's tube corresponding to the line of thermal saturation.

Let us consider the possible models for the attainment of geyser function, giving special emphasis to a description of the physical factors which determine their fundamental characteristics: periodicity and the existence of a rest phase.

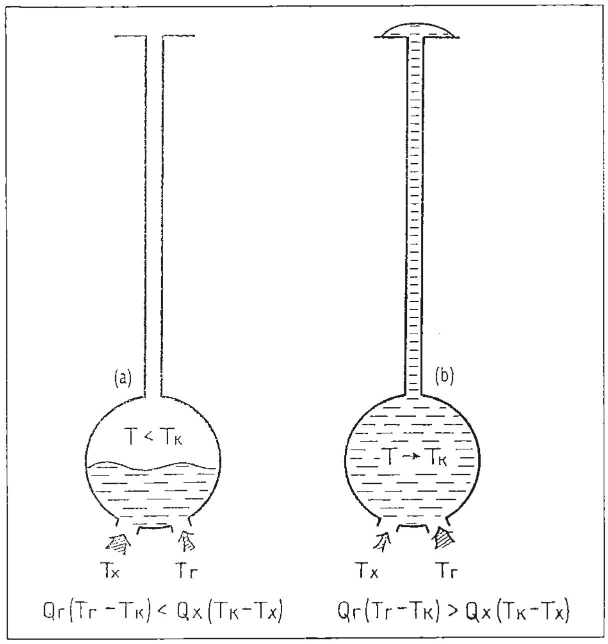

Figure 2. The "Mixing Model". Two streams, "hot" (T_Γ) and "cold" (T_X), enter the underground cavity. At time (a), at the end of an eruption, the temperature of the water in the cavity corresponds to the boiling point T_K. Refilling of the cavity occurs primarily with water colder than T_K and the temperature in the cavity is lowered. At time (b), during an eruption, primarily "hot" water ($T>T_K$) enters the cavity and the temperature in the cavity rises

"The Mixing Model"

Figure 2 represents the schematic of a model that is in accordance with the mechanism of geyser function described in the text of Allen and Day (1935). A mathematical description of the model is provided in the works of G.S. Steinberg.

The model adequately demonstrates that a certain ratio in temperature and discharge of hot and cold water is necessary for the geyser regime to function. It is necessary that the sum total of the temperatures in the two flows after the eruption, while the cavity is being filled, be less than the corresponding Tk temperature at the boiling point, but it must then be higher before an eruption. In the mathematical model, this condition is attained by a decrease in the cold water input coupled with an increase in the hydrostatic head within the geyser tube.

Such conditions may occur in nature in those cases where the discharge of hot and cold water depends in some way on the height of the water column in the geyser tube. For example, there are geysers whose erupted water, cooled off in the open area, then flows back into the geyser channel, ending the eruption.

It is generally known that the hydraulic resistance of a two-phase current is substantially higher than that of a one-phase liquid current with the same gravimetric discharge. Therefore, it is possible to assume that the necessary temperature ratio can be attained when the level of vaporization during an eruption reaches progressively deeper zones, entering into poorly permeable areas. As a result, the influx of hot water is sharply reduced and the total heat content of the waters entering the cavity becomes less than the boiling point (T_K).

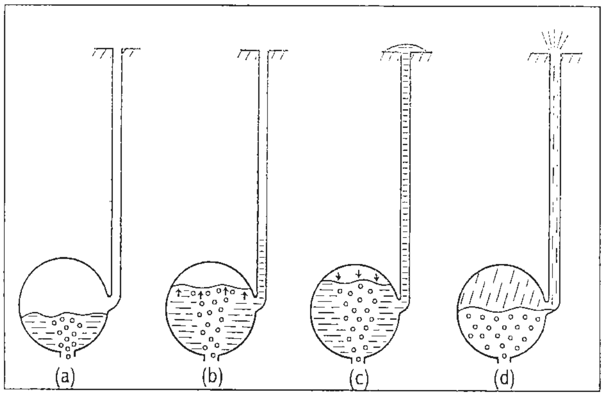

Figure 3. The "Chamber Model". The outflow is lower than the roof of the cavity. Time (a) shows the filling of the cavity and a free exit of steam. By time (b), the exit from the cavity is blocked, and pressure builds. At time (c) sufficient pressure has formed to expel water from the vent, causing overflow. During the eruption at time (d), the pressure declines as water and steam are expelled from the system.

"The Chamber Model"

Figure 3 shows a schematic of the model described in the work of I. Iwasaki (1962). The characteristics of the geyser process that can be realized pursuant to this model can occur in any two-phased mixture — for example gas and water — as the periodicity of its function is basically determined by hydraulic parameters. The thermal parameters play a secondary role. The main condition is the presence of a cavity with a special configuration that guarantees the separation of the volatile component, *e.g.*, steam or gas.

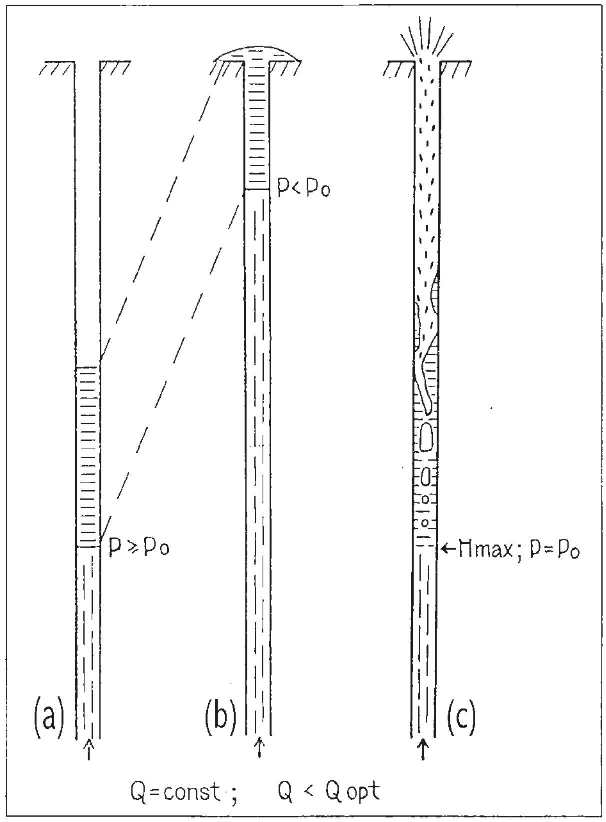

Figure 4. The "Well Model". A constant source of "hot" water (Q) enters the system, its temperature higher than the boiling point at atmospheric pressure. During the quiet period (a) the water does not boil due to the pressure of the overlying "cold" water. With overflow (b) the quantity of overlying water is decreased. During the eruption (c), if the expenditure of water is less than optimal, the level of boiling reaches its possible maximum at (P), a separation of hot and cold water occurs, and the pressure of the overlying water ends the eruption.

"The Well Model"

This model (Fig. 4), as well as the "pipe model", was first proposed by R. Bunsen (1848). A.S. Nehoroshevyi (1956) first described the process that occurs within the geyser tube, while the conditions necessary for geyser activity were formulated by V.V. Averiv (1960). V.A. Droznin (1980) developed a mathematical formula for the discrepancies between the mixing capacities of the vent channel and the heat conductivity of the water strata, based on the general theory of hydrodynamics for a stratified steam/water well system, which compared favorably to experimental data from stratified wells in the Pauzhetska field.

The geyser activity described by the "well model" can occur not only with superheated water, but also with any liquid saturated with gas, for example oil and lava. Therefore, the periodic activity of volcanoes, oil wells and mud volcanoes can also be explained within the framework of "the well model".

Dynamic Characteristics of The Kamchatka Geysers

The geysers that have the largest eruptions and can be observed from the excursion path are described below. The data cited was collected in 1994.

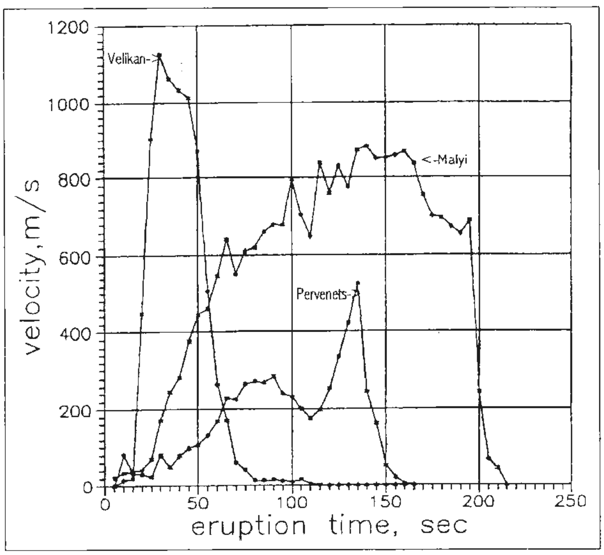

Figure 5. Velocity of discharge, measured at the vent, during the eruptions of the geysers Velikan, Malyi and Pervenets.

Velikan (Giant)

In the Valley of Geysers, Velikan is second only to the geyser Grot in its size. But the latter, unfortunately, generally functions as a pulsating spring. It periodically increases the discharge of water overflowing from its pool to 10 - 15 liters/second. When Grot was active during August – October 1991, its bursts had a length of 50 meters and enveloped the entire area of Vitrazh. The eruptions consisted of a series of four to seven bursts of gradually weakening power that occurred at 2 - 3 minute intervals. The volume of the erupted water was about 50-60 m^3. The intervening quiet period lasted about 4 hours.

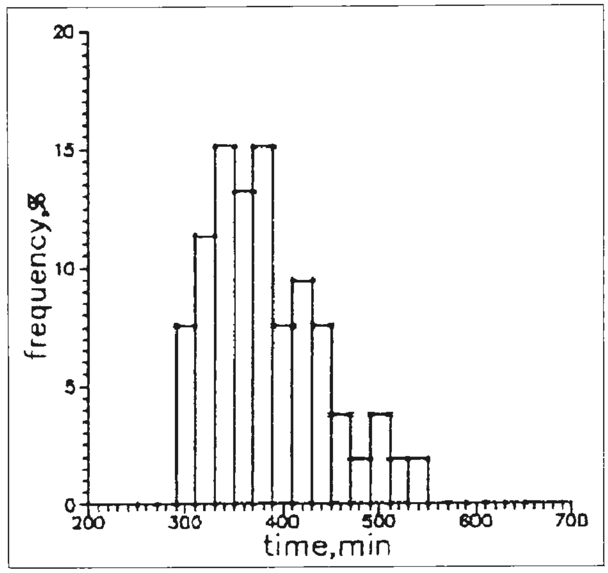

Figure 6. Frequency distribution of intervals for Velikan Geyser.

An eruption of the geyser Velikan is quite short (Fig. 5), lasting just a little over one minute. But in that time the geyser's system is emptied, discharging about 20 m^3 of water that flows westward down the runoff channel. The diameter of Velikan's water column is 1.4 m, and its height varies at 20 meters or more (the cloud of steam rises to the height of 200 - 300 m) (Fig. 23).

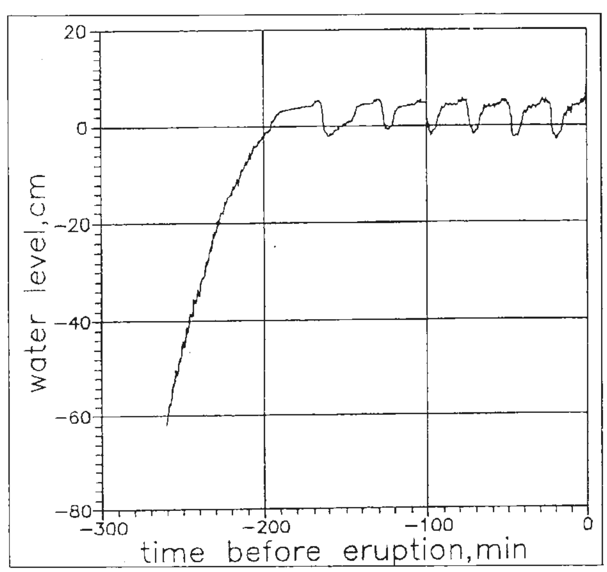

Figure 7. Typical changes in water level prior to an eruption of Velikan. In this case, Velikan erupted on the seventh hot period.

Figure 8. Velikan Geyser. Boiling and heavy overflow during a hot period. (Vachuda photo).

periods. The mechanism of the second process, which causes the main eruption, corresponds to "the mixing model". The large dimension of Velikan's pool (12 m^3) is very important in this regard, since it is able to accommodate rising steam, whose temperature is 130° C, and to cool it to 100° C. Since 1941, the average number of hot periods per cycle has increased from two or three to between 7 and 10, and correspondingly, Velikan's average interval has increased from 3 to 7 hours.

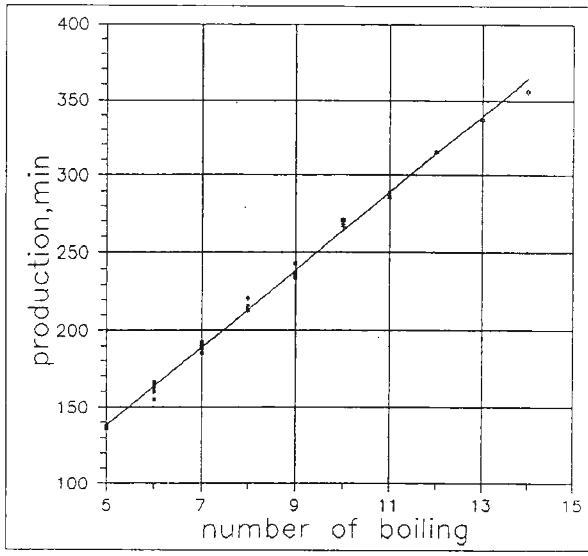

Figure 9. Velikan Geyser: correlation between number of hot periods and the length of overflow.

A distinguishing characteristic of Velikan is the irregularity of its interval (Fig. 6). There is a rest phase, which consistently lasts between 160 and 180 minutes, during which the underground plumbing system and the pool refills (Fig. 7). The subsequent overflow, which averages about 1 liter/second, is regularly punctuated by periods of splashing and heavy overflow (Fig. 8). The number of these hot periods determines the length of the overflow and hence the length of the interval (Fig 9).

Generally speaking, two geyser processes can be discerned in Velikan's pattern of activity. One, occurring at about 26 minute intervals, is dependent on "the well model" mechanism and explains the periodicity of the intermediate hot

Bolshoi (The Large One)

This geyser, like Velikan, has a large pool (1.5 x 3.2 x 3 m^3). During an eruption, which lasts over ten minutes, no steady water column is formed. Rather, the eruption consists of separate outbursts, which can reach a height of 12 meters. The free volume within Bolshoi's plumbing system after an eruption, estimated with the addition of cold water, is approximately 16 m^3. As shown in Figure 10, the duration of Bolshoi's rest phase is consistently about 75 minutes; however, the overflow period that precedes the eruption is not constant, lasting either 10 or 40 minutes. The bimodal nature of the distribution of overflow and interval is clearly noticeable: intervals between eruptions tend to be either 90 or

120 minutes long. The frequency of long periods increases in windy conditions and on rainy days.

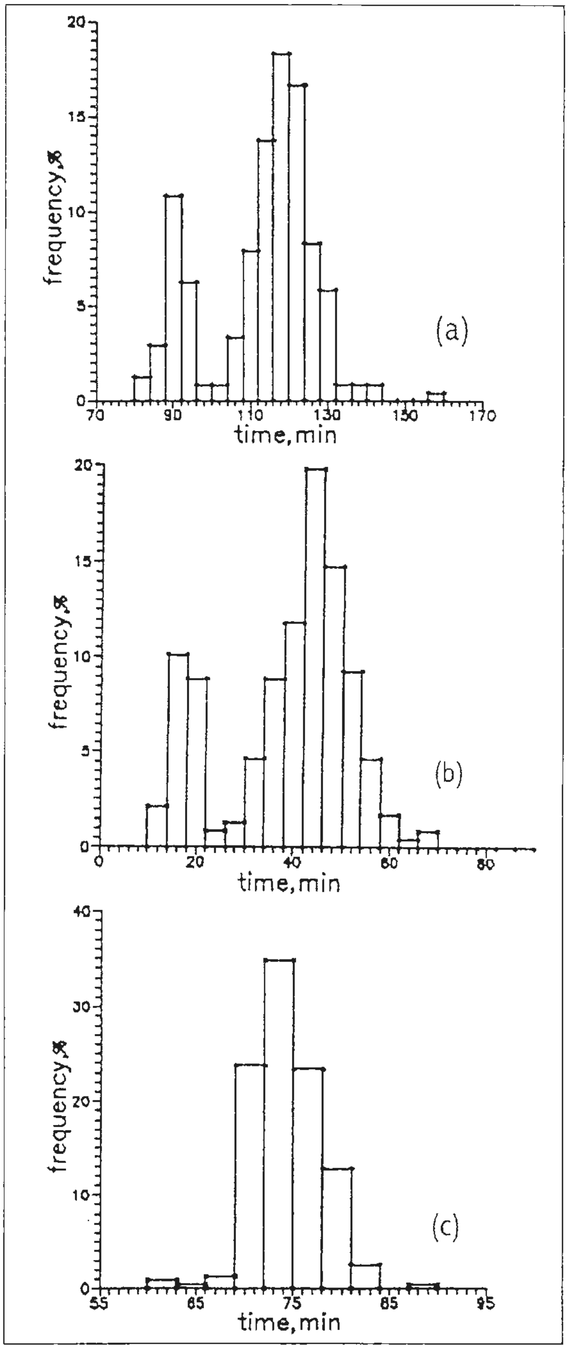

Figure 10. Bolshoi Geyser. Frequency distributions of (a) intervals, (b) overflow, and (c) rest period.

Malyi (The Little One)

The name of this geyser is justifiable only when one compares its smallish pool to those of Velikan and Bolshoi. During its eruption, which lasts about 6 minutes, a powerful, roaring column of steam and water is formed, reaching a height of 15 meters (Fig.22). A cross section of the base of the column is 0.8 x 0.4 meters, and the velocity of discharge during the eruption is about 8 m/sec (Fig.5). The rate of discharge during overflow, judging by the rate of fill, is over 6.5 l/sec. So the volume of water expended during each cycle is 2 m^3 during overflow and 9 m^3 during the eruption (of which 0.6 tons is steam). Since Malyi's interval is about 40 minutes, its average water discharge is 10 times that of Velikan and nearly twice that of Bolshoi.

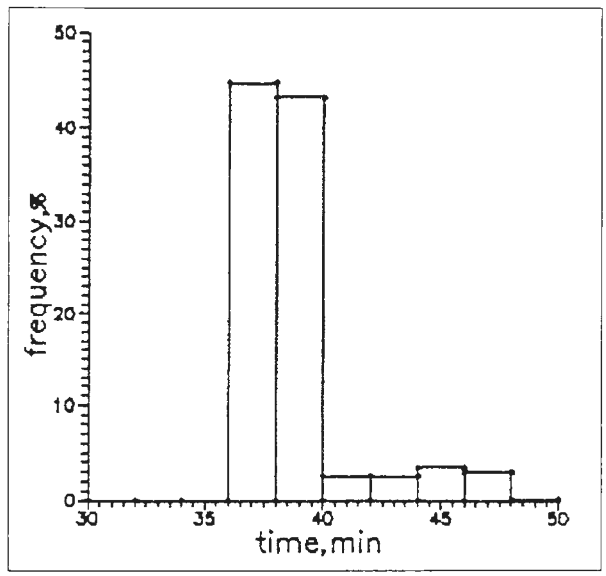

Figure 11. Malyi Geyser. Frequency distribution of intervals.

Malyi's intervals are fairly regular (Fig.11). In comparison to 1941, the interval has increased by 8 or 9 minutes, although the length of the overflow (6 min.) and of the duration of the eruption has not changed.

Shchel (Crack)

A peculiarity of this geyser is that its eruption is not preceded by overflow. The eruption lasts only a minute and its height is only 2.5 - 3 meters (Fig. 13), but this geyser's proximity to the excursion path makes it especially attractive for observation. In addition, it erupts regularly, with a very small variation in its intervals (Fig. 12). In 1994 its periodicity suddenly changed due to a landslide, from 36-37 minutes to 26 minutes.

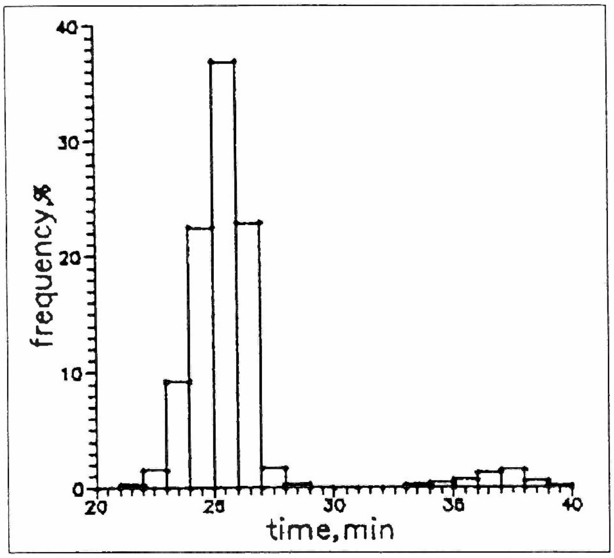

Figure 12. Shchel Geyser. Frequency distribution of intervals.

Figure 13. Shchel Geyser. (Vachuda photo).

Zhemchuzhnyi (Pearly)

During its eruption, which lasts 8 to 10 minutes, a symmetrical water column is formed, which is surrounded by large drops of water that glisten in the sun like pearls (Fig. 15). The initial velocity of the water column is 6 m/sec., and the height of the water column reaches 10 - 12 meters. The length of Zhemchuzhnyi's interval is characterized by a normal distribution, with an average period of about 3.5 hours. The length of the Zhemchuzhnyi's quiet phase is roughly equal to the length of the overflow and eruption.

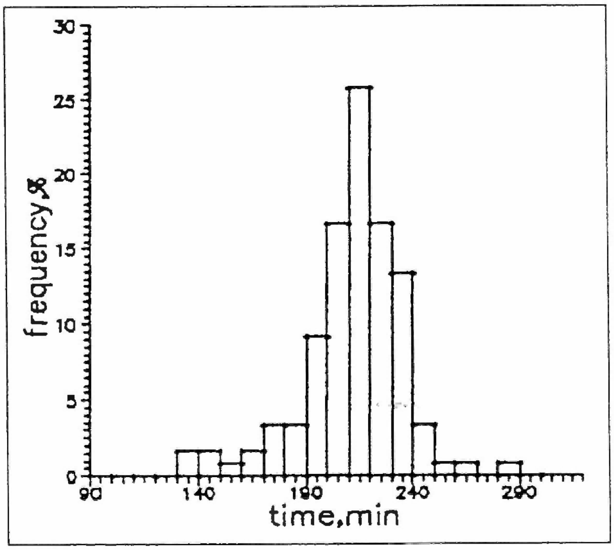

Figure 14. Zhemchuzhnyi Geyser. Frequency distribution of intervals.

The average interval of this geyser has been decreasing for some time, from 5.5 hours in 1941, to 4.2 hours in 1974, to 3.5 hours in 1994 (Fig. 14).

Paryashchii (Steamer)

This geyser does not operate regularly. For several days or hours it remains in the rest phase, then for various lengths of time it pours out boiling water at a rate of 1-3 l/sec.

Averii

This is now considered a boiling hot spring with a pulsating discharge of 10 - 15 l/sec. It had previously functioned as a geyser.

Figure 15. Zhemchuzhnyi Geyser. (Vachuda photo).

Figure 16. Fontan Geyser. The volcanologist on the lower left provides scale. (Vachuda photo).

Fontan (The Fountain)

Long term, uninterrupted observations of Fontan have not been undertaken. Nearby Novyi Fontan is active most of the time and erupts to 2 or 3 meters. Fontan erupts every 20 - 25 minutes, and its eruption lasts for about 3 - 4 minutes. At first, its eruption is not high — 6 to 8 meters — but then after a short pause it begins to spurt to 12 - 17 meters. It is typical for the water from Fontan to flow partly into the vent of Novyi Fontan, and, at times, to extinguish its activity.

Nepostoyannyi (Inconstant One) and Dvoynoi (The Double)

Both of these geysers, located near each other on the slope of the Vitrazh, produce a sizeable volume of overflow. Their frequent activity consists of irregular, but powerful bursts of water. It is especially interesting to look for the moment of synchronized activity by both vents of the Dvoynoi.

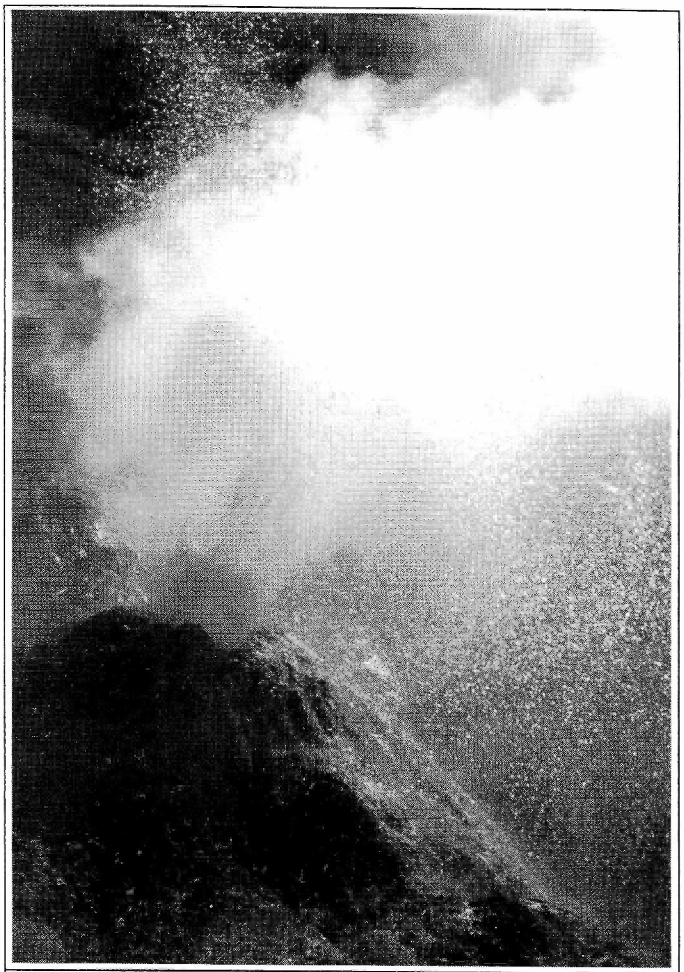

Figure 17. Konus Geyser, also known as Konus Khrustalnyi. (Vachuda photo).

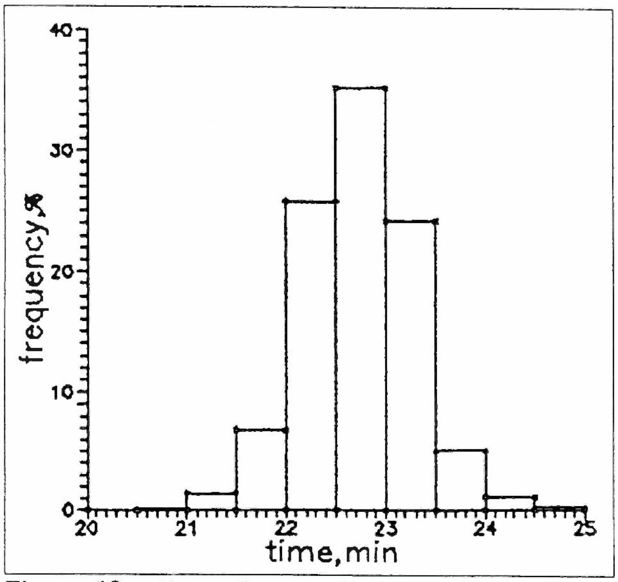

Figure 18. Konus Geyser. Frequency distribution of intervals.

The Chemical Structure of Thermal Water

The chemical structure and the character of the thermal waters undergo definite and regular changes from the presumed area of their source (the massif of the volcano Kihpinych) to the discharge zone in the lower reaches of the river Geysernaya. A change is apparent from the acid sulfates and mixed cation water composition of the grottos of the Kihpinych volcano, to the steam and carbonaceous gas vents of the upper portions of the geyser field, to the alkaline springs and geysers. The mineral content of the water of the boiling springs and geysers, reflecting the composition of the thermal water complex, is generally of the chloride-sodium type. Mineral content does not exceed 2.4 g/l, the pH is alkaline, with elevated levels of silica (up to 430 mg/l), boric acid (up to 150 mg/l), and arsenic (0.4 - 1.7 mg/l).

The variety in the observed compositions of underground waters is determined by hydrothermal differentiation during steam formation and degassing, mixing with groundwater, and discharge conditions. The fluid temperature of water at depth in the areas that supply the geyser basin, determined by use of the hydrochemical geothermometers (Na, K, Ca and SiO), averages 250°C, with the maximum recorded of 330°C).

The total thermal water discharge, determined from the concentration of Cl at the lower stream channel of the Geysernaya River, is 250-300 l/sec.

The natural heat power, determined according to the volume of discharge, is 300 megawatts.

For the analyses of the chemical structure of the geyser water (Fig. 19), samples were taken at the moment of the eruption or immediately beforehand.

	Malyi Geyser			
Sample dates:	7/28/94		8/15/94	
pH	8.82		8.74	
	Mg/l	mg/zkv	mg/l	mg/zkv
NH_4^+	0.1	0.005	0.1	0.01
Na^-	460.0	20.01	423.2	18.41
K^-	25.8	0.66	26.2	0.67
Ca^{2-}	15.2	0.76	16.0	0.80
Mg^{2+}	0.2		0.2	
Cl^-	613.0	17.30	614.2	17.30
SO_4^{2-}	115	2.40	134.4	2.80
HCO_3^-	65.9	1.08	65.3	1.07
CO_3^{2-}	3.0	0.10	2.1	0.07
H_3BO_3	74.8		77.5	
H_4SiO_4 (sol.)	180		169.5	
H_4SiO_4 (col.)	147		75.5	

	Konus Geyser			
Sample dates:	7/28/94		8/17/94	
pH	8.65		9.03	
	mg/l	mg/zkv	mg/l	mg/zkv
NH_4^+	0.1	0.01	1.25	0.07
Na^+	437.0	19.01	433.7	18.87
K^+	30.8	0.79	28.6	0.73
Ca^{2+}	16.0	0.80	16.40	0.82
Mg^{2+}	0.2		0.2	
Cl^-	609.9	17.20	617.7	17.40
SO_4^{2-}	134.5	2.80	134.4	2.80
HCO_3^-	65.9	1.08	59.8	0.98
CO_3^{2-}	1.8	0.06	4.3	0.14
H_3BO_3	73.4		78.9	
H_4SiO_4 (sol.)	173		183	
H_4SiO_4 (col.)	98		107	

	Bolshoi Geyser			
Sample dates:	7/28/94		8/15/94	
pH	8.75		8.71	
	Mg/l	mg/zkv	mg/l	mg/zkv
NH_4^+	0.85	0.04	0.4	0.02
Na^+	535.3	23.28	549.9	23.74
K^-	31.8	0.81	34.3	0.88
Ca^{2-}	24.0	1.20	22.0	1.10
Mg^{2+}	0.2		0.2	
Cl^-	766	21.6	766.8	21.60
SO_4^{2-}	144	3.00	144.0	3.00
HCO_3^-	53.7	0.88	53.7	0.88
CO_3^{2-}	1.8	0.06	1.8	0.06
H_3BO_3	104		89	
H_4SiO_4 (sol.)	188		185	
H_4SiO_4 (col.)	152		106	

	Zhemchuzhnyi Geyser			
Sample dates:	7/29/94		8/16/94	
pH	8.85		8.9	
	mg/l	mg/zkv	mg/l	mg/zkv
NH_4^+	0.4	0.02	0.1	0.01
Na^+	591.4	25.73	608.5	26.47
K^+	38.4	0.98	40.2	1.03
Ca^{2+}	23.6	1.18	22.6	1.13
Mg^{2+}	0.2		0.2	
Cl^-	830	23.40	866.2	24.4
SO_4^{2-}	178	3.70	172.8	3.60
HCO_3^-	67.1	1.10	61.6	1.01
CO_3^{2-}	3.0	0.10	3.3	0.11
H_3BO_3	102		90.3	
H_4SiO_4 (sol.)	180		172	
H_4SiO_4 (col.)	110		214	

	Shchel Geyser			
Sample dates:	7/28/94		8/15/94	
pH	8.50		8.23	
	Mg/l	mg/zkv	mg/l	mg/zkv
NH_4^+	1.7	0.09	1.85	0.10
Na^+	512.6	22.30	87.6	21.21
K^+	36.2	0.93	30.3	0.77
Ca^{2+}	20.2	1.01	18.6	0.93
Mg^{2+}	0.2		0.2	
Cl^-	716	20.2	717.1	20.20
SO_4^{2-}	153.7	3.2	461.3	3.10
HCO_3^-	45.1	0.74	46.4	0.76
CO_3^{2-}	1.2	0.04	0.06	0.02
H_3BO_3	99.0		102	
H_4SiO_4 (sol.)	174		180	
H_4SiO_4 (col.)	172		154	

	Velikan Geyser			
Sample dates:	7/28/94		8/15/94	
pH	8.85		8.9	
	mg/l	mg/zkv	mg/l	mg/zkv
NH_4^+	1.25	0.07	0.4	0.02
Na^+	592.0	25.75	611.8	26.61
K^+	42.7	1.09	44.4	1.14
Ca^{2+}	22.0	1.10	24.0	1.20
Mg^{2+}	0.2		0.2	
Cl^-	851	24.0	873.3	24.60
SO_4^{2-}	153.7	3.2	163.2	3.40
HCO_3^-	66.5	1.09	67.1	1.10
CO_3^{2-}	2.2	0.07	2.1	0.07
H_3BO_3	114		117	
H_4SiO_4 (sol.)	177		137	
H_4SiO_4 (col.)	244		294	

Figure 19. Chemical composition of geyser water.

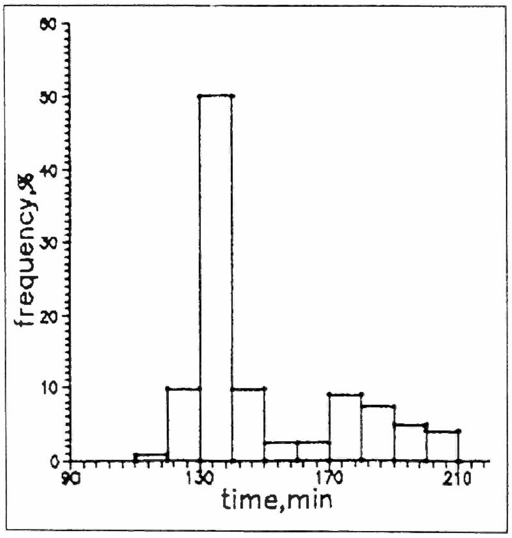

Figure 20. Troynoi Geyser. Frequency distribution of intervals.

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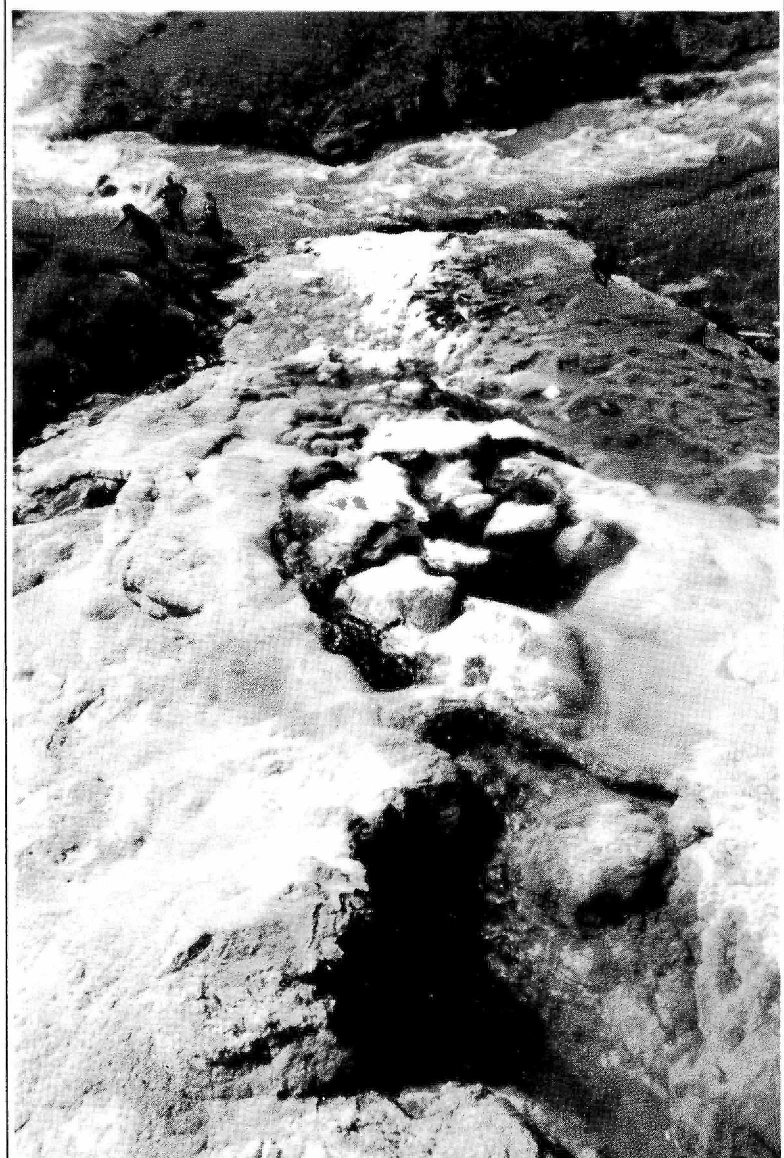

Figure 21. The vents and formations of Troynoi Geyser, looking towards the river. (Vachuda photo).

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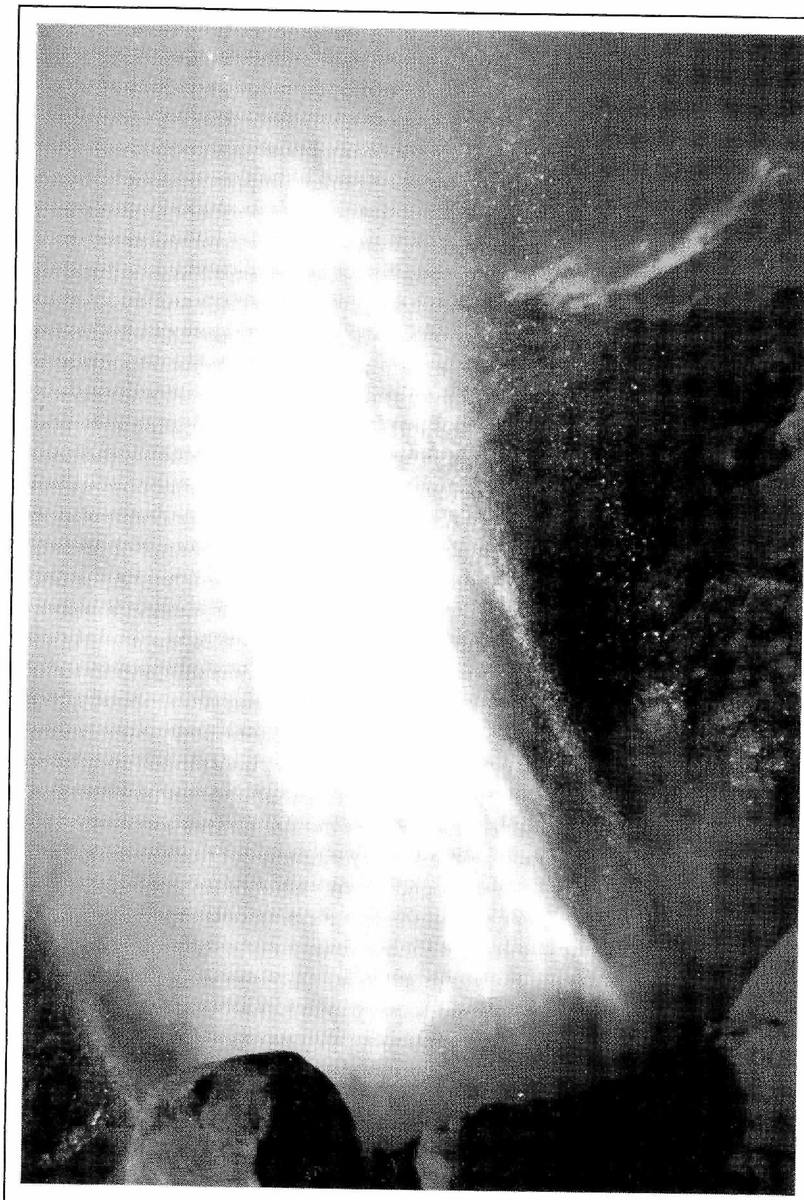

Figure 22. The lower portion of the water column of an eruption of Malyi Geyser. (Vachuda photo).

Figure 23. Velikan Geyser, during a typical eruption. The geyser gazer in the lower right foreground provides scale. (Vachuda photo).