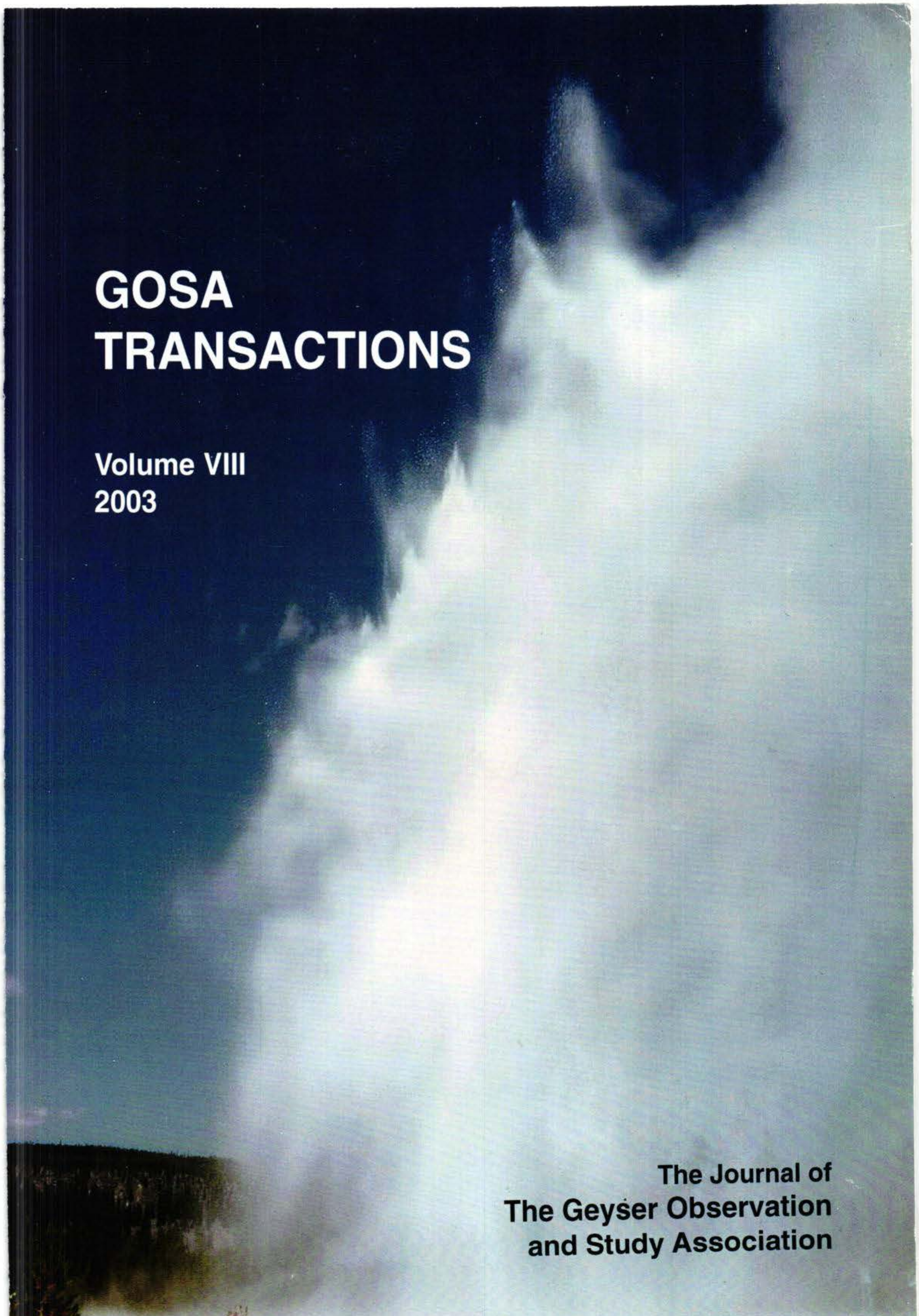
GOSA TRANSACTIONS

Volume VIII
2003

The Journal of
The Geyser Observation
and Study Association



The GOSA Transactions

The Journal of The Geyser Observation and Study Association

Volume VIII
Published October 2003

Senior Editor:
T. Scott Bryan
Indio, California

Editorial Content Readers:

All articles in this volume were reviewed for content and style by at least two people in addition to the editors. Their comments, returned to the authors, resulted in the final copy for publication.

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

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

Cover Photograph:

Splendid Geyser plays considerably less often than, but is also far larger than, nearby Daisy Geyser. Inactive since 1997, this photo shows the geyser during one of its first active phases during the early–1970s rejuvenation of the Daisy Group. See the accompanying article starting on page 12 of this volume. Cover photo by T. Scott Bryan, August 15, 1973.

Printed by:
Four Star Printing
Palmdale, California

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

The Geyser Observation and Study Association (GOSA) is a non–profit organization, incorporated in California as a scientific and educational corporation for the public benefit. GOSA is certified as non–profit under IRS Code 501(c)(3), #94–3093295.

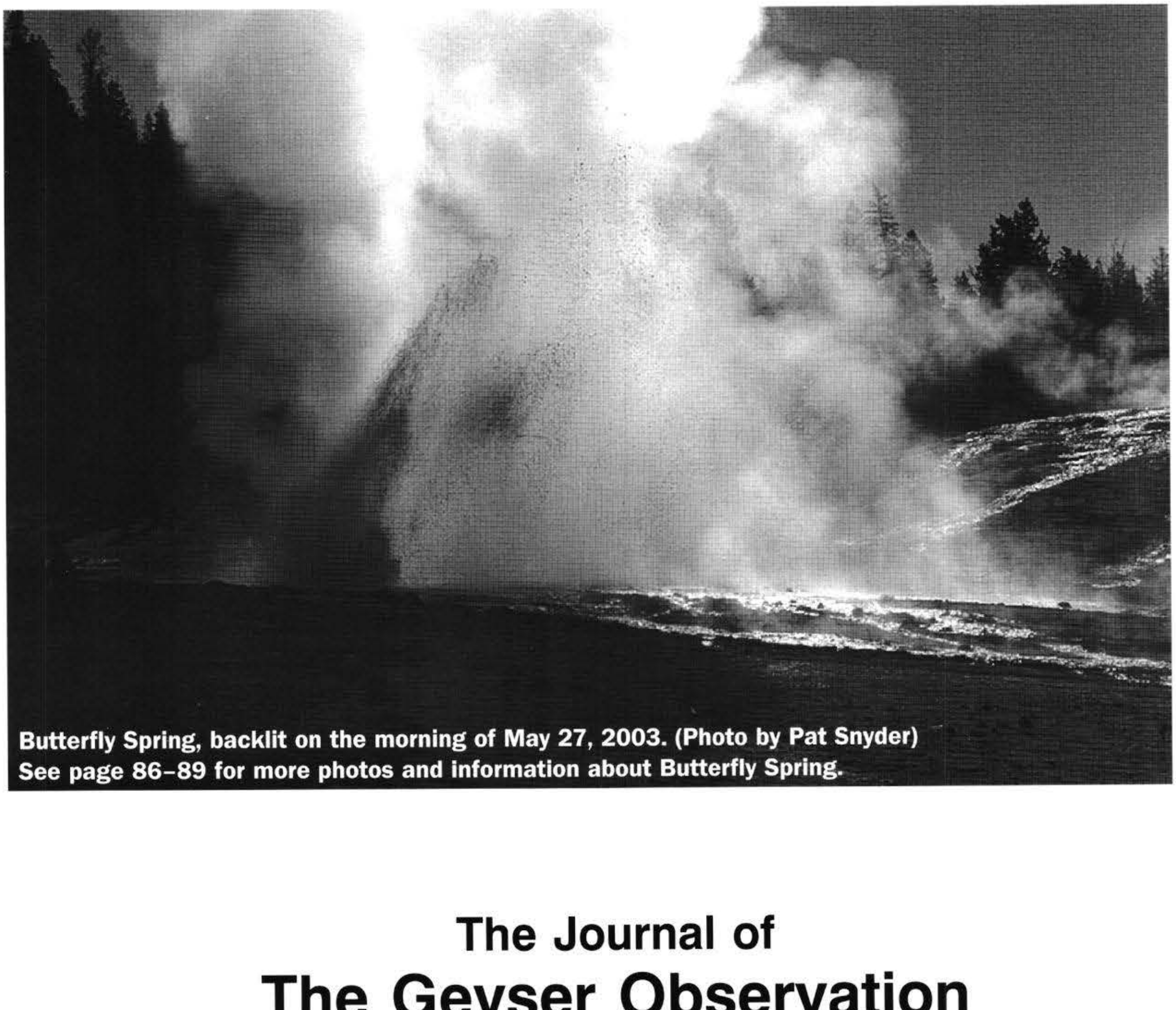
Membership as an associate of GOSA, which includes a subscription to the bimonthly *The Geyser Gazer Sput* newsletter and information about GOSA's other publications, operations and programs, is available from:

The GOSA Store and Press
c/o Udo Freund
39237 Yellowstone Street
Palmdale, California 93551–4155 U.S.A.

For other information, see the GOSA Website: www.geyserstudy.org

GOSA

TRANSACTIONS


Butterfly Spring, backlit on the morning of May 27, 2003. (Photo by Pat Snyder)
See page 86–89 for more photos and information about Butterfly Spring.

The Journal of
The Geyser Observation and Study Association

Volume VIII
2003

An Explanation of GOSA Measurement and Language Conventions

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

Distance and Height Measurements

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

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

Time Measurements and Their Abbreviations

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

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

Other Abbreviations

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

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

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

Past Tense versus Present Tense

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

Baby Daisy Geyser

Previously known active only in 1952, when accompanied by Biscuit Basin Geyser and eight other nearby springs and then alone for a short time following the 1959 earthquake, Baby Daisy Geyser began erupting on about February 14, 2003. The activity was continuing as this volume was in final editing, in late September 2003. The height of eruptions varied between 30 and 50 feet. Most durations were between 2½ and 3 minutes, while intervals varied from only 18 minutes to over 70 minutes with a running average near 40 minutes. A nearby spring, informally called "Baby Splendid Geyser," evidently underwent one or more massive eruptions at the very start of Baby Daisy's activity, but none is known to have been observed. (Photo by Mike Newcomb, May 24, 2003)

Abbreviated Table of Contents

The GOSA Transactions

Volume VIII, 2003

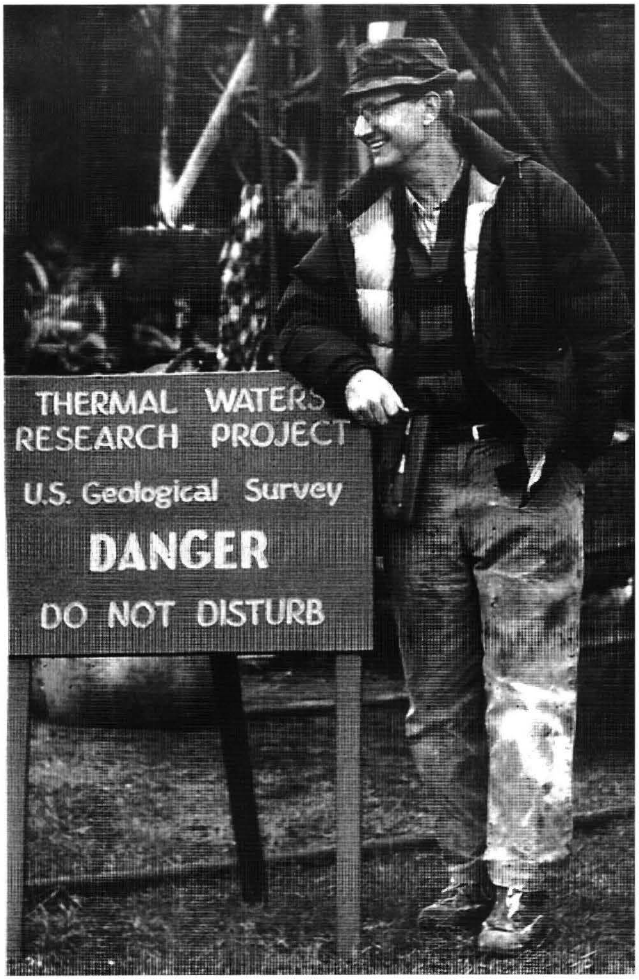
A GOSA Memoir

GOSA

Dr. Donald E. White
May 7, 1914 – November 20, 2002

USGS

Dr. Donald E. White began his career at the U.S. Geological Survey in 1939. During his 54 year career, he was especially well known for his research about the origin of ore–forming metals. Another major focus was geothermal processes, particularly the hot springs system at Yellowstone National Park. He was invited to Mexico, Iceland, New Zealand, China and numerous other countries throughout the world, in order to deliver professional presentations and to serve as consultant. Because of research and theoretical contributions to geology, he was selected to the National Academy of Science in 1973. He also earned two of the most distinguished awards in geology, the Geological Society of America's Penrose Medal in 1984, and the Society of Economic Geologists Penrose Medal in 1992. [from *San Francisco Chronicle*, November 24, 2002]



Dr. Donald E. White, in Yellowstone during the post–earthquake surveys in the1960s. Photograph by Dr. Robert O. Fournier, provided for this publication by Mrs. Helen ('Jo') White.

An eruption of White's "Beowawe Geyser" (his Vent #29), photographed on September 22, 1945. The height was not less than 25 feet.The observer may be Dr. P.F. Fix. Photograph by Dr. White, scanned from USGS Bulletin 1998.

Editor's Introduction. I first met Dr. White while working as a Ranger–Naturalist at Yellowstone's Norris Geyser Basin during the summer of 1974. On one highly educational day, I assisted him and his USGS field partner, Manuel Nathanson, on an all–day spring depth and temperature survey. I was fortunate to also accompany him on several field trips in Yellowstone as well as during a formal mapping project of hydrothermal explosion breccia deposits east of Fishing Bridge.

In later years, Dr. White provided me with copies of numerous reports and publications, as well as a complete set of the USGS "Thermal Maps" that were produced during the 1960s. He strongly promoted all levels of education about geysers. In the course of several personal letters written to me, he encouraged my international geyser research and also, in writing, provided the positive review that convinced the Colorado Associated University Press (old name) to publish the first edition of my *The Geysers of Yellowstone*, in 1979.

I feel privileged to have known Dr. White, at least a little bit, and believe there could be no better memorial in his honor than to publish the following two items that bear on the preservation of geysers. The first is a Memorandum, typed on U.S. Geological Survey letterhead but intended for a New Zealand audience. The second is the text of a talk (and short question–answer session) he presented in New Zealand. In both articles, text that was underlined for emphasis by Dr. White is underlined here; hand written comments that he inserted into the copies he gave to me are inserted, in place within brackets.

T. Scott Bryan, Editor

United States
Department of the Interior
Geological Survey
Geologic Division
Menlo Park, California

February 26, 1979

MEMORANDUM: To Whom It May Concern

From: Donald E. White

Subject: Effects of geothermal exploitation on natural geysers, specifically with respect to Whakarewarewa, New Zealand

I have recently been advised of tentative plans to utilize the geothermal energy of the Whakarewarewa area by the New Zealand Forest Service. As a non–New Zealander, I am fully aware that the basic decisions must be made by New Zealanders; my function must be limited to that of an interested advisor. The purpose of this memo is to insure that New Zealanders are fully aware of the effects that deep geothermal exploitation has had on natural geysers of other areas, and is likely to have on Whaka if present plans are carried out.

My experience with geothermal systems and natural geysers extends over 35 years of professional study, from 1944 to the present time. During nearly all of this interval I have benefited from innumerable contacts with New Zealand scientists and I have visited New Zealand's principal hot spring and geyser areas in 1949, 1965, and most extensively, 1977. I am interested in seeing the results of my studies applied to the utilization of geothermal energy, but I become a strong conservationist when major geyser areas are threatened. For any given geyser area, we have the choice of exploitation for geothermal energy, or non–exploitation for preservation of the natural geysers. In general, <u>we cannot exploit the geothermal energy</u> of an area and <u>also preserve its geysers</u>.

Whakarewarewa seemingly is an exception to the above statement, where the city of Rotorua is extensively utilizing its hot water resources without clear–cut effects on Whaka's nearby geysers. Let me return to Whaka after reviewing briefly the effects of exploitation that I have observed in other geyser areas.

True geyser action is one of the rarest phenomena of nature. In general, many hundreds of hot springs exist for every notable geyser. Although natural geysers have been observed in perhaps 30 different areas, only 10 to 12 were really outstanding, according to my personal evaluation. Three of these areas were in Iceland, three in New Zealand (four, if Waimangu is included), two in the United States, one (possibly two) in Chile, and one in Kamchatka, U.S.S.R. Although opinions would differ in the ranking of these areas according to number, magnitude, and beauty of their geysers, New Zealand's Orakeikorako, Geyser Valley, and Whakarewarewa were probably surpassed only by two or three other areas in the world.

Of my ten world–ranking areas, only Yellowstone Park, U.S.A., Uzon Geyser Valley, [Kamchatka] U.S.S.R., and Hveravellir in Iceland are essentially undisturbed. Four other areas have been adversely affected by man's activities [in New Zealand, Whaka and Orakeikorako, El Tatio, Chile, and Steamboat H.S., Nevada, U.S.A.], and at least three major areas (Geyser Valley, New Zealand, Beowawe Geysers, Nevada, U.S.A., and the Hveragerdi area, Iceland) and several minor areas have seen the total destruction of their geysers.

In New Zealand, Orakeikorako is still outstanding but was greatly changed by the damming of the Waikato River in 1961. Geyser Valley was the principal natural discharge area of the Wairakei geothermal system. In 1949 at the time of my first visit, this area would have ranked perhaps 5th among the major geyser areas of the world, but discharge of water from springs and geysers started to decline in the late 1950's coincident with Wairakei's declining reservoir pressure. The last natural geyser eruption in Geyser Valley occurred shortly before my 1965 visit. Wairakei's declining pressure has evidently affected the seemingly independent Tauhara (Taupo) system [from 1 to 4 km SE of Wairakei]; interconnection at depth was proved when Tauhara's pressure also decreased, and the less well known geysers of The Spa ceased erupting in the 1960s. [Except for Tauhara (The Spa), the affected geyser areas responded to exploitation of each individual geyser system by diverting the geyser "supply" water through discharging wells.] In 1977, at the time of my last visit to both of these areas, trails and geyser cones were overgrown by vegetation, only a few small steaming areas remained, and tourist interest was essentially nil.

The little–known Beowawe Geysers of Nevada, U.S.A., was second to Yellowstone on the North American continent. At least thirty of the fifty existing vents were personally observed to erupt as active geysers (the highest proportion on record) between 1945 and 1958, when geothermal exploration began. Four productive wells were drilled but the quantity of steam was insufficient to be commercial at the time. The wells were permitted to discharge and by 1961 <u>all</u> springs and geysers had ceased flowing. A similar destruction of the small geysers of Steamboat Springs, Nevada, occurred in response to geothermal exploitation between 1950 and the early 1960's.

Thus, I can state that the natural geysers of at least four different areas have become inactive, coinciding with geothermal exploitation. Such results are not surprising, and in fact should actually have been expected. The <u>natural discharge</u> of <u>water</u> and <u>heat</u> is increased by <u>two to ten</u> times by most exploitation programs. Even a small production from wells — say, 10 percent of natural discharge — bypasses the natural vents, and is almost certain to result in some changes. However, detailed measurements and observations over a number of years may be necessary to prove change, largely because of the natural variations that relate to rainfall, earthquakes, and other phenomena.

Let us now return to Whaka. This is still an outstanding geyser area, extremely important to New Zealand's tourist industry and the local Maori people. More than 300 shallow wells utilize the hot water and heat in Rotorua, down–slope to the north from the Whaka geyser area. This extensive utilization is widely interpreted as indicating infinite geothermal resources in the Whaka–Rotorua system, but such a conclusion is unwarranted and is probably drastically incorrect. Unfortunately, no detailed studies have been made to determine the interrelationships between Whaka and the Rotorua withdrawls. The shallow wells are probably in a subsurface thermal tongue that flows northward from Whaka, and thus would be on the low–pressure outflow part of the Whaka system. The estimated flows of hot water from all Rotorua drillholes in 1965 was only about 12 percent of Wairakei's drillhole discharge. This relatively small production, probably from the outflow end of Whaka's system, and the natural variability of Whaka's activity are believed to account for the lack of obvious correlations to date.

Deep production from the Whaka system seems certain to affect not only Whaka's geysers, the Maori people, and a thriving tourist industry, but probably also, in time, the shallow Rotorua wells. I have cited four areas where geothermal production has destroyed the natural activity, and other geyser areas are adversely affected. The proposed deep well of the Forest Research Institute, producing from the heart of the Whaka system, seems certain to destroy the geysers of this outstanding area. Unfortunately, the average New Zealander is probably completely unaware of these threats. Any changes, once made, are probably irreversable within our lifetimes, and perhaps not even in hundreds of years. I hope that all New Zealanders associated with this project will consider their actions carefully and will avoid precipitate action that could lead to unfortunate consequences.

— signed *Donald E. White* —

Unidentified except for hand–written "by USGS" and "1948" labels, this photograph was obtained from the Nevada Department of Transportation in October 1986. Almost beyond question is that this picture was taken by Dr. White on the occasion of his 1948 visit to Beowawe, when his "Teakettle Geyser" was at its most vigorous. The angled jet from one of the twin vents invariably reached over 15 feet high.

UNITED STATES ATTITUDE TO GEOTHERMAL SYSTEMS

text of illustrated public lecture
presented before *Geothermal Systems: Energy, Tourism and Conservation*,
a seminar organised jointly by the
Nature Conservation Council and the
Environmental Defence Society
Rotorua, New Zealand
10th and 11th October, 1981.

by
D. E. White
U.S. Geological Survey

The title of the talk I have been invited to give is "United States Attitudes to Geothermal Systems." There is very little that I wish to say directly on this, but you will be able to infer some attitudes from the material I subsequently present.

The situation is that there is no one attitude expressed by government departments and other bodies. There are as many attitudes in the United States as there are here, and they range from those advocating the immediate and complete exploitation of geothermal systems for energy purposes to those who advocate complete and permanent protection. My views are somewhere in the middle; it is clear to me that reserves of gas and oil are rapidly diminishing, and if we want to maintain standards of living even close to those of the present, other energy sources must take their place. Geothermal energy clearly should play a role in countries with favorable resources. This is particularly true in developing countries whose people may be living near subsistence levels, with few choices of undeveloped energy resources. We would never presume to say that they should not use any geothermal resources they may have. In New Zealand, the choice can lie somewhere in the range between complete exploitation and complete preservation. The choice must be made by New Zealanders, and not even strong recommendations should be made by outsiders such as myself. However, I hope that I can be useful in helping to understand some of the fundamental questions, so that there will be informed public opinion and informed government opinion when the critical decisions are being made.

My focus will first be on the United States, followed by a few experiences elsewhere. Let me first comment on The Geysers geothermal field in California. This was initially drilled about 60 years ago but was not developed then because bankers and financial institutions distrusted the reliability of geothermal energy. At that time, coal, oil, natural gas, and hydropower were all abundant and low in cost. All drilled wells produced super–heated steam, that could have been used to generate electricity. In recent years The Geysers has become the world's foremost producer of geothermal electricity, presently generating more than 1000MW of electricity, and expansion is continuing. Its potential as a major source of power seems assured. Incidentally, the name of the area, "The Geysers," is in fact a misnomer. The field produces steam alone, and there are no true geysers or flowing springs.

In New Zealand, the United States, and elsewhere, intense geothermal systems occur in close association with volcanism. I shall next outline what we know of recent volcanic and geothermal activity at Yellowstone National Park.

Intense volcanism here has resulted in major ignimbritic eruptions on three different occasions—the first was about two million years ago, the next was eight hundred thousand years later, and the third followed in six hundred thousand years. This last major event was about 600,000 years ago and with the recognition of major heat anomalies underlying Yellowstone, and with other striking geophysical properties, it seems highly probably that a huge "pot" of magma is there again beneath it now. We don't know if another ignimbritic eruption will occur or not, but the potential for one seems to be there.

It is only comparatively recently in the history of the United States that it was recognized what thermal manifestations occurred at Yellowstone. During the very early 1800's, trappers had come back with fantastic tales of spouting, boiling springs, but these were not generally believed. Not until a properly equipped expedition explored the area in 1870 and returned with a good photographic record did the full extent become known. Only two years later this area was declared a National Park — the first in the world. [I emphasized not only the first, but still the most remarkable, with more geysers and boiling springs than in all other areas of the world together! DEW]

The geysers of Yellowstone, such as Old Faithful, are now world–famous. There are dozens of geysers, each with its own characteristics: Daisy Geyser plays out at an angle of about 50º; Seismic Geyser developed after a major earthquake in 1959 and its development was studied in detail as it evolved from a new crack in sinter, a small spouting spring that enlarged itself to a major geyser in about 5 years; Grand Geyser is one of the largest and most powerful that is regularly active today. Yellowstone indeed at the end of the last century held the record for having the largest geyser in the world — Excelsior (until exceeded by Waimangu in New Zealand in the early 1900's). The violence of Excelsior's eruptions, throwing out masses of solid material, eventually so modified the channels and vent that eruptions ceased and today it is an enormous hot spring discharging 20,000 to 40,000 litres per minute of near–boiling water.

One of the more interesting areas in Yellowstone is Norris Basin, which contains the feature currently the world–record holder for spectacle and power — Steamboat Geyser. It is another vent whose behavior was changed apparently by the 1959 earthquake. After this event the geyser increased its height of eruption from an initial 10m to 100m and even more.

Norris Basin contains a wide variety of thermal phenomena. Cinder Pool is one example: a milky–white pool with black "cinders" floating on its surface. Analysis showed the "cinders" to be native sulphur with a small proportion of black iron sulphide. About 1970 I investigated this pool by lowering down a temperature probe. At a depth of about 20m the temperature was recorded as about 90ºC, only slightly higher than at the surface. I then had difficulty getting the probe to go any deeper, but I persisted and eventually found that it sank slowly through something resistant and the temperature rose abruptly to 120ºC, which is the melting temperature of elemental sulphur. Below this the temperature was again roughly constant. When the probe was withdrawn, it was encased in a black crust of the same composition as the surface "cinders." Clearly at the bottom of this spring was a pool of hot molten sulphur.

Another interesting feature in Norris Basin was Minute Geyser which occasionally played 20 to 25m high until 1947. Tourists were responsible for this geyser ceasing activity. They threw rocks in and the western vent was eventually filled. The rocks became firmly cemented with silica and eruptions were prevented.

The interesting and varied chemistry of hot spring areas is best exemplified by Norris Basin — turbid acid sulphate pools with bright colors — chloride water with so much silica that polymerization commences in the spring basin, producing water with an iridescent blue hue. This characteristic appearance immediately indicates a relatively direct connection to a high–temperature geothermal reservoir, at 250ºC or more.

Norris Basin is the site of some very early research investigations of hot spring areas by drilling — back in 1929 and 1930. The U.S. Geological Survey carefully drilled an experimental bore there in 1968 to a depth near 330m, and recorded a temperature close to 240ºC, the highest temperature at such a shallow depth yet identified. Being within a National Park, we tried to be very careful in our research drilling, but even so we had several minor incidents, one of which resulted in the area around being covered by a fine dust. Also we were careful to try to ensure that no changes in behavior of natural features were induced by these investigations.

Another area of intense thermal activity in the U.S. is the region surrounding Lassen Peak, Lassen Volcanic National Park. Here we have a probable example of the rather rare vapor–dominated type of hydrothermal system (like "The Geysers" of California). Since this is a National Park, we hope it is protected from exploitation.

Beowawe Geysers, in Nevada, is a thermal area in a semi–arid region. Its springs mostly discharged along the crest of a sinter terrace formed on a fault that ran near the base of a low range of hills. Prior to 1958 about 50 springs discharged from the crest of the terrace, and about 30 of them were geysers — the highest proportion of geysers to total springs known anywhere in the world.

The largest geyser erupted nearly 10m high and five others were 3 to 5m high. This area was second only to Yellowstone on the North American continent for its geyser activity. Today, some efforts might have been made to preserve it as a State Park, or a National Monument.

However, the springs were on private land. In the United States at that time, the owner was permitted to do anything he wished. He decided to lease the springs to be explored for geothermal power. Four drill-holes were sunk on the terrace in 1959, and for a while their production was satisfactory, but then declined. The springs on the terrace stopped discharging and soon emitted only steam. The developer evidently thought that the steam escaping from former springs was a leakage that was the cause of the decline, so he bulldozed them all over to try to block the channels. Of course this was not the real cause of his problems and in the end the attempt at exploitation was abandoned. So here was a third alternative to utilization or preservation that are the emphasized choices. Instead of ending up with either geysers or power, the developer ended up with neither. The possibilities still exist for a deep productive reservoir, but the geysers are destroyed and probably could not be revived again in many tens or even hundreds of years. Beowawe is a lesson in geothermal management that should not be forgotten.

Geyser fields, like those in Yellowstone and New Zealand are quite rare — we know of one impressive region in Kamchatka and there may be a few others.

Let me now illustrate changes I have personally observed in New Zealand during my visits to your country in 1949, 1965, 1977 and 1981.

At Ohaki you used to have a beautiful boiling spring with a fretted scalloped sinter margin at the head of a gently sloping open area which had been covered with silica deposits from the spring over many years. On my earliest visit here I saw the spring in this state. On my visit in 1977 all this had changed. Water–level had receded in the spring , flow had ceased, and surrounding sinter had started to collapse and vegetation was starting to take hold. I understand that water from a neighboring bore has recently been diverted to keep the basin full.

At Wairakei Geyser Valley on my first visit I saw most of the geysers playing. By 1965 water–levels had started to recede, and the last geyser had ceased 2 years earlier. These changes resulted from the building of the Wairakei Geothermal Power Station. The Twins Geysers had also ceased and their vent was a steaming cavity surrounded dry sinter. By 1977 the vent was surrounded by a luxuriant growth of vegetation, and almost no steam was coming from the site, which, by this time, was almost unrecognizable. This is similar to what has happened elsewhere in the Geyser Valley, and south of Wairakei, except that some features have become quite vigorous steam–vents.

At this point I should mention that New Zealand pioneered world efforts in utilizing hot water systems for generating electricity. The relation between Wairakei and Geyser Valley was not generally recognized, and destruction of the geysers was not expected.

You also have a problem at Whakarewarewa and Rotorua. At least to the present time, you have apparently been able to keep your geysers (or some of them), and you also can supply local domestic heating and spa requirements. Perhaps there is a fine balance where both can coexist together. However, rainfall varies from year to year, and a series of dry years could critically "overload" the capacity of this remarkable system. Some evidence indicates that the geysers' water supply is declining, and several important geysers and spouters have ceased erupting, even though rainfall has been high. Of critical importance is the establishment of a good monitoring system to determine the changes in pressures and flows that are occurring.

Decisions on the uses to which your geothermal systems are to be put will have to be made by New Zealanders and I wish you well in your decision–making.

I conclude by thanking you for inviting me to address you. ——

Questioner: At Ohaki, which is at present in the investigation stages for power development, you have illustrated the changes that have occurred in the springs and in particular in the main large Ohaki spring. Can you comment on the irreversibility of such changes?

White: I would say that the evidence at Beowawe, where investigation wells only were sunk, is that permanent or semi–permanent changes seem to have occurred. At Yellowstone minor changes were caused by our research drilling in Norris Basin, apparently in spite of our great care. What happened was this. We drilled 130m south of an earlier research hole drilled by the Carnegie Institution of Washington in 1929–1930. We had finished drilling for the season, but when we came back the next season changes were found in the old drill–hole nearby. We filled ours with concrete but the changes did not reverse.

Lloyd: Were the changes at Beowawe during the investigation stage?

White: Yes — 4 wells were sunk, all were investigation, and no commercial productive use has been made of the bores.

Dark: Would you agree that wells ought to be sunk for monitoring purposes?

White: Wells are necessary for a well–designed monitoring system. They can be combinations of shallow wells and deep wells. Certainly, very useful results can be obtained.

Mahon: Observation holes are of course highly desirable.

White: There is an area known as Island Park, a volcanic caldera just southwest of the Yellowstone Park Caldera and geyser basins. A considerable debate in the U.S. has been precipitated by plans to investigate and perhaps use any geothermal resources of Island Park. Many people are worried that the Yellowstone activities may be affected. The Island Park Caldera is sufficiently far away (30km from the nearest significant geyser basin) for careful testing to be allowed, provided that the region in between is monitored for pressure changes that may indicate adverse effects if the work continues. [* I specified my preference for a buffer zone at least 5km wide just outside the Park boundaries; monitoring, including monitoring wells, should be carried on within the buffer zone, and also in any available wells in the Island Park Caldera.] The situation is somewhat similar to the debate over the Rotorua–Whakarewarewa geothermal field except that the distances are greater, and reinjection can be used to maintain reservoir pressures.

Bellamy: I would comment that the situation in New Zealand is different in this way: at least at Yellowstone you have a National Park with all the safeguards that represents. Here there is no thermal that has been allocated for preservation.

White: No nibbling has occurred in Yellowstone so far, but I am not certain that changes in policy might someday allow exploitation even there, although I hope this will never occur.

A geyser at **Pong Hom**, in the San Kamphaeng area of Thailand. In 1979, Dr. White put Scott Bryan in touch with Dr. Tavisakdi Ramingwong, of the University of Chiang Mai. Although this and another feature look as though they might be spouting wells, Dr. Ramingwong states that these are natural, true geysers.

A GOSA Memoir

Marie Wolf

April 6, 1949 — October 21, 2001

Marie Wolf unexpectedly passed away on October 21, 2001. Introduced to geysers in 1971, she became a dedicated geyser gazer in 1972 when she began summer employment in Yellowstone (that year in Mammoth Hot Springs, subsequently at Old Faithful). In company with her future husband, Rocco Paperiello, who she married in 1987, she developed an intimate familiarity with geysers throughout Yellowstone, and she co–authored the *Report on Lesser Known Thermal Units of Yellowstone National Park, 1981–1985*, a typescript manuscript of 1,271 pages illustrated with her sketches that is now available from GOSA. Marie also served as the primary editor of *The GOSA Transactions*, Volume VI.

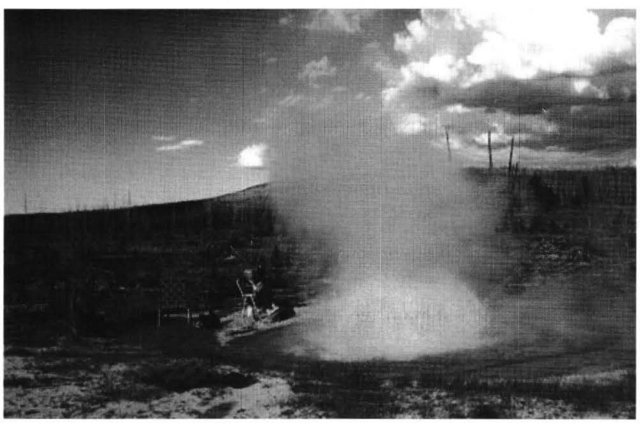
Marie was above all fascinated by the complex activity of the Daisy Geyser Group. She came to be known as 'Daisy Marie' because of the great amount of time she spent in that area. She presented the following paper to Yellowstone National Park in 1978, while serving as a "Volunteer in Parks" observer. The original was a typescript manuscript. Marie gave a photocopy to editor Scott Bryan in 1980, and that served as the master for this transcription.

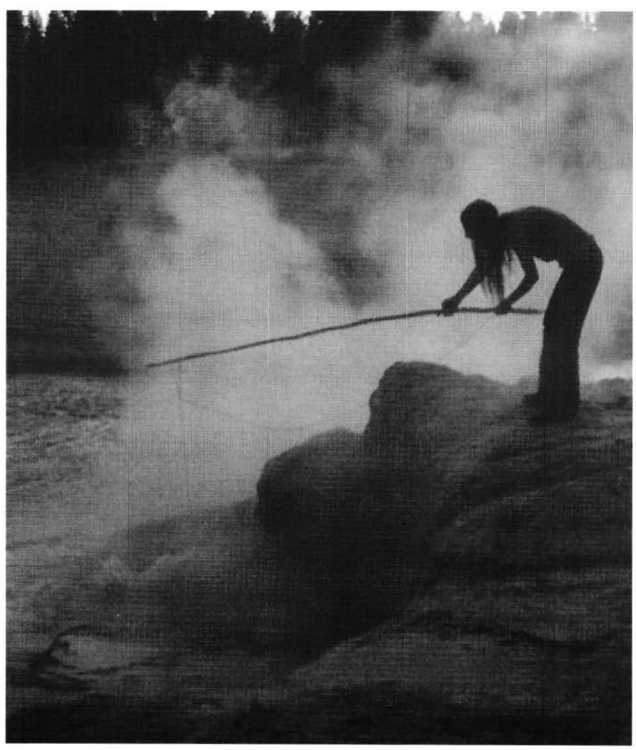
In editing the paper for this memoir, only a few minor grammatical alterations were made to the text. Otherwise, the language, mode of expression, punctuation, numerical values, usage of time units and so on are unmodified from Marie's original. The footnotes and historic photos with bracketed, in–text references to them have been added by the editor.

Several comments within the manuscript imply that this paper was intended to be the first in a series of reports about the Daisy Group. Marie certainly made many more years of detailed observations of those geysers, but if such papers were ever written and distributed, then I have never seen them.

Her several references to observations by Dr. George Marler are probably to his published *Inventory of Thermal Features of the Firehole River Geyser Basins...* [1973], or to the smaller *Studies of Geysers and Hot Springs along the Firehole River...* [1971]. Dr. Marler retired following the 1971 season and in 1972 presented only a single "Tuesday Night Seminar" talk to the ranger staff.

T. Scott Bryan, Editor





Above — Look closely and you'll see Marie Wolf ensconced in a chair while enjoying an eruption of Mud Spring, a feature rarely seen in eruption in the Upper Geyser Basin's Pine Springs Group. (Photo by Mike Keller)
Right — In earlier years, Marie's service as a Volunteer in Parks included thermal observations in the geyser basins, such as taking the temperature of a boiling, overflowing Riverside Geyser. (Photo by Chris MacIntosh, September 1975)

The Early 1970s Rejuvenation of the Daisy Geyser Group

Overview of activity from 1971 through 1973

By Marie Wolf

all photos by T. Scott Bryan

Abstract

With the exception of two brief episodes of action in 1968, the geysers of the Daisy Group were dormant from February 1961 until July 1971. This paper provides a record of the detailed observations that were conducted during the first three summers of this rejuvenation.

PART I
How It All Started

1967 and 1968

It is relatively well–known that that the magnitude 7.3 Hebgen Lake earthquake of 1959 caused all major units of the Daisy Group to cease eruptive activity by 1961. Bonita Pool, just to the east of Daisy Geyser itself [Figure 1], began a perpetual overflow that continued, with only occasional ebbing, for nearly ten years.

In 1967, Bonita was discovered in a state of ebb on a number of occasions, during which times the water level and surging activity in Daisy rose. There were, however, no reported eruptions.

On July 31, 1968, the first eruption of Daisy in eight years was reported. After this, a general shift of water and heat energy was noted, as the water levels in Brilliant Pool, Daisy Geyser and Splendid Geyser rose two inches, and there was a noticeable increase in the vigor of Daisy's surging.

No further activity was noted until September of 1968. On September 18, there were sixteen known tremors in the Old Faithful area, some of which could be heard indoors. On the night of the 19th, Splendid erupted for the first time since 1959. Daisy followed with nine known plays, all but two of which were announced by eruptions of Daisy's Thief.

For Daisy to be triggered by eruptions of one of the westernmost geysers was something relatively new. It was to set a pattern that played a most important role in the activity of the 1970s.

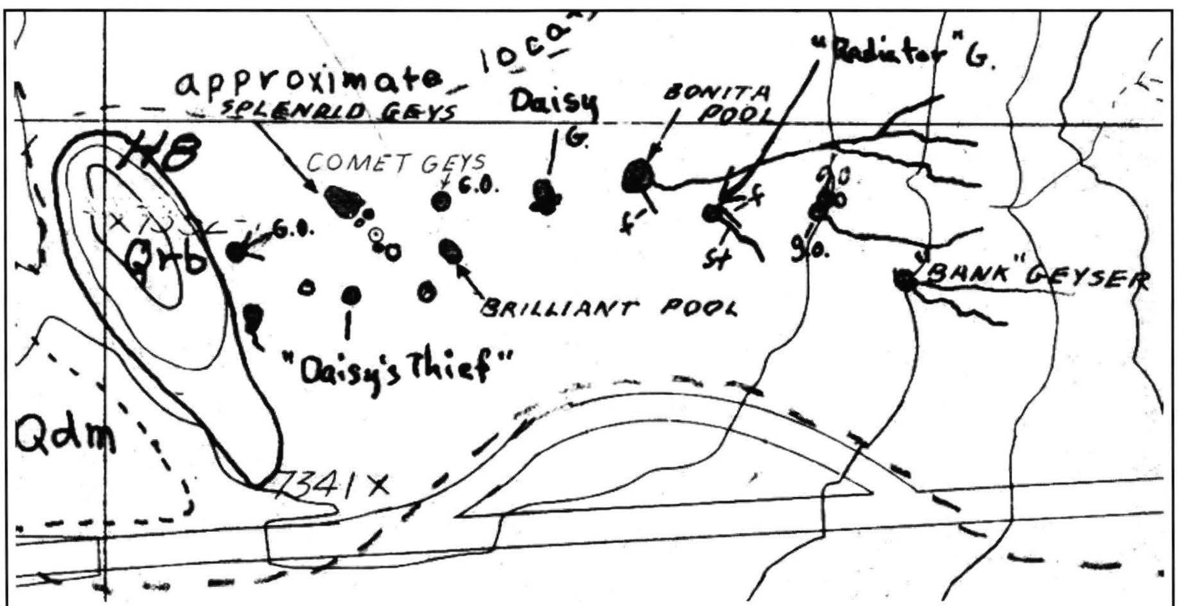


Figure 1. Map of the Daisy Geyser Group, Upper Geyser Basin, Yellowstone National Park. Scanned from the USGS Thermal Map V.A.2. "Hillside." North is up; scale is enlarged to 1 inch = approx. 125 feet. Names with lower–case lettering added by Dr. Donald E. White.

July 22–23, 1971 — A day-and-a-half of action

A lot of fingers were crossed after the slight rejuvenation of 1968. Yet no further eruptions of either Daisy or Splendid were known to have occurred until 1971.

On July 22, 1971, three plays of Splendid were witnessed at intervals of less than 2 hours. No evidence of soap was discovered, except for a trace of foam in the small vents between Splendid and Brilliant Pool. But Marler does report that the barometer was low that day — and Splendid was even then suspected of being sensitive to barometric pressure. The latter may have been all it took to trigger Splendid, if a general energy shift had already begun in that direction. Often, the only effective way to actually determine these more subtle shifts is to take regular temperature surveys of the entire group; it is doubtful that this had been done. Even if Splendid had been set off by soap, the fact that more than one eruption occurred indicates that some kind of energy shift had taken place.

Figure 2. Daisy Geyser on July 23, 1971, either the first or second eruption of the geyser ever observed by photographer Scott Bryan.

In the early morning hours of July 23, 1971, Daisy began playing [Figure 2]. Observed eruptions took place at 8:25 a.m., 10:36 a.m. and 12:15 p.m., with a final play at 2:25 p.m. At approximately 6:00 p.m., Splendid played again. After this, the energy slipped back to Bonita Pool.

This active phase was brief — but it was the beginning of a whole new round of activity that followed a pattern not seen since the 1880s.

August 1972 into 1973

On August 11, 1972, Daisy and Splendid erupted together in the first concerted action witnessed in this century.

Steam was sighted from the group at 8:40 p.m. from the Visitor Center. Two eager observers headed out immediately to learn the source. What they found was two patches of soaked boardwalk — one in front of each geyser — with a dry space in between. Since the observers had arrived on the scene immediately after the steam was sighted, it was concluded that they had just missed a concerted eruption of both Daisy and Splendid.

No suds were found to indicate soaping, but one observer claimed that the runoff had a slightly soapy taste. The odd taste, however, could just as easily have been attributed to the encrusted algae that had been scoured from the craters of both geysers.

After the concerted action, Daisy followed up at 9:38 p.m. This was a relatively new form of behavior, but it was destined to become common in following years. Instead of being rendered dormant by activity in Splendid, Daisy was now triggered by big brother. Splendid had replaced Daisy's Thief in this function.

At 10:40 p.m., after Daisy's follow–up to the first round of activity, Splendid played again. Three minutes into Splendid's 5–minute eruption, Daisy also took off. The latter eruption was well below even the 75–foot height normal for Daisy, and the column consisted mostly of steam–charged spray. One observer attributed this to Splendid's draft on the water; but I am nearly certain that it was the

Figure 3. Although this picture was taken 24–plus years after the scope of this article, the image of Daisy and Splendid in concert as seen from Grand Geyser might convey a sense of the exciting view that was witnessed on August 11, 1972. (Photo taken June 30, 1997.)

fact that three eruptions — two of them concerted plays — had occurred at intervals little more than an hour long. Splendid by itself uses an estimated 40,000 gallons of water for a solo play; therefore, the first concert must have drained the system substantially. There was no time for a full recovery before Daisy followed; the second concert took place with the water supply already severely depleted.

During this period of frenetic activity, both geysers did a little house cleaning, throwing sinter–encrusted algae considerable distances from their craters.

Exhausted, both geysers then collapsed in repose until 1:26 a.m. of August 12, when Daisy initiated a series of plays at approximately 90–minute intervals. The second eruption occurred at 3:05 a.m., and a third took place between 3:05 and 7:00 a.m. (there may have actually been *two* unwitnessed plays in this span of time, but we will never know for certain).

Shortly after 7:00 a.m., Bonita Pool began overflowing again, once more putting a stop to further major geyser activity.

Further activity resumed August 19, when Daisy and Splendid once again erupted in concert — this time coughing out at least six bars of soap. Daisy had one follow–up amid the suds before Bonita snatched the energy back.

On September 1, Splendid had a natural eruption at 5:30 p.m. (This was the first eruption of either geyser that I personally witnessed; I was stationed at Mammoth in '72, and watched geysers only on days off.) Daisy followed at 6:42. No more activity occurred that night until 8:00 p.m., when Daisy and Bonita had an overflow race. Daisy won the race, but Splendid began surging violently, then erupted at 8:06. Splendid's play lasted 4 minutes, and Daisy joined in 1 minute after big brother had started.

After this concerted action, Daisy had the usual follow–up — then continued to erupt at just over hourly intervals over the entire day of September 2. Daisy preceded by overflow every eruption but the two that immediately followed Splendid. During this time, Bonita Pool never filled more than half way.

This activity was the beginning of renewed activity in the group. During the latter part of 1972 and the early months of 1973, Daisy developed a regular routine of activity consisting of 3 to 5 days of regular eruptions, separated by 10 days of quiet. During the active phases, Daisy preceded each eruption with overflow, which kept Bonita from filling more than half way; intervals of Daisy ran 90 minutes to 2 hours. After the 3 to 5 days was up, Bonita would fill and begin overflowing, which would effectively stop Daisy for a 10 to 14 day period.

Activity in Splendid was seldom reported during these months. But, since there were very few people here to observe geyser activity at that time, it is my opinion that it was this lack of observers that accounted for the lack of reports on Splendid, and not relative inactivity of the geyser. Based on extensive observations from May to October, 1973, I believe that Splendid was the moving force in keeping Daisy going. After Bonita had been overflowing for over a week at a time, it was most likely Splendid who initiated a new round of activity in Daisy by pulling Bonita well below overflow. Once this was accomplished, Daisy had no trouble performing by herself.

By May, 1973, an entirely different pattern had established itself. Both geysers proceeded to break all of the old rules established between 1920 and 1959 — and they entered into a type of activity that had not been witnessed for almost a century.

PART II
1973 — A New Beginning

Recorded active phases for spring and summer, 1973, were as follows:

- March 27 to May 18
- May 30 to June 27
- July 11 to August 19 [1]
- August 27 to September 15
- September 22 to October 9

Cooperation and Interaction — the group as a whole

The activity in the Daisy Group this season was a complex share–and–exchange system of thermal energy among all of the pools and geysers. The actions of each member of the group were tightly interwoven with the actions of the rest of the members.

The active cycle of July 11 to August 19 progressed according to a very exact pattern. Each member played out its part in a careful sequence of events, from beginning to end. Even though this particular cycle provided the best example of the exchange of function among members of the group, all of the rest of the active cycles were but variations of it. This active phase is summarized in the next section.

During all cycles — except the weak one beginning September 22 — Bonita Pool started out weakly and grew stronger. Daisy followed Bonita's activity closely, responding to every change. She started out each cycle playing independently and frequently. Splendid erupted alone. Then, in response to Bonita's steadily–increasing strength, Daisy became increasingly erratic, and dependent upon Splendid to weaken Bonita. Since Daisy was then held in check by Bonita, she was on a hair–trigger nearly every time Splendid played. Thus, toward the end of each cycle, concerted eruptions came with relative frequency; Daisy seldom played, except with or immediately following Splendid. Finally, Bonita stole *all* the energy, eruptions ceased, and periods of quiet ensued.

During quiet periods, Radiator Geyser carried on various minor solo activities. But when Splendid or Daisy played, Radiator often responded by spurting up 3 to 8 feet. Brilliant Pool, too, bubbled and boiled during periods of quiet. But eruptions of Splendid would rouse it frequently to violent eruptions of its own, shooting 5 to 20 feet. Even yukky Bonita Pool was coaxed into several vigorous eruptions by concerted activity of Daisy and Splendid. All of the small geysers — except Comet, upon whom the effect was just the opposite — depended on the big geysers to trigger their eruptions.

As might be expected, Daisy and Splendid themselves were very sympathetic to one another. Both had altered their patterns of activity from those recorded by Marler and his contemporaries. Both played from craters well below overflow, and activity of one no longer brought about dormancy of the other. Instead of stealing energy from each other, they now had a close–knit interrelationship of energy *sharing* that promoted concerted activity.

Splendid inspired Daisy to closely follow his own eruptions. Instead of Splendid knocking

[1] This active cycle actually continued through August 21; see also Footnote 6. However, Marie's "August 19" date has not been changed in this transcription.

Daisy out as in the past, he promoted her activity. If she didn't have the energy to join Splendid for a concert, she responded to his eruptions in other ways — by surging violently as her water level was pulled down, or roaring steam immediately following Splendid, or both. And Daisy exerted her share of influence over Splendid with her quick follow–ups, which, for the most part, put a stop to Splendid's series of eruptions.

Between Daisy, Splendid and Bonita Pool, there was a delicate balance of sharing and controlling that set the stage for concerted activity. For most of the season, Bonita only exerted enough control on Daisy to keep her on a knife's edge, waiting for Splendid. When Splendid played, he then stole just enough energy from Bonita to release Daisy to go off with him. If Bonita had not held Daisy back, she would have blown away her energy and not been ready when Splendid finally erupted. Yet Bonita was *not* so strong that it put restraints on Splendid, too.

It was the tipping of this delicate balance exclusively toward Bonita toward the end of the season that began to ruin everything.

The Energy Shifts of the Cyclic Activity

Between quiet periods and active cycles, there was a distinct shifting of energy from west to east. As the group prepared to resume activity, the energy gradually moved back from east to west. This energy–shifting was quite visible in the behavior of the various springs in the group.

As the energy shifted for a quiet period, certain signs manifested themselves. Usually, for the first day of quiet, Daisy and Splendid would continue to surge as heavily as usual. Then, by the second or third day, Splendid quieted down, and Bonita began splashing more vigorously. (Bonita always overflowed steadily during the geysers' rest periods.) For the first two or three days, Daisy continued to surge fairly heavily, even after Splendid had calmed down. But after three days, Daisy, too, would lose vigor. Brilliant Pool, also, would show no more life than to bubble occasionally. The levels in all major springs rose 3 to 4 inches above their active phase status, with a distinct pool rising even in Comet Geyser's crater. Bonita then splashed 1 to 3 feet, and the holes southeast of Radiator [these are part of today's UNNG–DSG–1 – *ed.*] filled and bubbled. Radiator itself would begin having small quiet–phase eruptions of dry crater type, or splashy plays from a small pool. The levels of Splendid, Comet, Brilliant and Daisy rose to just below overflow, and everything except Bonita remained sluggish or completely quiet.

This state would persist until one to three days before activity was due to start up again. Then the energy also shifted back gradually, before activity resumed.

During this time, Daisy's level would drop an inch or two, and her surging would gradually gain vigor. Radiator began spitting weakly from a dry crater, and the southeast holes dried up. Daisy, Splendid and Brilliant would begin to drop their water levels 2 or 3 inches. A day or two before the first eruptions began, Splendid began surging heavily, and Bonita visibly lost some of its vigor.

The first day or two of activity then further subdued Bonita and pulled the pool out of sight in Comet's crater. As the cycle progressed, the energy gradually shifted back to Bonita, until a new quiet period ensued.

Variations in the Cycles of 1973

The activity of the entire group had a distinct rise, climax and decline over the season, except Bonita who had a steady increase.

The active cycle of May 30 started the rise of events. It was at this time that Splendid seemed to really come alive, while Daisy was yet playing frequently. Almost exclusively, Daisy was having nice, average eruptions 3 to 4 minutes long and 70 to 80 feet high, preceding each with at least 30 minutes of heavy surging 2 to 4 feet high. As Splendid gradually grew more active later in the cycle, he began surging heavily almost all the time — instead of only an hour or so before an eruption. And, because Bonita Pool was beginning to bridle Daisy, the first concerted activity occurred.

During the May 30 cycle, Radiator began showing its first spurts in response to Splendid. Most of these follow–ups jetted only 2 or 3 feet, but it was a beginning. Brilliant also made its debut as a geyser at this time, awakened by Splendid's increasing activity.

The cycle beginning July 11 marked the climax of activity in the group. Daisy's plays were mostly higher (80 to 90 feet) and longer (4 to 5 minutes) than average. Concerted plays were more powerful and prevalent. Surging during pauses between eruptions was vigorous in both geysers (reaching 5 to 10 feet for Splendid, 2 to 4 feet for Daisy), and Splendid was frequently throwing massive 20– to 50–foot bursts. During this time, Radiator played 2 to 8 feet in response to both Splendid and Daisy, and Brilliant nearly always answered Splendid with vigorous eruptions. Even lowly, irritating Bonita Pool erupted on several occasions.

The cycle beginning August 27 marked the beginning of the decline. Daisy's eruptions once again fell to average height and duration, except for an occasional long or short one. Concerted activity, for a time, occurred with relative frequency. But Daisy sometimes lacked the energy to join Splendid; and Splendid began slowing down. During quiet periods, he threw fewer and fewer big bursts, then quit cold before the cycle was even finished. Radiator and Brilliant both played less frequently, and with less vigor, than during the previous cycle.

The active phase of September 22 was pathetic. Splendid played only twice in 15 days, and Daisy only eight times. Quiet period surging became so feeble it did not even clue an observer to impending activity, and Splendid ceased throwing the big bursts altogether. Radiator had only one weak follow–up play, and Brilliant was not seen to erupt at all.

The members of the group played their parts well that summer. But by October 6, it looked as though the curtain was falling on their moment of glory.

Part III
Details on Individual Geysers

Radiator Geyser

Radiator in 1973 played from a nearly–circular basin approximately 18 inches across and 10 inches deep. The vent was located just below a crumbly sinter ledge that bordered it along one side, but did not obscure it in any way. The vent itself was a tiny hole slightly more than an inch in diameter.

Under close inspection, Radiator proved to be a rather versatile little geyser. Its eruptions ranged from spurts 2 or 3 inches high to a stream of water 4 to 6 feet high, sometimes higher. The larger plays followed activity of Daisy and/or Splendid, and thus came mostly in July and August. On July 19 Splendid had an exceptionally large play, and Radiator responded with a stream of water nearly 10 feet high. However, most of its responses to Splendid and Daisy reached only 1 to 2½ feet [Figure 4].

When not pulling follow–ups to its larger neighbors, Radiator frequently carried on a variety of solo activities. These could be divided into two types: eruptions from a dry crater, and eruptions from a shallow pool. Dry crater eruptions squirted water 3 inches to 1 foot in height; most lasted 10 to 50 minutes, but some went on for hours, with pauses of only a few minutes between them. Eruptions from a pool were usually much shorter, lasting less than a minute. Likewise, intervals were also very short. The pool formed at the beginning of each play and drained right afterward, and the spurts jetted 6 inches to 2 feet in fountain–type bursts. Sometimes the two types of eruptions would follow one another, alternating back–and–forth.

During periods of inactivity — even the short intervals between pool–type eruptions — Radiator would hiss, steam and spit spray. Quiet periods characterized by this type of carrying–on often lasted several days, especially when the large geysers were active.

Figure 4. Radiator Geyser, photographed in July 1973.

Southeast of Radiator run two nearly–parallel [*sic* – *"perpendicular"*] fracture vents and the sandy, shallow southeast holes. When Radiator was active, water would spurt from the fracture vents and fill the holes. One, and sometimes both, of the southeast holes would often spurt up 3 to 8 inches at the same time. Then, when Radiator was not erupting, the fracture vents hissed and spat dryly, and all of the water vanished from the holes.

Radiator is a relatively new spring. It apparently formed after the old parking lot had been placed on the flat area east of Bonita. Because of its youth, we can expect numerous changes in its appearance and behavior in the future.

Figure 5. Bonita Pool undergoing one of its "troublesome" eruptions, in July 1973.

Bonita Pool

I tend to agree with Marler that "Bonita" was a misnomer for this blah, colorless spring. It takes a place next to Rift as one of the most worthless and troublesome features in the Upper Basin. With its nondescript sputtering and splashing, it can control the activity of Daisy and Splendid [Figure 5].

Bonita displayed a variety of activity in 1973, most of which served to frustrate unfortunate souls who wished to see Daisy perform. By dissipating energy through a cluster of steam vents on the northwest edge of the crater, Bonita could keep Daisy on a hair–trigger as long as 36 hours without allowing an eruption.

On September 25, a fracture running southeast from Bonita's main vent, along the pool's bottom to the edge, began bubbling vigorously. This sucked even more energy from the geysers. The activity increase lasted nine days, when steam finally ceased to escape from the crack. I have no doubt, however, that the fracture will be heard from again. [2]

During the first portion of Daisy's July 11 active phase Bonita behaved very strangely, much to Daisy's advantage. For the remainder of July and into the first part of August, Bonita's steam vents had only sporadic activity. This decrease in Bonita's energy allowed it to actually signal Daisy's eruptions, instead of stopping them. It reverted back to the same type of performance that had characterized it during the 1920's and 1930's.

After Daisy or Splendid — or both — had played, Bonita always filled slowly until water had risen near the top or just over the vent. At this point it would begin splashing vigorously and filling quickly. Sometimes it would take 2 hours or longer to fill over the vent, and less than 10 minutes to reach overflow from there. But during those first weeks of the July 11 active phase, something different would occur instead of the usual continuous overflow: when the steam vents were quiet, Bonita would fill about half way, or barely reach overflow, when it would suddenly start draining again. By the time this had taken place, Daisy had had time to warm up and get ready to go. Thus, by the time Bonita had drained back down to the top of the vent, or slightly lower, Daisy took off.

Unfortunately, after the middle of August this type of performance had ceased altogether, as Bonita's steam vents were then active most of the time.

During its typical disgusting behavior, Bonita displayed a number of types of activity from the main vent, many of which were controlled by the steam vents. When Bonita was recovering from an eruption of one of its neighbors, and the water level was just beginning to rise rapidly, huge bubbles began rushing up the main vent, causing a vigorous splashing. If the steam vents were not active at the time, this heavy surging waned to bubbling when Bonita reached overflow. However, during the latter part of August and all through September, when the steam vents were almost constantly active, this

[2] This fracture was active at least as early as July 1973. It is visible in the photograph of Figure 5.

heavy surging did not wane, but often grew stronger after overflow was reached.

The steam vents themselves gradually grew more active over the course of the summer. If they were sputtering when one of the geysers erupted, they would usually cease as the pool drained. By early September, however, the steam vents continued their activity unhindered; when this was the case, the level of the pool never dropped as far as it did if the steam vents had quit during the eruption.

The bubbling along the southeast fracture meant that Bonita had grown still stronger. When Bonita was refilling after an eruption of one of the geysers, the steam vents and the fracture both remained active. On these occasions, the main vent often began a vigorous bubbling or boiling with the level still down a foot or two.

During inactivity of Daisy and Splendid, Bonita's main vent did everything from bubble, to surge 1 to 3 feet. Between eruptions of the geysers during an active phase, Bonita always filled, and usually overflowed; in previous years, overflow from the active geyser kept Bonita's level down. In 1973, with both Daisy and Splendid erupting with their levels down several inches, there was nothing to restrain Bonita. Main vent bubbling went hand–in–hand with the overflow; the main vent remained quiet unless the pool was rising toward overflow, or had already reached that status. With overflow common in 1973, Bonita's main vent also became consistently active. In May, June and July, with the steam outlets only active occasionally, this activity rarely became more vigorous than splashing to 1 foot. In latter August and all through September, this surging grew stronger as the steam vents became more active, until nearly all splashes rose to 2 feet. When the southeast fracture was active, the surging became especially strong, rising 2 to 3 feet high in bursts almost that wide.

On infrequent occasions, Bonita would surge heavily from the main vent with the steam outlets quiet. But this activity, in itself, could not delay or stop Daisy like the active steam vents did. As long as those outlets were quiet, an eruption of Daisy could almost be guaranteed, no matter how hard Bonita's main vent surged and splashed, or overflowed.

Back in the 1930's, overflow from Bonita was an indicator of an eruption of Daisy. Years later, this same overflow was reported to make Daisy erratic. At this time, however, the first known mention was made of side vents that sputtered even after the pool was drained. This would seem to indicate that it was not the overflow alone from Bonita that began stealing energy from Daisy, but the birth or reactivation of the heat–robbing steam vents.

The steam vents were also responsible for Bonita's debut as a geyser. Several times during concerted activity of Daisy and Splendid, Bonita erupted 3 to 5 feet in massive bursts. This violent behavior never started until Daisy joined Splendid. Each time Bonita was observed in eruption, the steam vents and the main vent had been quite active beforehand. On September 27, Bonita was going especially strong with the southeast fracture bubbling as well. Bonita was always in control before concerted eruptions anyway, with Splendid having to break that control in order for Daisy to play. Bonita's occasional reluctance to release its foothold on the two geysers seemed to inspire its eruptions.

At the beginning of Daisy's first two active cycles, Bonita only exerted sporadic control. As each of the cycles progressed, Bonita grew more and more active, only to subside at the beginning of the new cycle. But by the end of the season, Bonita's steam vents were active almost constantly. When Daisy did erupt, Bonita's level was pulled down only 1 or 2 feet — compared to 3 or 4 feet at the beginning of the season; the shallower draft on Bonita allowed fast recovery and a quick refill. Thus, Daisy's plays came less and less frequently. And Splendid seemed to give up the ghost completely.

Daisy Geyser

When I arrived in the Park May 1st [1973], I was informed that Daisy was going into active phases about every 10 days, each cycle lasting 3 to 5 days. I heard nothing about Splendid. Daisy was supposedly keeping herself going by overflowing before each eruption, which prevented Bonita from filling more than half way, until the five–day active

Figure 6. Frank Jay Haynes' historic shot of Daisy Geyser. (Haynes #14013)

cycle of Daisy had ended. During these cycles, Daisy was playing with considerable regularity, about every 70 minutes.

After I had been in the area about four days, I learned that Daisy had been active since my arrival. However, I was at the same time warned that the cycle was already five days old, and ready to quit for a 10–day rest. Still, I hoped that I would get to see even one eruption, as I had never seen Daisy before.

When I arrived at the group, Bonita was overflowing lightly and bubbling feebly from the main vent. Because of the report that Bonita overflowed only when Daisy was inactive, I was certain that I'd missed my big chance by mere hours. I was dejectedly walking down the boardwalk, when I suddenly heard loud splashing and turned to see Daisy just taking off. I was surprised and elated.

The next time I saw Daisy was on May 10, when she erupted twice at an interval of just over 90 minutes. Again, Bonita was overflowing lightly and boiling, then draining and refilling after each eruption. Daisy was, on the other hand, playing with her water level down 4 to 5 inches. If there had been a quiet period between the 4th and the 10th, it had to have been an extremely short one, as Daisy was seen in eruption by other observers between those dates, making this active phase much longer than the reported five days.

Just when Daisy had broken away from the eruption pattern reported during the winter months is unknown; the Naturalists on duty in the Visitor Center that spring were under the impression that the pattern was still unchanged. Yet they must have witnessed *some* eruptions of the March 27 active phase, because they were able to tell me how many days had elapsed since it had started. Therefore, they must have seen Daisy playing from an overflowing crater, because no one reported otherwise. By the time I saw it on May 4, however, Daisy had abandoned this aspect of her behavior, and did not return to it until late in the summer of 1974. Thus, the switch from classic eruption pattern to "radical" eruption pattern had to have been abrupt and final, and had to have occurred right in the middle of an active phase. It *may* have happened when the expected five–day period of activity had elapsed — and when Bonita began to overflow, Daisy simply refused to quit. Since a considerable quantity of water was then being discharged by Bonita, Daisy was forced to erupt with her level below the usual mark. At any rate, the latter condition prevailed for the remainder of the 1973 season.

Occasional eruptions of Daisy were witnessed until the 18th of May. Two occurred on the 17th, again with Bonita overflowing. Daisy's interval ran about 2½ hours.

After May 18, no more major activity was seen from the group, as they had gone into a quiet phase that lasted until May 30. On that day, Splendid played for the first known time that spring. This action seemed to start Daisy off. For the next week, I saw her almost every day, at least once. On June 3, I first witnessed Daisy's follow–up activity after Splendid. It came before the craters had even refilled, slightly more than an hour after Splendid had finished. This follow–up pattern was repeated on June 6.

I began to see, then, as quickly as Daisy followed Splendid, it would be only a matter of time before they went off together, with Daisy coming in right on Splendid's heels. Meanwhile, Daisy's solo plays were coming at intervals that varied from 90 minutes to nearly 3 hours.

On June 10, my suspicions about concerted activity became an actuality. Again, less than 90 minutes passed before Daisy followed with a solo. Thereafter, concerted activity with quick follow–ups by Daisy occurred with some frequency until the end of the active cycle.

The May 30 – June 27 active phase marked a distinct change in Daisy's behavior, from what it had been in the late winter and early spring. Bonita Pool began exerting more influence — and then Splendid entered dominantly into the picture. The type of activity that ensued was a history–making even in the lore of Yellowstone geysers.

The nature of change

1. Daisy's role in four active cycles

During the active phases from May 30 to June 27, and July 11 to August 19, Daisy followed a distinct pattern of behavior, which Bonita eventually spoiled.

Bonita dominated the quiet phase between these two unique active cycles. Then, as the energy shifted back to the geysers, Splendid was first to erupt. Daisy followed close behind, sometimes with a whole series of eruptions, before Bonita stole the energy back.

The reasons for this dependence upon Splendid seemed to be Bonita's increased activity and Daisy's sudden preference for a lower water level before an eruption. Before she went dormant in 1961, Daisy preferred an overflowing crater before eruptions — and, from all accounts, followed this pattern at the beginning of the March 27 active phase. But, during the 1973 season, for the first time recorded, a high water level in either Daisy or Splendid was a *bad* sign. Instead of overflow, Daisy now preferred a level of 5 to 8 inches below the high water mark on the crater rim. If the water reached much higher than that — like 1 to 3 inches below the water mark — Daisy's plays were greatly delayed, sometimes for over 24 hours. The high levels occurred only when Bonita was in control. Then it was Splendid's eruptions that pulled the energy from Bonita, and drew Daisy's water level down to a more satisfactory level. This permitted Daisy to erupt.

At the beginning of each active cycle — with Bonita in a weakened condition — Daisy performed quite consistently, at intervals of 1½ to 3 hours. Bonita's steam vents were active only occasionally. Thus, Daisy depended less on Splendid to keep things going — and it was possible to predict with a fair degree of accuracy the time of Daisy's plays by examining conditions in the crater beforehand.

After the cycles progressed (one week for the first cycle, about three for the second), Bonita grew steadily more active, stealing energy from Daisy. Intervals then ranged widely, from 1½ hours to as long as 4½ to 5 hours. She grew irregular and unpredictable, sometimes sitting on a knife's edge all day without erupting, while Bonita splashed and sputtered. Other times — even with the steam vents active — Daisy defiantly took off in spite of Bonita.

Soon Daisy just waited on a hair–trigger for Splendid to draw energy away from Bonita. Sometimes these waits lasted 2 or 3 days. When Splendid played, finally, Daisy was released from her restraints to erupt with big brother. Rather than individual eruptions of Splendid, concerted activity now triggered series of Daisy's plays. Splendid still occasionally played alone; but these single plays usually came *after* Daisy, so that she had not yet stored up enough energy to follow along. Toward the very ends of the active cycles, concerted activity grew to be a constant practice, as Bonita's strength waxed. The best example of this was the last week of the July 11 cycle, when Daisy didn't erupt at all unless it was with or following Splendid. Without Splendid's aid in breaking Bonita's strangle–hold, Daisy probably could not have erupted at all during the final days of each cycle.

Two cycles — both long — of this type ran through completely before trouble began. Daisy's new cycle of August 27 got off to a bad start, as Daisy took off first instead of Splendid. And, as the cycle continued, Bonita failed to show any signs of weakening; it began choking off Daisy right from the start. With Splendid suddenly less active, Daisy found that she could not keep going alone.

The number of eruptions of Splendid in a week took a drastic plunge, often forcing Daisy to start herself off after a period of inactivity. These plays were sometimes 100 feet high, voluminous and of unusual duration — but this small, isolated energy increase did not in any way improve the overall picture. Eruptions in a series, even when Splendid played first, were few and far between. Bonita hindered Daisy to the point that concerted activity began only a week into the cycle; even then, Daisy sometimes lacked the energy to join Splendid. At times like these, Daisy would surge massively, trying to take off, then would run out of water and roar steam in frustration. On one occasion, Daisy even failed to produce a follow–up after a concerted play. All of this indicates a general decline in both heat and water to the springs west of Bonita.

This weak active phase lasted only until September 15.

On September 22, a new active phase began. From this date until the cycle ended on October 9, Splendid had only two known eruptions — one to christen the new active cycle, and once for a concerted play. Bonita's steam vents sputtered almost continuously, and Daisy erupted twice a day at the most. Sometimes there would be 2 or 3 days between eruptions. During the 17 days of this cycle, Daisy had only eight known plays.

By the time I left the Park, Daisy's future looked pretty black.

The nature of change
2. Specifics of Daisy's behavior

The length and height of Daisy's eruptions often depended upon what her neighbors did — or didn't — do.

Lengths of Daisy's plays ranged from 2½ to 5½ minutes. All of the plays under 3 minutes came after an eruption of Splendid, and after or during concerted activity. Plays over 5 minutes long usually came when Daisy had been inactive for a considerable length of time, and Splendid had conked out: thus, in order to get a running start, Daisy broke her on quiet periods with eruptions of exceptional length and larger than usual discharge. The longest recorded eruption, however, was an exception, coming during concerted activity. Most eruptions were between 3 and 4 minutes. Bur during the latter part of the May 30 – June 27 active phase, durations of over 4 minutes became more common. Then, almost all through the July 11 – August 19 period — when the energy available to the geysers was at maximum — *most* of Daisy's plays were over 4 minutes. But from August 27 to October 9, the majority of eruptions fell back to the average 3½ minutes.

The height also varied, from 60 to 70 feet, to over 100. The shorter plays with less discharge usually followed Splendid's eruptions or concerted activity. The really big plays (over 100 feet) usually occurred during eruptions *with* Splendid. [3] However, there were exceptions, as on two of the occasions when Daisy broke her own quiet periods, and once when she tried and failed to erupt with Splendid. She pulled only one 100–footer with no apparent cause. Most eruptions were between 70 and 80 feet — the classic height given by Marler. But during the July 11 – August 19 cycle, higher eruptions — as well as longer ones — grew common. Many plays rose 80 to 90 feet, though most of these were quite thin. After August 27, these higher eruptions were much less prevalent.

The majority of Daisy's eruptions occurred with the water level down 5 to 8 inches, although some came with the level almost to overflow. Plays after Splendid and after concerts occurred with the level no higher than 18 inches from overflow.

Eruptions coming from a high water level were usually huge in either volume or height, or both. With the added pressure of 2 to 4 inches of water over the preferred level (5 inches down), Daisy had to have generated just that much more power before she could get started, and there was just that much more water to blow out. By the same token, *most* of the plays that came with the level below 18 inches were short and thin because most of the fuel had already been used up. Eruptions coming with the water at the preferred level of 5 to 8 inches down were, for the most part, average 70 to 80 foot plays with a few skinny 80 to 90 footers thrown in here and there.

As Marler stated, Daisy announced pending activity with vigorous surging. When she refilled

---

[3] It was Marie who, during a 1973 concert, measured the true above–ground height of the tallest eruption ever recorded for Daisy — 152 feet.

after her own eruptions, she filled quietly. After about an hour, bubbles began rising. This gradually increased to surging. As the energy increased, and the temperature went up, this surging became more vigorous, often rising 4 to 5 feet. Such really massive surging prevailed up until the August 27 cycle, when this activity, like that of the whole group, lost much of its vigor. From then until October 9, the preliminary splashes rose 3 feet at the most.

During the surging activity, the intensity and the water level fluctuated commensurate to one another. When Daisy was in a period of heavy surging, the really big splashes were not constant until seconds before the eruption started. There were periods lasting several minutes when the violence of the activity decreased and the water level dropped about an inch. Then violent activity was renewed again for another several minutes, and the level rose about an inch. As the eruption neared, the periods of decreased surging grew shorter while the periods of heavy surging became longer. When the 3– to 5–foot surges became a continuous roiling and heaving, the eruption was less than a minute away.

After an eruption of Splendid, or after concerted plays, Daisy almost always pulled a quick follow–up 45 to 90 minutes later. These plays came with the level down 18 inches or more — usually more. At these times, instead of filling quietly, Daisy would roar steam for sometimes a half hour after Splendid or a concert had finished. Then, as the water gradually trickled in, Daisy would begin surging and churning from the bottom of an empty crater. As more water trickled in, she surged with more volume and greater violence. There would sometimes even be efforts to erupt with the level down 3 to 4 feet; surges would rise 10 to 15 feet for several seconds, then subside for lack of sufficient water. This kind of preliminary false–start was rare with Daisy when she followed her own plays. But when she was pulling follow–ups to concerts and Splendid's solos, it was fairly common. Sometimes one of these false–starts with the level down 3½ feet would unexpectedly break into the eruption; when this happened, the play was always exceptionally thin.

Daisy displayed a remarkable variety of activity in the 1973 season — much of it without precedent. And the seasons following were no less fascinating.

Comet Geyser

Comet is known for its near–constant activity. It surges up 4 to 6 feet, sometimes 8 feet, recedes for several seconds, and surges up again. The only activity to affect this perpetual surging was a full–scale eruption of Splendid, or concerted activity. Daisy halted Comet but rarely. Most of the time, Comet's surging was merely enfeebled by Daisy's activity, or reacted by foaming up in masses and running over the sides of the cone. Splendid's eruptions stopped Comet completely for 5 to 15 minutes, and concerts stopped it for 15 to 20 minutes. When Daisy did halt Comet completely, it was only for 1½ to 3 minutes.

When Daisy and Splendid were in an active phase, Comet appeared to surge up from an empty crater. But during the quiet periods, a pool would become visible during moments of less vigorous surging. As the days of quiet in Daisy and Splendid continued, the level of the pool in Comet rose, until it would almost overflow from the crater's low north edge.

Comet is one of the less spectacular members of this group. But by the same token, it is also about as inoffensive as a spring could get. It was affected by its companions, though only slightly — and it does *not* affect them. Thus, its role in the spectacular events of this season was very minor, and quite harmless.

Brilliant Pool

Brilliant is largely ignored by all but those who are intimately familiar with the members of the Daisy Group. Usually it just lies behind Comet and bubbles, or does nothing at all. It is, however, a far more attractive spring than Bonita ever dreamed of being, with a deep aquamarine hue.

When not reacting in some way to an eruption of Daisy or Splendid, Brilliant did carry on a variety of activities. The most prevalent of these was just to bubble from two vents, one at the north edge and one at the east edge. (On other occasions, bubbles would also be seen rising from the approximate center of the pool, and its southwest edge.)

Figure 7. Splendid Geyser at 11:20 on August 15, 1973. This particular active cycle had started precisely 24 hours prior to this eruption. Figures 8 and 9 were taken on that previous day.

This light bubbling was almost constant, but boiling came at intervals of a few seconds to several minutes. During the quiet periods between eruptions of Daisy and Splendid, Brilliant's level would lie anywhere from 3 inches to a foot down; and sometimes this level fluctuated, rising and falling 1 to 3 inches. The most violent quiet phase activity occurred along the north edge of the crater. From there, on occasion, Brilliant periodically foamed up 1 to 4 feet in pillars 1 to 2 feet across.

After an eruption of Daisy, Brilliant was pulled from 4 to 9 feet down. Sometimes, while refilling, it would bubble or boil periodically. The level would rise in spurts instead of steadily, but still filled considerably faster than Bonita. It never filled completely to the brim or overflowed.

After solo plays of Splendid, or concerted activity, Brilliant was pulled 5 to 12 feet down. Then it often erupted violently from the north edge. Sometimes this activity did not become visible above ground. When it did, water would surge straight up, the more powerful surges slanting at an acute angle to the southeast. Heights, or lengths, varied from 3 to 20 feet. These eruptions occur *only* as a follow–up to Splendid.

Like Radiator, Brilliant was stimulated into a kind of activity that hadn't been seen since Splendid went dormant in 1959. In 1972, Brilliant had its first chance in twelve years to erupt, when Splendid became consistently active. This season, that activity, like Splendid's, saw an increase. Brilliant Pool can now take its place in the rank of geysers.

Splendid Geyser

A reawakening

Since the 1959 earthquake and up until the summer of 1972, Splendid had been largely dormant. Marler reports a single play in 1968, and three in 1971. Then in the summer of 1972, he began erupting with increased frequency, and at least twice in concert with Daisy in a history–making performance.

From my arrival on May 1st, 1973 until May 30, 1973, Daisy held the stage almost without competition. Splendid surged 3 to 6 feet with some vigor, but there wasn't strong enough activity to indicate impending eruptions. Finally, on May 30, Splendid played.

As with Daisy, I had always read that Splendid erupted from an overflowing crater. So, on May 30, when I saw Splendid's level down about 18 inches, I tried to shrug off the fact that he was surging massively and heaving frequent jets 20 to 30 feet high. Still, as I sat waiting for Pyramid to erupt, I kept a suspicious eye on him. And suddenly, one of the big surges started rising. Realizing at once

[4] Park policy has changed a great deal since 1973. At that time, a "Volunteer in Parks" was free to leave the walkways when making valid geothermal observations, even without the benefit of a uniform. In this case, Marie ran across the meadow that lies between Pyramid Geyser and the Daisy Group. Doing so was perfectly proper procedure.

what was happening, I jumped up and ran full blast through grass and mud to get a close view. [4]

This eruption seemed to start Daisy off after a rest period. Then, instead of waiting for several weeks, Splendid played again on June 3 and June 6. And, instead of Splendid following up his own eruptions in a series, Daisy played 70 to 85 minutes after each eruption of Splendid.

This was when Splendid first demonstrated the ability to break Bonita Pool's control when Daisy couldn't. Bonita was overflowing before each eruption, and Daisy had not played for at least several hours.

Daisy's dependency upon Splendid finally brought about the long–hoped–for concerted activity on June 10. As Bonita's strength waxed, Splendid started off numerous concerts.

May 30 marked a new pattern of behavior for Splendid. He no longer had series of eruptions with intervals as short as 3 hours; yet he played every few days, instead of weeks. Between eruptions there was now near–constant activity in the crater. Normal surging rose a massive 5 to 10 feet. This action was spiked with frequent big bursts rising 15 to 50 feet, indicating an almost constant readiness for action. One could never be sure when Splendid was just horsing around, and when an eruption was imminent. And the eruptions, when they came, now served to perpetuate a fascinating state of affairs for several months.

Climax and Decline

1. Splendid's role in four active cycles

It is hard to say what prompted Splendid into activity while Daisy was still playing so frequently. But the fact remains that it happened at just the right time to help Daisy fight a stronger, more active Bonita Pool. The first two active cycles that Splendid took a major part in were from May 30 to June 27, and July 11 to August 19. During this time, Daisy erupted the most frequently, but Splendid was the dominant force.

During the first two–thirds of the May 30 active cycle, Splendid played every 3 to 5 days. This increased toward the end to every 1 to 3 days. The sporadic activity during the first 20 days of the active phase could have been due to two factors: the lack of available observers to catch the eruptions that did occur, or Splendid just getting warmed up after months of erratic behavior.

All through the July 11 cycle, Splendid stuck to a fairly distinct pattern of play, erupting every day to every 3 days. He seemed to keep going on the same pattern throughout the cycle — in spite of increased activity in Bonita and Daisy's subsequent erratic behavior. Toward the end of this cycle, Splendid was performing with the same frequency as at the beginning. Somehow — regardless of what was going on in the rest of the group — Splendid remained remarkably stable.

At the beginnings of the May 30 and July 11 cycles, Bonita had rather sporadic activity, and Daisy was pretty much able to perform without Splendid's help. During those weeks, Splendid played alone, sometimes every day, sometimes every 2 or 3 days. Upon occasion — even later in the cycles — Splendid erupted twice in one day. Most of these plays went according to the traditional 1– to 3–hour interval, or close to it, often dragging Daisy along. On one occasion, two concerted plays occurred within 3 hours of one another. This kind of action was, however, quite rare.

It was always Splendid who was responsible for concerted activity. He always started. Nothing Bonita did could stop Splendid when he was ready to go.

In every way, Splendid was in control of things. Even when he played solo, Daisy would react by surging massively, roaring steam, or both. And Daisy's plays with Splendid were often much larger than her plays alone. Not only Daisy, but Radiator also had its largest play of the season in response to Splendid. Brilliant Pool erupted *only* after Splendid; and Bonita erupted only in response to concerted activity, for which Splendid was ultimately responsible.

The active phase beginning August 27 marked the beginning of a change in this state of affairs. Daisy started things off, and Splendid followed. The first four days after those backward events, however, went normally enough, with Splendid erupting every day but on the 29th. Then there were four days of inactivity.

Concerted activity finally occurred on September 4, 5 and 6. Then, on September 7, Splendid played right after Daisy, which caused a solo instead of a concert. On September 9, concerted activity occurred again, but this time without a follow–up Daisy. On September 11, Splendid played for the last known time in the cycle, which ended on September 15.

All during this cycle, Splendid's plays had come in clumps with more than the usual number of days between them. And he conked out right at the end of the cycle, letting Daisy struggle on for the last three days alone.

The fact that Splendid quit before the cycle was over proved to be a sign that something was wrong. He started off the new active phase on September 22, but then was not observed to erupt again until September 27, when he initiated a concert. From then until the active period ended on October 9, Splendid did not play again.

Since Splendid was the force keeping Daisy going, she became very sporadic without him. Perhaps Bonita's energy had finally increased to the point where even Splendid could no longer fight it.

Climax and Decline

2. Specifics of Splendid's behavior

Unlike Daisy, Splendid was not so much affected in the height and duration of his plays by what other members of the group were doing at the time.

Most of Splendid's eruptions soared well over 150 feet, even during concerted activity. [5] Most of the effect on Splendid by other members of the group was minimal. On some occasions, however, heavy surging from, or an eruption of, Daisy would have a more drastic effect on Splendid's height. One example of the latter was when Daisy tried to join Splendid during an eruption: Daisy's first 10– to 15–foot heave pulled Splendid's height down at least 20 feet; as soon as Daisy ceased the massive surges, Splendid soared back up to his former height. Such weakening of Splendid, however, occurred very seldom.

Splendid had one habit that Daisy never displayed: he would die down completely during an eruption, then surge up again. Sometimes the bursts that followed this pause went only 50 to 60 feet high. Other times the column soared to the full height again. As might be expected, this behavior came mostly during eruptions over 6 minutes long.

Occasionally, Splendid would almost seem to run low on water during an eruption. This did not only come during longer plays, as the pauses usually did. The length, apparently, had nothing to do with it. Neither did it seem that it was due to activity in Daisy: water–shortages would occur just as frequently with Splendid playing ½ hour after Daisy as they did with Splendid playing 24 hours after Daisy. But, like Lion and Castle, Splendid would spew steam and spray during the last portion of some eruptions, often with a considerable roar.

There did not seem to be any particular force governing the length of Splendid's eruptions, how-

Figure 8. Splendid Geyser on August 14, 1973. Moments later, this proved itself to be a concert with Daisy (Figure 9).

---

[5] The greatest eruption height ever recorded for Splendid Geyser, 218 feet, was triangulated by Marie during the July 11, 1973 active phase.

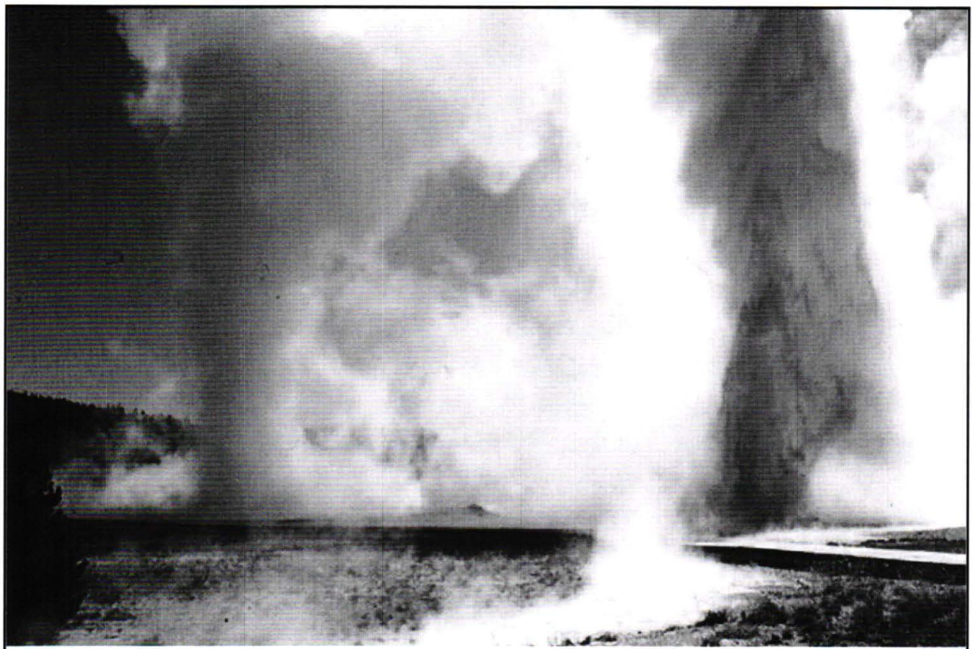


Figure 9. Splendid (right) and Daisy in a concert on August 14, 1973. This same eruption by Splendid, before Daisy joined the play, is shown in Figure 8.

the level would rise again.

The surging itself was quite vigorous. For most of the season, surging rose 5 to 10 feet during active phases, with frequent bursts of 20 to 50 feet. The big bursts often hung in the air, rising and falling for several seconds, as though struggling to take off in a full–scale eruption. This action was soon called the "false start." The exact–same action preceded actual eruptions. But the false starts often occurred right before plays of Daisy.

Usually, even Splendid's strongest surging action and largest preliminary bursts had no effect on other members of the group. But once, Brilliant Pool and Daisy were lowered several inches by a large (non–eruptive) burst from Splendid. This action almost triggered Daisy — but Bonita wouldn't relinquish its hold. Brilliant slowly refilled to its former level, but Daisy did not.

During periods of quiet between active cycles, the surging lost some of its vigor, and none of the false starts occurred. It was not uncommon then — or even sometimes during the 2– or 3–day lulls in activity — for Splendid's noisy west vents to shoot water out almost horizontally 10 to 20 feet.

The main vent activity was most vigorous during the July 11 active cycle. Heavy surging was near–constant, and the false starts were very frequent. Then, by August 27, Splendid had lost some of his former vigor. The surging did not go much over 8 feet, and false starts came less and less frequently. By September 15, surges were rising only 3 to 5 feet. By September 27, Splendid no longer had the strength to even precede his own play with a 15– to 30–foot burst. In fact, there had been no evidence at all beforehand to hint at the pending eruption.

ever. They lasted anywhere from just over 4 minutes to just over 10. Sometimes the long plays were solos, and sometimes they were concerts. Likewise, short eruptions occurred with and without Daisy.

The most significant thing involving Splendid's durations concerned series of eruptions. The rule had been in the past that, any time Splendid played for less than 6 minutes, a follow–up could be expected to occur 1 to 3 hours later. This pattern was eliminated in 1973. The reason for it was apparently Daisy: her quick follow–ups took the energy Splendid needed for a second play. With both geysers so active at one time, it was seldom possible for each individual to play according to its usual solo pattern.

The water level in the crater beforehand did not seem to affect the length of the plays, either. The level could lie anywhere from 5 inches down to 2 feet down. And, like Daisy, Splendid never overflowed before eruptions. A level anywhere from 8 to 24 inches down was satisfactory for action. And Splendid would play just as long (or short) with the level down 2 feet as he did with the level down just 8 inches.

Also like Daisy, Splendid would shift water level when surging; sometimes during moments when there was a pause in the activity, the level would drop as much as 18 inches. Then, as surging began, Splendid was a great mover of events that season. If he had ceased to play then, his loss would have been a great one.

PART III
Summaries of Two Active Cycles

July 11 to August 19 [6]— Climax

When this active cycle first began, Splendid mostly erupted every ½ to 1 hour after Daisy, with Daisy playing again an hour later. Splendid's plays at this time rarely went over 120 to 130 feet. Daisy's intervals ran from 1½ to 2 hours, and the height from 70 to 90 feet. Bonita Pool's steam vents were active only occasionally, and there was minimal activity from the main vent, allowing Daisy to play with considerable regularity. Without Bonita to worry about, it was possible to predict Daisy's plays with a fair degree of accuracy by examining conditions in the crater beforehand. And it was not uncommon to have Bonita drain right after the initial overflow, and thus actually trigger Daisy.

After about three weeks of activity, Bonita Pool grew more active, stealing energy from Daisy. Bonita's steam vents began sputtering almost constantly, and the fill–then–drain act no longer occurred, except rarely. Daisy's intervals were sometimes as short as 1½ hours, or as long as 4 to 5 hours. She became extremely irregular and unpredictable, sometimes sitting on a hair–trigger all day without playing while Bonita splashed and sputtered. Sometimes, Daisy took off in spite of Bonita. An observer never knew what to expect. The only consolation was an increase in Daisy's eruption height to 85 to 100 feet.

During this time of erratic behavior on Daisy's part, concerted activity with Splendid occurred with a frequency that increased steadily toward the end of the cycle. As the cycle progressed, day–long pauses in Daisy's activity became increasingly common. Then, nearly every time, Splendid would finally go off, triggering Daisy.

[6] This active cycle actually continued through August 21, a Tuesday and a day off for Scott Bryan who recorded eruptions of Daisy at 10:14 am, 1:47 pm and 7:18 pm, and one of Splendid at 4:25 pm. His notes also state that no eruption by either geyser was recorded on August 22.

Splendid seldom played alone. Daisy would seem to sit on a knife's edge and wait for Splendid to lower the water level in it and Bonita Pool, then take off. The longer Daisy's pause, the higher the water level stood. During shorter intervals, the preferred level was 4 to 7 inches down; but during the 24–hour delays, the level rose to just 1 to 4 inches down. When Splendid erupted, Daisy usually followed 1½ to 2½ minutes into the play; by that time, the water level would be pulled down about 2 feet, and it would rise suddenly as Daisy began foaming up 3 to 5 feet. Surging in Bonita then died to practically nothing, and the steam vents normally quit; overflow ceased about 5 minutes into the geysers' concerted activity.

Daisy's plays during this activity were often long and huge (5 minutes, 100 feet), in spite of Splendid's draft on the energy. Splendid's eruptions had also risen to 150 to 170 feet at this time.

When the new quiet period first began, Daisy still looked like she might erupt. But the water level gradually rose, and the surging lost its vigor. After two days of inactivity, it looked like a long rest from the group would be forthcoming.

August 27 to September 15 — Decline

In several respects, this active cycle was quite different from the two preceding it. Daisy started it off, which was unusual in itself. Then she was quite erratic, even at the beginning. Splendid was less active than usual, and Bonita sputtered and splashed unchecked. Even the heights to both geysers went down from the previous active phase: Daisy once again went 70 to 90 feet, and Splendid played 130 to 150 feet.

Concerted activity began unusually early in the cycle, then declined markedly in frequency. Daisy then tried to erupt on her own but could manage only one or two, sometimes three, eruptions in a 24–hour period. Many plays were probably missed due to a lack of observers, but even when I was personally in the basin all day, she would go off only once or twice, or not at all. Markers placed in the runoff channel at night were still commonly in place the next morning.

The cycle was short. Daisy's infrequent performances just stopped — as though she had simply grown tired of fighting Bonita's persistent activity. The water gradually rose with a steady, marked decline in the vigor of the splashing, and the quiet period settled in.

PART IV
Earthquake — Mexico City, 3:57 am PST, August 28, 1973 [7]

At 5:13 pm, August 27, Daisy erupted, starting off a new active cycle. This was the only cycle all summer that Daisy started. In spite of the general decline in the size of Daisy's plays that manifested itself over the next few weeks, this initial eruption was abnormally large (110 to 120 feet with massive discharge) and long (5 minutes, 20 seconds).

Starting at 11:45 am, August 28, both Daisy and Splendid had some strange intervals, as follows:

Daisy — 11:45 am

Splendid — 12:28 pm, 43 minutes after Daisy

Daisy — 12:44 pm, 16 minutes after Splendid and 59 minutes after prior Daisy

Daisy — 1:48 pm, Daisy interval of 1 hour, 04 minutes (extraordinarily short)

Daisy — 4:02 pm, normal interval of 2 hours, 14 minutes

Daisy — 5:24 pm, moderately–short interval of 1 hour, 22 minutes

Daisy — 8:25 pm, normal interval of 3 hours, 01 minute

[7] This earthquake had a magnitude of 7.2. The focal depth was 52 miles, and the epicenter was south of Orizaba, Mexico, therefore almost 200 miles east–southeast of Mexico City.

Note that in her original manuscript, Marie curiously used Pacific Standard Time ("PST") for this earthquake. According to a search engine operated by the National Earthquake Information Center (NEIC; retrieved on December 30, 2002), the earthquake of August 28, 1973 actually took place at 9:51 am local Mexico time, equivalent to 7:51 Pacific *Standard* Time but also equivalent to 9:51 am Mountain *Daylight* Time. Hence, the origin of Marie's "3:57 am PST" is unknown.

This time correction places the onset of Daisy's unusual activity less than two hours after the earthquake, increasing the possibility of a relationship.

All but two of Daisy's intervals were unusually short, and her follow–up to Splendid was even more remarkable. The group seemed to suddenly have an abundance of energy and water. There were remarkably fast recoveries after each eruption. This, plus the fact that Daisy initially started the active cycle with an abnormal eruption, means that *something* must have influenced their activity from outside. It seems that it would have been more than mere coincidence that all of these events occurred shortly before and after an earthquake, and at no other times. Activity in the rest of the active cycle indicated a general decline in overall energy–availability in the group. Why this one, single spurt of intense energy–discharge?

The Daisy Group has long been known to be sensitive to an extreme to outside influences. The fact that the Mexico City quake was large, and not so terribly distant, makes the possibility of its affecting some of the thermal features not unlikely. (Other springs also reacted, and quite obviously. [8]) This may be the sought–after explanation for why Daisy, and not Splendid, started off this active cycle. And the fact that the cycle was so weak *may* have been a result of the group being jarred into activity before they were ready — before they had sufficiently rebuilt their energy stores after the extraordinary round of activity just past.

[8] None of these "other springs" were either identified or described by Marie.

Daisy (left) and Splendid Geysers erupting in concert, July 1987.

A Special Report

The Extraordinary Thermal Activity of El Tatio Geyser Field, Antofagasta Region, Chile

J. Alan Glennon
Department of Geography
University of California, Santa Barbara
Santa Barbara, California 93106

Rhonda M. Pfaff
Environmental Systems Research Institute
380 New York Street
Redlands, California 92373

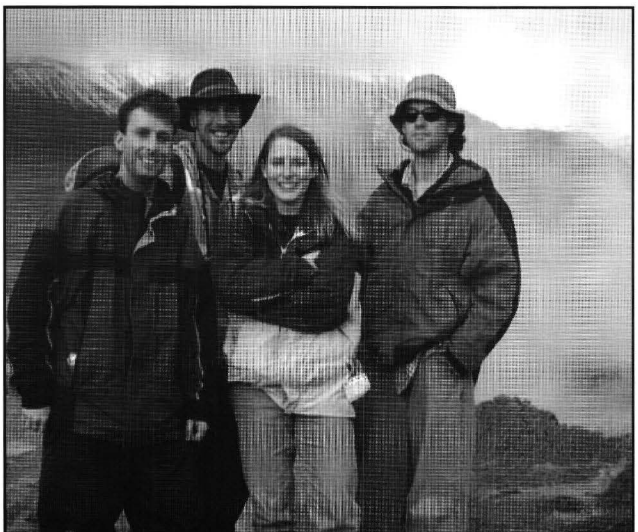
Abstract

El Tatio Geyser Field (locally known as Los Géiseres del Tatio) is located within the Andes Mountains of northern Chile at 4,200 meters above mean sea level, 150 kilometers east, southeast of Calama, Chile. With over 80 active geysers, El Tatio is the largest geyser field in the southern hemisphere and the third largest field in the world, following Yellowstone, USA, and Dolina Geizerov, Russia. From March 19–21, 2002, the authors visited the geothermal field to inventory the geysers and their behavior. Of over 110 erupting springs documented, more than 80 were identified as true geysers and an additional 30 were perpetual spouters. Despite reports that geyser activity occurred only in the morning, no abatement in activity was observed at any time within any part of the field. Although the observed activity was vigorous, eruptions commonly reached less than one meter. Of the erupting springs cataloged, the mean spouting height was 69 centimeters. Of the true geysers cataloged, the eruptions averaged 76 centimeters. El Tatio Geyser Field contains approximately 8 percent of the world's geysers.

TABLE OF CONTENTS

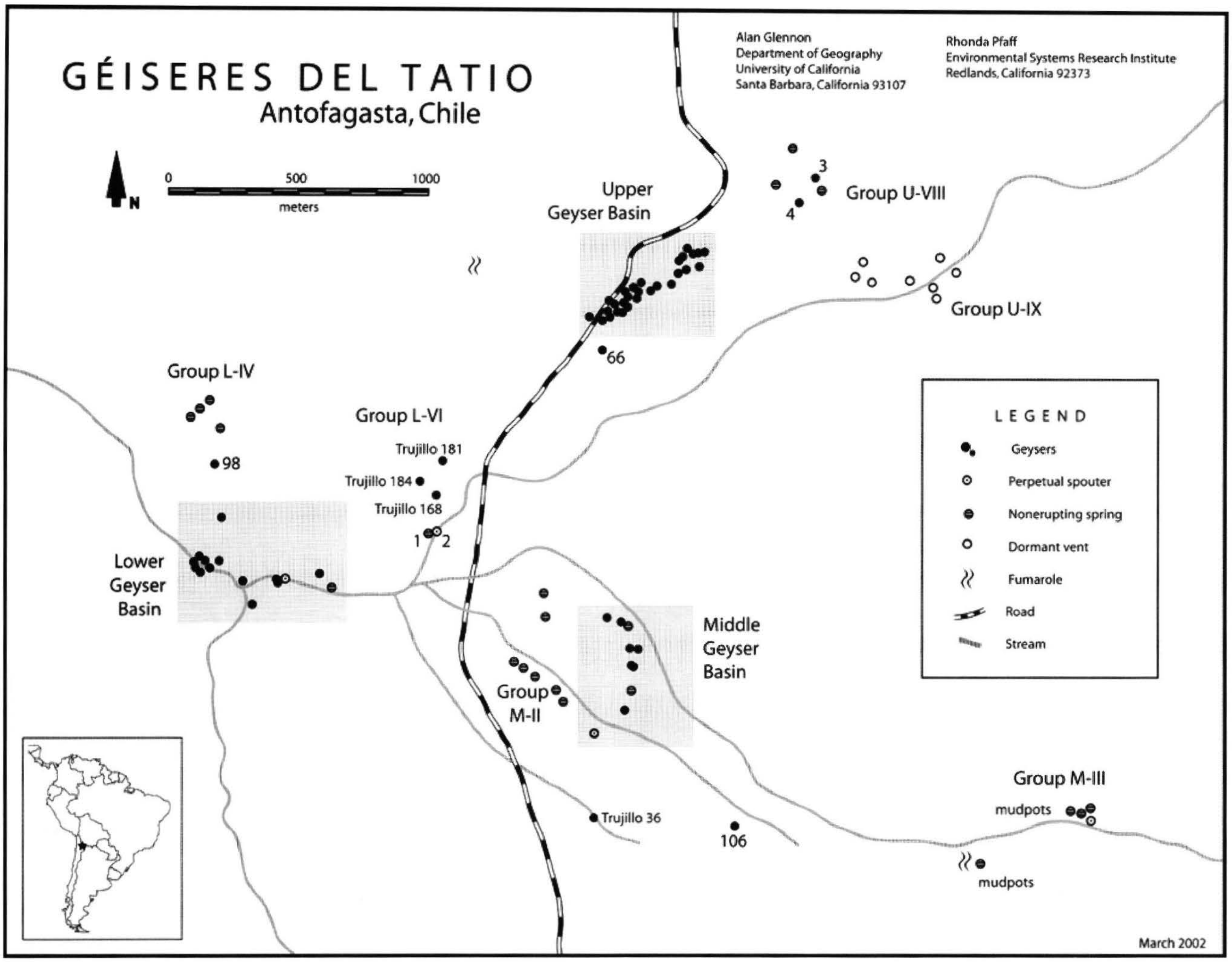
Acknowledgements

We wish to thank our friends Shane Fryer and Weldon Hawkins for their assistance in the field. Scott Bryan (Geyser Observation and Study Association) and Randall Marrett (Department of Geological Sciences, University of Texas at Austin) were particularly helpful in providing information on previous investigations to the area. Thanks to Keith and Arlene Pfaff for aiding in travel logistics. Cyril Cavadore graciously allowed the use of several photographs of the basin. Special thanks to Larry Fryer for making special travel arrangements for our group.



The authors among the mudpots of Group M–III. Left to right: Alan Glennon, Weldon Hawkins, Rhonda Pfaff and Shane Fryer. (Photo by Alan Glennon)

Map A — Index Map to El Tatio Geyser Field



PART I. EL TATIO GEYSER FIELD

I. INTRODUCTION

El Tatio Geyser Field, with over 100 erupting springs, is the largest geyser field in the southern hemisphere and the third largest field in the world, following Yellowstone, USA, and Dolina Geizerov, Russia. From March 19–21, 2002, a four–person team visited the geothermal field to inventory the area's geysers and their behavior. Of over 100 features documented, more than 80 were identified as true geysers and an additional 30 or more appear to be perpetual spouters (however, some of these spouters may be geysers with long durations). Three regions at El Tatio where geysers have been previously reported were not visited. An extended study at El Tatio would likely find many more true geysers. Although the observed activity at El Tatio is vigorous, eruption heights are commonly less than one meter. Numerous uncataloged springs continuously boil and occasionally eject small erratic splashes.

The Tatio geysers (locally known as Los Géiseres del Tatio) are located within the Andes Mountains of northern Chile at 4,200 meters above mean sea level, 150 kilometers east, southeast of Calama, Chile. El Tatio spans a 10 km^2 region of Andean altiplano. Geyser activity is fueled by water heated by a volcanic complex that lies primarily east of the field. Ignimbrite (which is compositionally similar to rhyolite) is the likely source of silica needed for development of the geyser plumbing network.

Within the field (Map A, above), three separate zones of geysers exist, each with a different character. The three major geyser zones are: 1) The

Upper Geyser Basin (or Main Terrace) lies near the floor of a gently sloping valley and is characterized by relatively low water discharge but well–developed sinter terraces. Numerous large active and inactive geyser cones lie within the Upper Basin. The Upper Basin is the largest of the fields (spanning 5 km^2) and contains the greatest single number of erupting springs. A feature in this zone was the tallest observed geyser of the basin, erupting to 5 meters or more. While a majority of the erupting springs at El Tatio appears erratic, numerous geysers in the Upper Basin appear to have predictable intervals and durations. 2) The Middle Geyser Basin, a flat sinter plain, lies immediately to the south of the Upper Basin. A series of 3–meter deep pools have frothy, fountain–type eruptions. The intervals are short (near continuous) and the eruptions are erratic in duration and height. 3) The Lower Geyser Basin (or River Group) lies along the banks of the Río Salado, approximately 2 kilometers downstream from the Middle Basin. At least ten springs erupt in and near the river to heights of 1 to 3 meters. Some features in the Lower Basin erupt from within the flow channels of the river itself, including several underwater geysers whose eruptions eject sediment onto the riverbank. Very little sinter accumulation has occurred in this downstream river group.

Previous Work

Mentions of geysers in the altiplano were first included in descriptions of northern Chile by Bertrand [1885] and Sundt [1909]. In 1921, Italian engineer Ettore Tocchi [1923] began a study of the geology and geothermal manifestations to determine their suitability as a source for electricity production. The next attempt at a detailed study of El Tatio was by Brueggen [1943]; however, due to the isolation of the area and difficulty traveling to the geysers, only a few observations were made. In 1953 and 1960, Dr. Angelo Filipponi, a professor at the Universidad Técnica Federico Santa María, Chile, described the characteristics of the hydrothermal phenomena at El Tatio and made comparisons with the geothermal source and production facilities in Italy [Filipponi, 1953, 1960; Andres *et al.*, 1998]. Zeil's 1956 and 1959 works were the first to provide a numerical count of features and a description of the springs' geochemistry.

The next detailed investigation began in 1968 with the joint work of the United Nations Development Program and the Government of Chile. These investigations included a detailed survey of the natural features of the basin by Trujillo *et al.* [1969], in which over 200 features were mapped. Continuing investigations were commissioned to assess the economic feasibility of geothermal electricity production and water desalinization. These studies included discussions of regional geology, structure, and geochemistry [Trujillo, 1969; Lahsen and Trujillo, 1976; Cusquicanqui *et al.*, 1976]. Six exploration wells (at depths to 740 meters) and production wells (to 1,821 meters deep) were drilled between 1969 and 1974. The majority of these wells are 2 kilometers south of the Main Terrace. In 1974, a pilot desalinization plant was sited adjacent to the Main Terrace. In 1981, the Chilean Economic Development Agency (CORFO) conducted a study on the basin concluding that, with existing wells, El Tatio has electrical production potential of 15 to 30 megawatts [Andres *et al.*, 1998]. In March 2002, no wells were discharging and no geothermal electric production facilities were in place at the field. The abandoned desalinization equipment still stands within 100 meters of El Tatio's tallest geyser (T25). Other recent scientific work has examined El Tatio's silica deposition, with an emphasis on geyser eggs and pearls around thermal pools and geyser cones [Jones and Renaut, 1997].

Purpose and Scope of This Study

The purpose of the investigation was to inventory and characterize the behavior of the geysers of El Tatio. The study is restricted to assessing the geysers themselves; within the limited time of only three days at the basin, many significant hydrothermal manifestations were not inventoried. While at least 30 perpetual spouters were noted, descriptive information was not collected for all of them. Based on previous investigations, our inventory includes approximately 25 percent of the thermal features in the field. Numerous perpetual spouters, mudpots, warm springs, solfataras, and fumaroles, await future investigators. In addition, with our limited time, we were able to collect only basic, preliminary data for each cataloged feature.

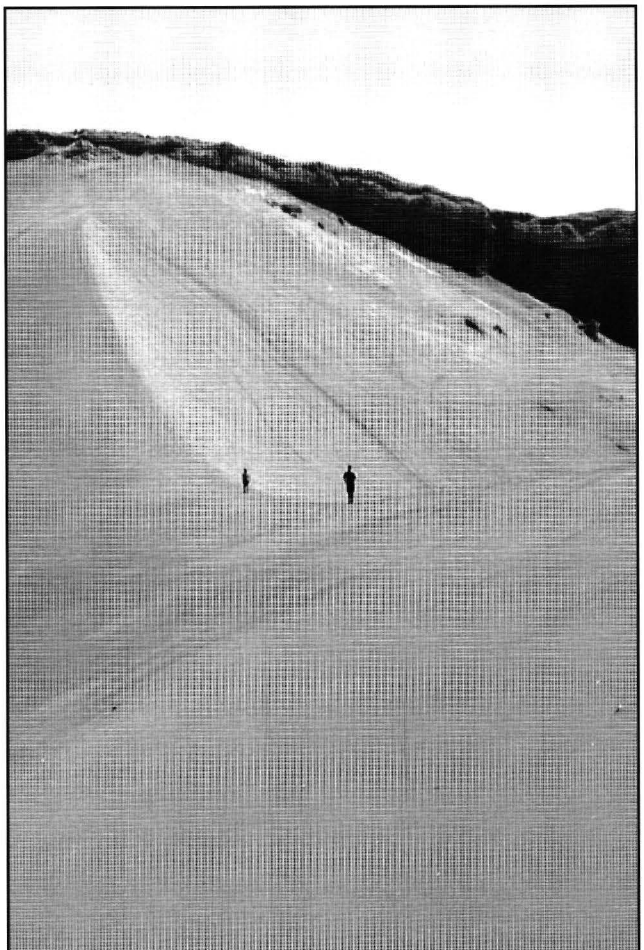
For most of the geysers, only one or two closed intervals were observed. Data presented reflect these short observation periods and should be evaluated accordingly by readers. In addition, the behavioral data represent a three–day snapshot of conditions at the basin. Seasonal climactic variations, seismic effects, and anthropogenic intervention are just a few of many factors that could greatly affect data presented in this report. During the study, we obtained only passive information from the basin and transcribed data to field notebooks; no water or rock samples were collected. During our visit to the geysers, no other people (guides, tourists, or workers) were at the basin. Thus, the cultural component of names and history of various features were not collected. According to local guides in San Pedro, the larger geysers and cones and several of the pools have been named. However, for this study, individual features are presented with a code assigned in the field. Where possible, we correlate these codes to the Trujillo *et al.* [1969] map numbers.

II. GEOGRAPHY

Regional Geography

The geysers of northern Chile are found in the Atacama Desert, a region of South America known for being one of the driest places on earth. The Andes Mountains bound the eastern side of Chile, with a high plain (altiplano) nestled between the mountain peaks. The Andes are tectonically active; volcanic eruptions and earthquakes are common. The mountains are forming as the Nazca oceanic plate subducts under the South American continental plate. Surface hydrothermal activity is present over a wide area of northern Chile and southern Bolivia, including several areas containing geysers or perpetual spouters. The known geyser fields of Chile include El Tatio, Polloquere, Puchultisa, and Tuja. Though unconfirmed, geysers and erupting springs also have been reported at San Andres de Quiguata near the village Lirima. The Sol de Mañana geothermal field lies across the international border from El Tatio in Bolivia.

The main cities of interest in the Antofagasta (or Region II) province of Chile, the zone in which El Tatio is located, include Antofagasta, Calama, and San Pedro de Atacama. The city of Antofagasta, with a population of 275,000, is the capital of the region. Antofagasta is a coastal harbor city that serves as a shipping center for the mineral resources produced in northern Chile and landlocked Bolivia. Calama lies about 300 kilometers northeast of Antofagasta at an altitude of 2,250 meters. Calama has the nearest commercial airport for travel to El Tatio. Calama, with a population of 150,000, is the service center and residential base for the Chuquicamata mine that is located 16 kilometers north of Calama. The mine is one of the largest copper mines in the world.



Shane Fryer and Weldon Hawkins atop a large sanddune at Valle de la Luna, near the village of San Pedro de Atacama. (Photo by Alan Glennon)

San Pedro de Atacama is about 100 kilometers southeast of Calama. San Pedro is a small village of about a thousand permanent residents settled around an oasis in the Atacama Desert. The village emerged as a rest on a cattle trail and a stop connecting the llama herders of the altiplano with the fishing communities on the Pacific [Graham *et al.*, 1999]. San Pedro, at 2,440 meters in elevation, now serves as an eco–tourism mecca — a springboard for tours to the Atacama Desert, the Altiplano, and Andes Mountains. El Tatio, 86 kilometers northeast of San Pedro, is located at 4,200 to 4,300 meters above mean sea level.

The altiplano, or *puna*, is a stark region with unique wildlife. Several types of llama are found in this area, with vicuña most commonly seen around El Tatio. Small nocturnal animals, such as chinchillas and their relatives, *viscachas*, also live in this region. The desert, in many places, is void of vegetation. The rocky, reddish volcanic soils are exposed throughout, except where shrubby grasses and trees grow in wetter areas. Hydrothermally altered soils are widespread in the geyser basin and throughout the regional linear depression (graben) extending north and south of El Tatio. The thermal areas often feature rich, brightly colored algae and bacterial mats.

"El Tatio"

"El Tatio" comes from the Atacama word, *el tata*, meaning "the grandfather." Volcán El Tatio lies 10 kilometers southeast of the geyser field. According to local legend, the Grandfather, the volcanic mountain, protected the Atacama people and has provided the force of steam for hundreds of years [ENTEL Antofagasta, 2002].

Tourism at El Tatio Geysers

Our experiences at El Tatio were quite different from those of the typical visitor. We arrived later, stayed longer, had our own transportation, took notes, and saw more water than steam from the geysers. For the normal visitor, tours from San Pedro to El Tatio leave at 4 a.m. and return by noon, costing about US$20 per person. Regarding El Tatio, *Lonely Planet* stated that the "visual impact of its steaming fumaroles at sunrise…is unforgettable and strikingly beautiful" [Bernhardson, 2000, p. 287].

Another guidebook, *The Rough Guide*, said of the El Tatio tourist experience [Graham *et al.*, 1999]:

> First, you drag yourself out of bed in the dead of the night, with no electric lights to see by; you then stand shivering in the street while you wait for your tour company to come and pick you up at 4 a.m.; and finally, you embark on a three–hour journey across a rough, bumpy road. Add to this is the somewhat surreal experience of finding yourself in a pre–dawn rush hour.

These guidebooks recommended that the morning is the best time to see the geysers. Tourists typically watch the sun rise, eat breakfast, view the geysers, and take a soak in a warm pool before returning to San Pedro de Atacama. The tour agencies tell tourists that El Tatio is only active in the cool, early morning when there are tall, billowing steam plumes. As expected, we found that though the large steam clouds do diminish as daytime temperatures rise, geyser activity continues throughout the day unabated.

Tours also typically include breakfast at El Tatio, often consisting of eggs boiled in hot springs. Some tourists we spoke to at our hotel said that their guides served pieces of the hot spring bacterial mats and hot tea and milk warmed with thermal water. Several springs on the Main Terrace appeared altered for tourism. For instance, spring T60 had probably been used for cooking—its calm greenish–brown water had a thick film on its surface and had trash scattered around it. The pool's temperature was measured at 43.8°C, with an adjoining pool measured at 25°C. These temperatures were at least 30°C lower than other surrounding, non–erupting springs.

At El Tatio, there are no boardwalks or designated roads. Unfortunately, footprints and tire tracks are found all over the field. In fact, some sediment–filled spouters lie in the middle of tire ruts. Many springs had been vandalized with rocks jammed into their vents; one of the larger cones had a metal rod, trash, and rocks stuffed into its vent. We removed artificially placed rocks and pebbles from at least ten Main Terrace springs.

Many of these geysers erupted to greater heights after their obstructions were cleared. Given its generally unmanaged, unprotected status, it is probable that large amounts of geysersite and sinter pearls have been removed over the years. Overall, even though subjected to a great deal of abuse, the appearance and intensity of activity within the field is extraordinary.

Getting Around in the Basin

No roads from San Pedro to El Tatio or within El Tatio itself are paved. With its approximately 10 km^2 area, the main geyser areas are within 3 kilometers of one another. Tire tracks from other vehicles are visible throughout the basin and roads to drilled wells are obvious. The entire length of the Main Terrace is accessible by road, although we walked along the banks of the river to visit the springs downstream along the Río Salado (Lower Geyser Basin). Although no trail existed, it was a relatively easy walk. A manmade dam–like structure, possibly a weir, was located just upstream of the lowest spring group. The presence of the dam likely indicates the existence of a nearby road with easier access to the area; the road would likely be on the south side of the river. Some of the Río Salado could be waded, since it flows as a shallow (less than a 50 centimeters deep), braided river throughout much of the basin. Only a visit to the Lower Geyser Basin or to a thermal swamp above the wells required traveling more than 2 kilometers from the Main Terrace. A series of roads at the drilled wells lead upward to the thermal swamp and its perpetual spouter. The roads were built for geothermal drilling, and require a high–clearance vehicle; they also easily could be walked. Although El Tatio Geyser Basin poses the safety hazards of a typical major hydrothermal field, navigating within the basin is relatively straightforward.

III. HYDROGEOLOGIC SETTING

El Tatio Geyser Field is located in northern Chile on the western flank of the Andes at an altitude of 4,200–4,300 meters. The boiling point of water at the Upper Geyser Basin is 86.3°C. Though hydrothermal manifestations occur over a 30 km^2 area, the primary geyser field comprises only 10 km^2. Other smaller thermal areas have been noted southeast of the geyser area at altitudes greater than 4,600 meters.

El Tatio is situated in the Altiplano–Puna Volcanic Complex. Surface thermal manifestations are located on the upper levels of the sunken block called the Tatio graben, which is oriented north–south for approximately 20 kilometers. The graben is limited to the west by the horst of Serrania de Tucle–Loma Lucero and may be limited to the east by the modern volcanic chain that reaches altitudes above 5,500 meters [Lahsen and Trujillo, 1976; de Silva and Francis, 1991]. The horst and graben originated in a Pliocene extension that was largely responsible for the uplift of the Andes. El Tatio is set on ignimbrites and lavas of the upper Cenozoic overlying a basement of Mesozoic sediment. Silicic volcanism has occurred in the region for at least 10.4 million years [de Silva and Francis, 1991]. The hot water of the basin is mainly confined to two aquifers, which are overlain by relatively impermeable formations. The Puripica and Salado ignimbrites, forming the lower aquifer, are overlain by the impermeable Tucle tuffs. Another aquifer spanning the central, southern, and southeastern region of the basin is formed in the Tucle dacite, which is overlain by the impermeable Tatio ignimbrite [Cusicanqui *et al.*, 1976].

Preliminary tritium data for thermal waters within El Tatio Geyser Basin yielded an age of 15 to 17 years at discharge [Cusicanqui *et al.*, 1976]. In contrast, geochemical dating at Yellowstone indicates that the water ejected by Old Faithful Geyser today fell as precipitation approximately 1100 years ago [Rye and Truesdale, 1993]. The likely source basin for the Tatio water is an area 15 to 20 kilometers east and southeast of El Tatio, although the topography of the region may cause the water to travel twice that distance. The rate of water movement has been estimated at about 1 kilometer/year [Cusicanqui *et al.*, 1976]. The Sol de Mañana thermal field is located 30 kilometers east, southeast of El Tatio Geyser Basin. It is likely that the El Tatio and Sol de Mañana hydrothermal fields are both fueled by the Pastos Grandes and Cerro

Guacha caldera systems, with Sol de Mañana being closer to the thermal source and El Tatio being a lower elevation distal discharge location [Healy and Hochstein, 1973; Lahsen and Trujillo, 1976].

Spring discharge from El Tatio Geyser Field coalesces to form the headwaters of the Río Salado. The river flows westerly out of the basin, through a narrow gorge penetrating the Serrania de Tucle Horst. Discharge of the Río Salado varies by season from 250 to 500 liters/second [Lahsen and Trujillo, 1976]. These measurements can roughly be compared to a range between the discharges of Yellowstone's Excelsior Geyser of the Midway Geyser Basin (223 liters/second) and the Upper Geyser Basin (518 liters/second) [Allen and Day, 1935; Rinehart, 1980]. Previous investigations at El Tatio have denoted an average thermal water pH of 7.2 [Lahsen and Trujillo, 1976], denoting an approximately neutral basin.

IV. METHODS

For this investigation, a *geyser* is defined as a hot spring in which eruptive activity is induced by boiling at depth within a plumbing system that forcibly ejects water out of the vent in an intermittent fashion [White, 1968; Bryan, 2001]. A *perpetual spouter* is a hot spring that ejects water out of its vent or pool with continuous eruptive activity.

In order to inventory and characterize the erupting springs of El Tatio, a combination of handwritten notes, Global Positioning System (GPS) locations, temperatures from a digital thermometer, still photographs, and video were collected during the three–day visit in March 2002. Working in the basin from the northeast to southwest, a two–person team took notes about each feature. For each feature exhibiting geyser–like behavior, the feature was assigned a code number. The feature's latitude and longitude, temperature, interval, duration, eruption height, and any other notes concerning unusual characteristics or behavior were then collected. GPS coordinates were obtained as close to the erupting vent as possible (within 1 meter horizontal and vertical) using a Garmin GPS III Plus handheld unit. Horizontal (degree, minute, decimal minute) and vertical (elevation in meters, with reference to mean sea level) locations were obtained in the WGS 1984 coordinate system; these data were recorded "raw," as non–differentially corrected. For the report's maps, initial positions were adjusted to reflect data from existing maps, satellite imagery, and relative feature locations in field sketches. For many of the features, vent and runoff channel temperature data were obtained, in degrees Celsius, using a digital thermometer. For most features, due to the prevalence of activity and time constraints, only two or three closed intervals were observed. It is likely that longer observations would show the geysers' behaviors to be more complex.

As two people inventoried and collected GPS locations, another person videotaped each feature, while the fourth individual conducted reconnaissance. Digital video was collected using a JVC GR–DVL815U mini–DV digital camcorder. In all, over six hours of video were taken at El Tatio, capturing the eruption of over 100 springs. Each of the four team members had a camera and several hundred still photographs were taken within the basin. With our team's limited time in the basin and the unexpectedly large number of true geysers, numerous perpetual spouters, mudpots, non–boiling springs, solfataras, and fumaroles were not inventoried.

Upon returning to the United States, field notes were transferred to a Microsoft Excel spreadsheet. Careful analyses of the field video and still photographs allowed the spreadsheet and notes to be verified and supplemented. In particular, the digital video provided the team with a method to develop detailed descriptions of both eruptive activity and feature appearance. Maps of the basin were created by importing name, location, and behavior data into the Environmental Systems Research Institute (ESRI) ArcInfo 8.3 Geographic Information System (GIS). A basemap of the basin was created by digitizing portions of topographic maps (Cerros de Tocorpuri and Toconce) from the Instituto Geográfico Militar [1985, 2001b] and further enhanced with NASA Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data. An Instituto Geográfico Militar [2001a] topographic map of Mauque, containing the

Puchultisa thermal area, was also digitized and added to the GIS. Given the close proximity of features compared to the resolution accuracy of sources, maps produced for this report are best suited for relative positioning and locating features in the field.

In the field at El Tatio, we used a map of thermal features by Trujillo *et al.* [1969]. Before the trip, Scott Bryan provided a list of feature numbers from the Trujillo *et al.* map that had been reported as geysers. Unfortunately, the density of springs made identification of individual features on the Trujillo *et al.* map difficult. Nonetheless, the map provided a reference to major spring groups and facilitated general navigation. Once the GIS was created, we attempted to reference our field numbers with the Trujillo *et al.* feature numbers. Using the ESRI ArcView Image Analysis extension, the Trujillo *et al.* map was georeferenced to the basemap. Overall, the density of thermal features decreased our ability to correlate specific numbered points from the Trujillo map. However, general spring groupings are apparent and consistent.

V. DISCUSSION AND FUTURE RESEARCH

Investigations at El Tatio Geyser Field have determined that it contains at least 100 erupting springs. With geothermal energy production and other exploitation impairing the major geysers fields throughout the world [Allis, 1981; Collar, 1990; Hroarsson and Jonsson, 1992; White, 1998; Sorey, 2000; Bryan, 2001], El Tatio stands as the third largest geyser field on earth and the largest geyser field in the southern hemisphere. The greatest number of geysers remains in the hydrothermal basins of Yellowstone, USA and Dolina Geizerov, Russia [Bryan, 2001]. With 80 or more, El Tatio's geysers account for approximately 8 percent of the world's active geysers. In addition, at least seven features previously reported [Trujillo *et al.*, 1969] as geysers were not visited. While many geysers and erupting springs were inventoried in this study, there are hundreds of other thermal manifestations at El Tatio to be documented, precisely mapped, and described. Additional mapping is necessary to gain greater detail, including observing more closed intervals, examining interrelationships among features, and updating behaviors that have changed since this and previous studies. Detailed maps of all features, not just the geysers, should be completed with higher–grade GPS units and applying differential correction or carrier–phase processing to the data. High–resolution satellite imagery can also provide an effective mapping tool for the area. A thermal feature inventory may be useful to evaluate the effects of previous and future hydrothermal drilling on the region.

Previous information reported that the geysers were only active in the morning. El Tatio tours typically arrive at the basin in the cool, early morning hours when tall steam plumes hide the geysers' relatively short eruption heights. We observed sustained geyser activity throughout our visit to El Tatio. There was no abatement in activity for any length of time within any part of the field. Although activity was consistent, geyser eruptions were observed to be relatively short in height. Of the erupting springs cataloged, the mean spouting height is 69 centimeters. Of the true geysers cataloged, the eruptions averaged 76 centimeters. A total of 31 geysers in the basin erupt to at least a meter; of these geysers, 13 have eruptions greater than a meter in height. Compared to Yellowstone and Dolina Geizerov, which both have a dozen or more geysers that erupt to 50 meters and greater, El Tatio geysers are small. The causes behind the short heights are unknown. More research is needed to determine if the heights at El Tatio are related to the plumbing system, the heat source, or other factors.

Many questions remain and numerous research avenues exist for the El Tatio geysers. Additional examination into the timeframe for the development and history of the activity of El Tatio, along with further tritium dating, are needed. The relationship between El Tatio and other Andean thermal areas, such as Sol de Mañana, should also be examined and quantified in future research. With its location in an active volcanic arc, opportunities exist to monitor relationships between seismic and volcanic activity and the field's hydrothermal behavior.

In addition, El Tatio's high altitude location within an exceptionally dry desert, create an extreme habitat for microorganisms. Microorganisms within other extreme environments, like the springs of Yellowstone, have been known to exhibit useful and financially marketable characteristics. Moreover, hydrothermal systems may be a "cradle" for early biosphere evolution, as thermophilic life may have the characteristics of the common ancestor of life on earth and other planets [Farmer, 2000; Walter and Des Marais, 1993; Farmer and Des Marais, 1994].

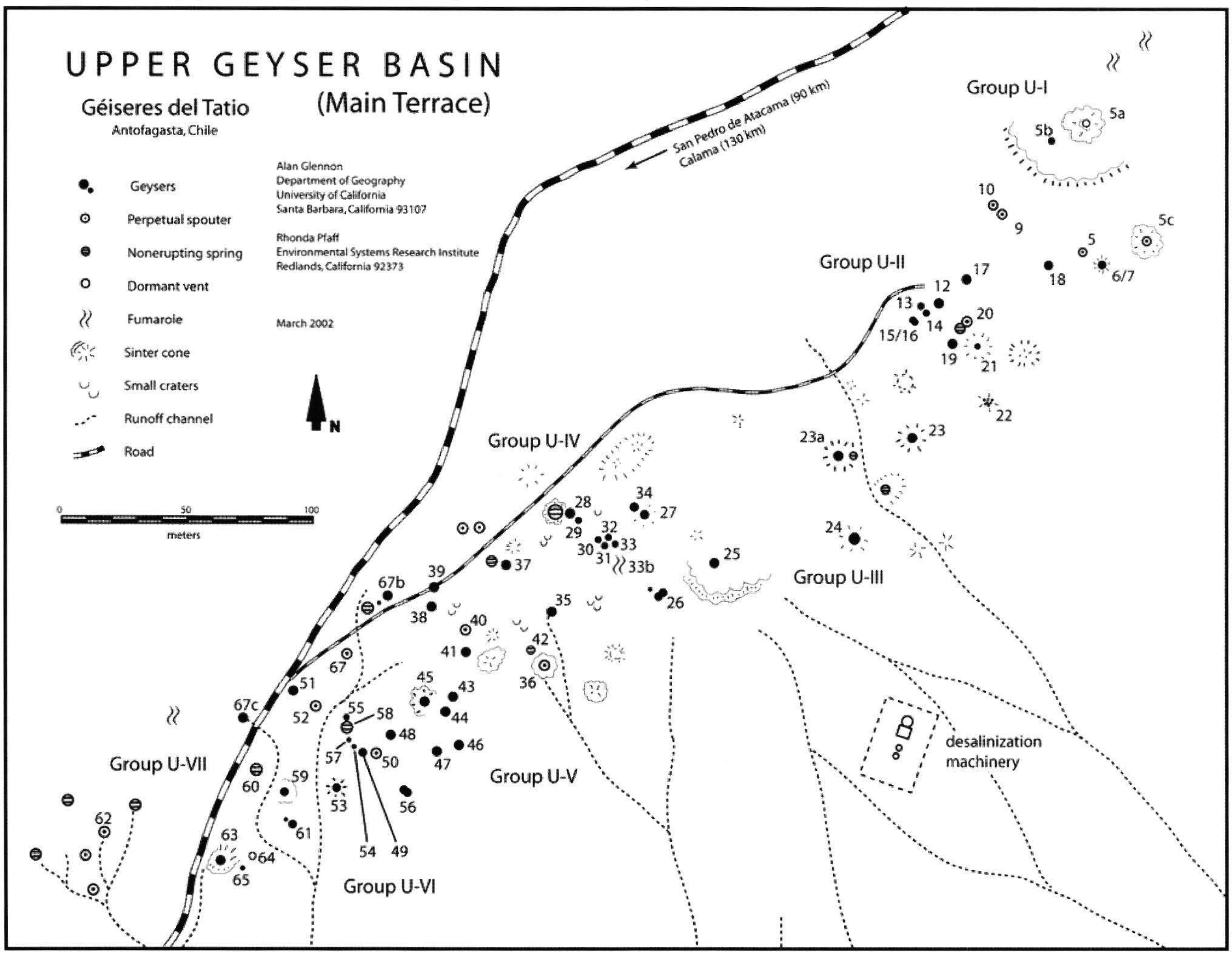
With its vigorous activity and rare display of geysers, El Tatio Hydrothermal Field is a unique, world–class natural resource. We hope this initial report will provide footing for researchers to develop a better understanding of this remarkable location.

PART II. SPRING DESCRIPTIONS

UPPER GEYSER BASIN OVERVIEW

The Upper Geyser Basin (or Main Terrace) lies near the floor of a gently sloping valley and is characterized by widespread, well–developed sinter terraces (Map B, below; see also Map A). The scene within the basin is stark. The broadly sloped flat of gray and white is punctuated by a handful of active and inactive geyser cones. During cold temperatures, steam is emitted from hundreds of crevices and vents. During warmer weather, viewing the area from a distance, it may appear that very little activity is occurring. However, a closer look reveals that the Main Terrace is always highly active. Numerous small spouters are in continuous eruption, several handsome pools bubble gently, and many of the largest geysers are usually nearing eruption.

Map B — Upper Geyser Basin (Main Terrace)



Within the Upper Geyser Basin of El Tatio, geysers surround the visitor.

Next to the broad flats of the geyser basin, the surrounding hills and mountains provide a contrast of color and scenery. To the west, north, and south, tall brown hills with scrubby grass line the basin. These steep hills are covered with reddish soils and have large boulders strewn along their slopes. The red soils are tempered by hints of green and yellow from grasses and stubby plant life. A wide, broad break in the hills to the southeast reveals the pass down out of the mountains. In the foreground of the pass, numerous steam plumes from the Middle Basin are visible low in the valley. Commanding the view to the east are the tall, snow–capped volcanoes of the Andes. The distant high–elevation mountains appear a shadowy blue.

The Upper Basin is the largest of the fields (spanning 5 km^2) and contains the greatest number of erupting springs. Though the Main Terrace extends into and down the valley to the Middle Basin, the primary zone of geysers stretches along a narrow band. The band follows a northeast–southwest lineament about 500 meters long and 100 meters wide. No less than 50 true geysers are in this small zone. Besides possessing the greatest number of geysers within El Tatio's three main basins, many geysers in the Upper Basin appear to have predictable intervals and durations.

Descriptions follow roughly from the northeast to southwest. With its small area and high concentration of springs, most Main Terrace features do not lend themselves to clear groupings. However, the springs' characters do change throughout the basin, with springs in close proximity often maintaining a similar character.

UPPER GEYSER BASIN, MAIN TERRACE

GROUP U–I

T5a (Suspect Geyser and Fumaroles)

In the far northeast zone of geyser activity, T5A is an elevated gray–white sinter terrace 3 meters high, spanning an area of 30–by–30 meters. Sitting atop the terrace is a large, steep–sided, highly weathered geyser cone. The cone is oblong–shaped and 1.5 meters high. With its crest approximately 3 meters above nearby features, within the eastern portion of the field, the terrace and cone are a dominating presence. Although we did not take detailed notes about the feature, Alan Glennon climbed to its top to assess its eruptive potential. Upon closer inspection, Alan found the feature not only highly weathered, but it also appeared to have been subject to explosive force. Large cracks had ripped open a portion of the cone, but its main vent was still intact. The feature's throat was approximately 15 centimeters in diameter. Unfortunately, several rocks had been lodged 50 centimeters down the vent. Regardless, below the rock jam, a loud belching churning sound could be heard. The vent itself was moist and hot with steam.

Approximately 20 meters to the northeast of the steep geyser cone, the sinter of the terrace meets the slope of the hill to the north. At the intersection, two deep, dangerous–looking, steep–sided rift craters are present.

T5b (Geyser)

Along the western base of the steep cone lies a small, round pool 20 centimeters deep and 50 centimeters wide. The pool occasionally sends radiating ripples along its surface as steam bubbles implode at depth. A deep thumping underground could be felt on the surface. Over a period of 10 minutes, the ripples increased. The pool began a slightly more vigorous overflow and weak splashing to 10 centimeters began. The splashing lasted about a minute before the pool level dropped approximately a centimeter and activity ceased.

T5c (Perpetual Spouter)

This is an attractive 1.5–meter high white sinter mound with a diameter of 2 meters. The mound gently slopes downward such that it is about twice as wide at ground level as at its vents. Water spurts nearly perpetually to 1 meter from at least two vents on its top. Three quarters of the mound is smooth and the other portion is rough and filled with jagged holes. Much of the mound is covered in orange and light brown–colored bacteria (or perhaps mineral deposition). Much of the runoff flows east. The nearby ground is composed of smooth, white sinter surrounded by small gravels.

T5 (Perpetual Spouter)

T5 is a small perpetual spouter that splashes to 5 centimeters from a vent 20 centimeters wide.

T6 (Geyser)

T6 plays from a 1–meter tall, 2–meter in diameter, white mound with occasional spurts to 10 centimeters for 5 seconds. While no major activity was observed, it appears to have larger eruptive potential. Vigorous, agitated boiling can be seen 50 centimeters down in the cone. A hole in the cone's side has developed as a secondary vent. Water in the spring rises and falls, but only occasionally did it rise high enough to splash outside its cone. There is some chance that the secondary vent and nearby small perpetual spouters are robbing the geyser of energy, but not enough is known about the feature to develop informed conclusions.

T7 (Perpetual Spouter)

T7 is a cluster of 4 vents covered in green algae on a dry, white 40–centimeter tall mound. Activity is apparently perpetual, with spurts to 5 centimeters.

T18 (Geyser)

T18 is one of several vents located on a 3–meter long light gray sinter mound. Most of the vents gurgle and hiss as small frying pans. The smooth mound is only 10 centimeters tall and 10 centimeters wide at its largest. The area around the mound serves as a splash pool for T18. Beaded sinter deposits and other pebbles are scattered about the area.

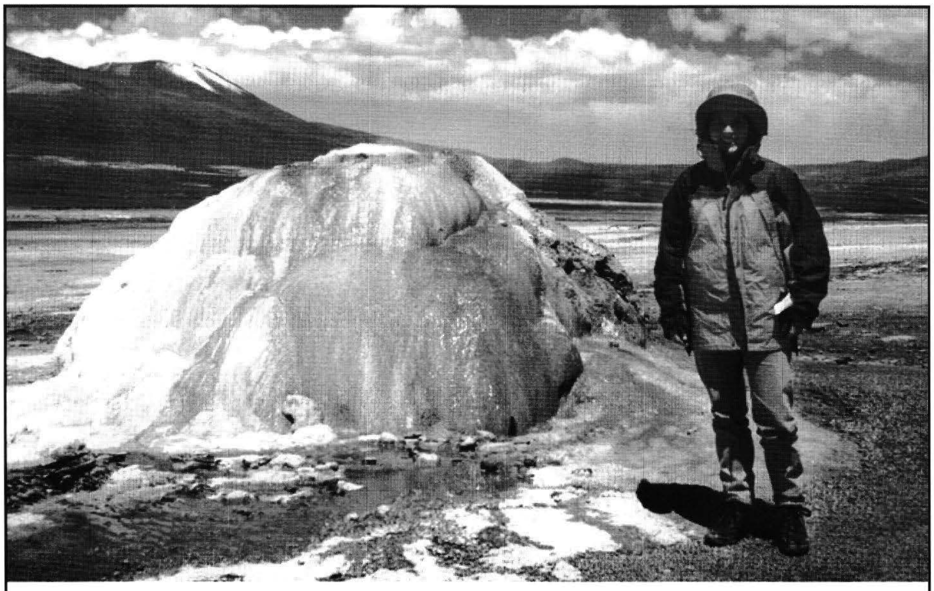
T18 is a small geyser that splashes to 40 centimeters from a tiny vent along a rift line on the low sinter mound. The geyser erupts for 1+ minutes every 15 to 20 minutes. When not erupting, only a meter–wide zone of wetness hints at the geyser's existence. Otherwise, not even a puff of steam is emitted from its vent. Eruptions begin quickly and consist of splashing pulses, alternating between 20 and 40 centimeters tall.

T9 (Perpetual Spouter)

T9 is a small, typical El Tatio perpetual spouter. It perpetually splashes to 20 centimeters from a 20–centimeter deep, 25–centimeter in diameter pool. A brick–like rock, now covered in sinter, has fallen into the vent.

T10 (Perpetual Spouter)

T10 perpetually boils vigorously to 10 centimeters from a small pool. Both T9 and T10 are located in a small flat area just slightly higher in elevation than the geysers to the south. The flat area is covered with pebbles, gravel, and sand.



Rhonda Pfaff at **Spring T5c**. (Photo by Shane Fryer)

GROUP U–II

T12, T13, T14, T17, and possibly T15 and T16, are a complex of interrelated geysers. During our observations, activity within T13 and T14 were closely related. As T13 ended its eruption, T14 began steaming intensely and erupted 50 seconds after T13's end. We noticed that at the end of an eruption of either feature, both would commonly simultaneously steam lightly. Their eruptions also appeared to affect the eruptions of the complex's major feature, T12, and vice versa. In addition, T17 and T12 also appeared to have sympathetic eruptions and steam phases. The features have relatively short intervals and durations and detailed observation may prove or disprove these hypotheses. In January 2003, Dr. Randall Marrett, Associate Professor of Geosciences at the University of Texas at Austin, conducted a multi–day investigation of this spring group. His findings have not yet been published.

A shallow, half–moon–shaped linear depression lies immediately south of the T12/13/14 complex. The feature was noted because of the suspicious zone of wetness around it. A couple of small fractures are vent possibilities. Further observation may show the feature to have eruptive potential.

T12 (Geyser)

T12 is a geyser that erupts from a sinter–rift complex. It appears to be the dominant geyser in a zone of several interrelated small geysers. The vent is located at the eastern base of the sinter mound. The current vent appears to be developed along the remnants of a geyser cone that has been cracked through its middle and is now heavily weathered. The geyser erupts up to 1.5 meters from a vent on the ground surface at the front of the rift crack. The play is vigorous, and during larger eruptions, a layer of water radiates to the northeast for approximately 3 to 4 meters. The discharge flows over a sinter apron and onto the sandy gravel beyond. Steam increases from the overlying rift and water weakly splashes from the primary vent in the pre–play. The eruption lasts less than 2 minutes and occurs on an interval of about 15 minutes.

T13 (Geyser)

T13 is a small geyser 4 meters northwest of T12 and is located on the sinter complex. It erupts from a gray crack and splashes to 20 centimeters for 2.5 minutes about every 15 minutes. Its play consists of continual splashes ejected as a wide, thin ribbon of water. It is likely to be closely related to the other geysers on the sinter complex, especially T14. At the conclusion of a T14 eruption, T13 typically begins steaming lightly.

T14 (Geyser)

Prior to eruption, steam billows out of a small crack (less than 10 centimeters wide) on a mound 2 meters from T12. Eruptions observed typically occurred within a few minutes of the conclusion of an eruption of T13. The crack and mound have a reddish–orange color. The eruption splashes clear water to 50 centimeters for 1.5 minutes. The play is at full volume and height after only a few seconds of thin spurting. The eruption ends over several seconds as volume, height, and splash intensity decrease. Quickly, water is no longer visible at the surface. The interval ranges from 3 to 15 minutes.

T15/T16 (Geyser)

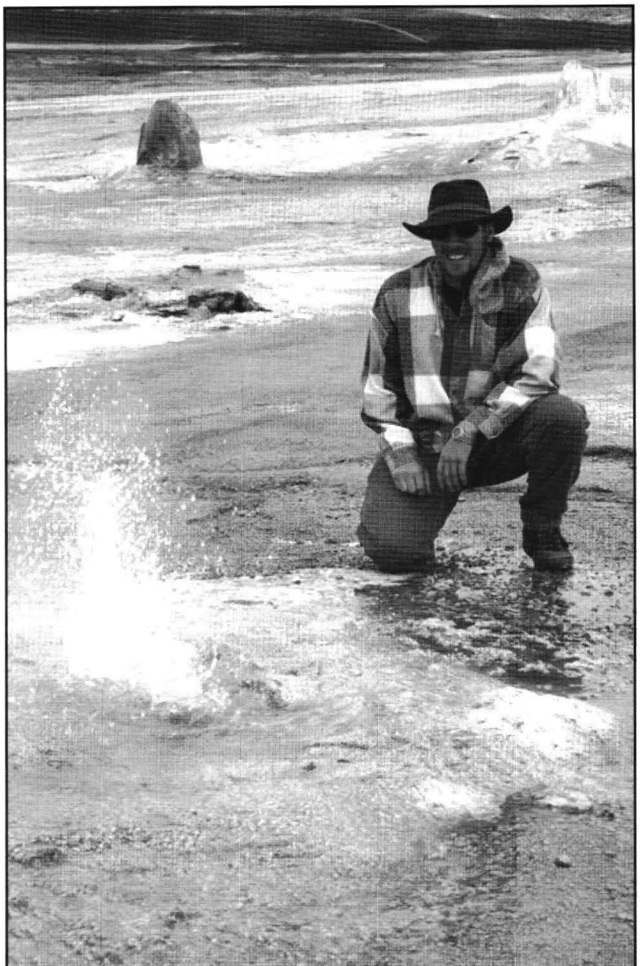
T15 and T16 are two adjoining fountain–type spouters that splash clear water to 10 centimeters nearly perpetually. The pools are located on top of a small sinter mound. The runoff channel has orange bacteria in it. The geyser plays for several minutes, with an interval of 4 minutes.

T17 (Geyser)

T17 is a small geyser that erupts from a gray sinter crater measuring 75 centimeters across and 30 centimeters deep. The vent at the bottom of the crater is about 5 centimeters in diameter. A light gray sinter crust lines the splashdown area around the crater. Clear water vigorously splashes to 50 centimeters for 9 minutes every 5+ minutes. Water rapidly fills the crater half–full and then gradually rises to overflowing during the eruption. When the eruption is finished, the pool's surface becomes still and the pool empties quietly. The pool is completely drained 30 seconds after the eruption's last splash.

T19 (Geyser)

T19 is a geyser that erupts from a shallow crater to heights of 1 to 1.5 meters. One of the more significant geysers of the Upper Basin, T19's eruptions consist of a surging, but sustained, fountain of frothy water. Its vent is located on a short, broad terrace. The vent is surrounded by a flat, platy sinter splashdown ring and its runoff flows south down the steeper side of its terrace. A black, softball–sized rock was located a meter east of the vent.



Weldon Hawkins at **Spring T19**. Springs **T23** and **T23a** are visible in the background. (Photo by Rhonda Pfaff)

The geyser erupts for 3 minutes every 20 to 23 minutes.

T20 (Perpetual Spouter)

T20 consists of a round, non–erupting pool and a ragged, splashing vent 25 centimeters away. The pool is about a meter across and 10 centimeters deep. The pool's rim is encrusted in white and tan sinter and has a silty, tan–colored bed. A softball–sized rock has been jammed into the pool's vent. The adjacent erupting vent perpetually splashes to 10 centimeters from a jagged hole. A wet, dark–brown–colored splash area extends 50 centimeters from the erupting vent. A 5–centimeter wide run-off channel carries its small discharge a meter before the flow disappears into sand and gravel.

T21 (Perpetual Spouter)

T21 is a 2–meter long white–gray mound with 10+ vents that sputter perpetually to 5 centimeters. The mound is banded gray and white with alternating wet and dry areas of sinter. A round non–erupting pool lies in sand and gravel about 3 meters north of the mound.

T22 (Geyser)

T22 is a very unusual, 50–centimeter tall, spiny sinter mound. It has at least 20 vents of pencil–sized diameter, out of which water sizzles for 2 minutes, every 5+ minutes. The eruption gains full strength within 30 seconds, with water spitting up to 30 centimeters vertically from several vents. Other vents shoot water short distances at many angles. The eruption slowly wanes over the next minute and a half. Eventually, only steam and a quiet sizzling sound can be heard. The steam persists for 30 seconds before leading to a 5–minute period of complete quiescence. There are two small runoff channels extending from opposite sizes of the mound. Intricate geyserite makes up the mound and

The unusual, multi–vented geyser, **Spring T22**. (Photo by Rhonda Pfaff) immediate area. Strips of thin sinter radiate in a few places farther from the mound indicating splash areas of individual vents. The color of the sinter ranges from whites to grays and dark browns.

GROUP U–III

T23 (Geyser)

T23 is a very steep, 1.5–meter tall, dark brown and orange–brown cone that has a nearby dry, white–colored twin cone (T23A). T23 nearly perpetually splashes from a 30–centimeter wide vent at its top. Several periods of minutes had markedly less activity (for instance, splashing every several seconds to less than 10 centimeters). During most of our visit, splashes commonly reached 40 centimeters, with occasional droplets reaching a meter. The splashes often discharged enough water to send a bath of water down all sides of its cone. Along with the T5c, T23 is one of the only large continuously wet geyser cones observed in the basin. Photographs from February 2000 by Cyril Cavadore show the cone of T23 completely dry with no steam. Another tourist photograph showed a tourist seated atop its dry cone. Though its durations and interval are unknown, it appears that the duration, at least, is days. Given the photographic record, the geysers' intervals are likely to be days long, also.

T23a (Geyser)

Twenty meters west of T23, T23a possesses a cone of similar shape and height (1.5 meters tall and steep sided). However, unlike its twin, the cone is completely white and dry. Several rocks and a metal rod have been stuffed down its vent. A February 2000 photograph by Cyril Cavadore shows the cone wet and several small springs along its base overflowing. Randall Marrett reported T23a active in January 2003 (with T23 inactive). When active, the geyser splashes 0.5 meters over its rim several times per minute. The geyser's interval and duration is days. The twin features (T23 and T23a) display an apparent exchange of function. Observers, so far, have noted only one of the springs active at a given time.

A small runoff stream flows between the two twin cones. Downstream, along its banks are several small boiling springs and perpetual spouters. Seven smaller, broad sinter mounds lie along the stream's downstream banks.

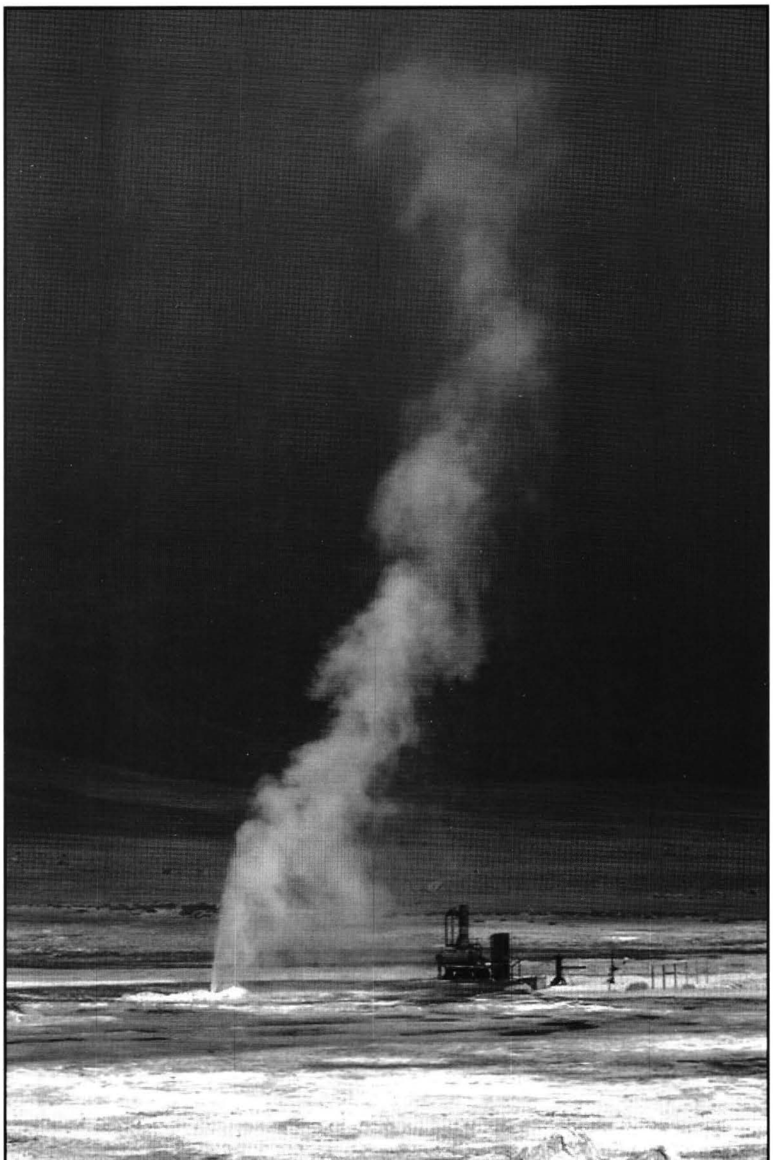
T24 (Geyser)

T24 is a geyser that erupts from a 2–meter wide cone with a 40–centimeter wide vent. The cone is light–to–medium gray–colored sinter and is 40 centimeters tall. The geyser splashes to a meter and forms a pool in the depression of its cone. Splashes infrequently reach 2 meters and land far beyond its elevated sinter mound. The duration of the splashing is less than 35 minutes, with an interval greater than 3 minutes. A series of rising and falling water levels were observed in the vent before the eruption, but future observation is necessary to characterize its exact behavior.


The cones of **Spring T23a** (left) and **Spring T23**. (Photo by Cyril Cavadore)

T25 (Geyser)

In terms of height and beauty, T25 is the star of El Tatio. The geyser, the tallest ob-



Storm clouds darken the sky behind **Geyser T25**. Machinery remains from an abandoned project to test steam–driven thermal water desalinization. (Photo by Alan Glennon)

served at El Tatio, can reach heights greater than 5 meters. The geyser is located on top of a wide, multi–tiered terrace 1.5 meters high. The southern portion of the terrace is a meter–high scarp covered with active columnar sinter. The runoff channel is composed of thousands of shallow microterraces. Beaded sinter and oncoids are located everywhere. The geyser exhibits lots of pre–play, consisting of slow building of water volume and height from its 30–centimeter tall mound.

The preplay builds for at least 30 minutes before the full eruption begins. The geyser plays for up to 15 minutes every 2 or more hours, although there was typically small splashes up to 30 centimeters at all times the geyser was observed. A short steam phase and several minutes of inactivity follow its major eruptions. During major eruptions, water is ejected nearly vertically to 5 meters, although a smaller amount of water is shot at a 45° angle to heights of 1.5 meters. During one eruption, the water phase appeared to taper into a longer steam phase. At the end of this type of eruption, the jet of water became increasingly narrow. The thin jet of water may reach heights exceeding 8 meters. Over several minutes, a narrow column of steam replaces the water. Of six eruptions seen, this higher type of eruption was observed only once. The geyser lies approximately 100 meters away from the abandoned desalinization well. A temperature of 62°C was taken from the surrounding splash pool that has orange bacteria growing in it.

Visitors in January and May 2003 reported hours to days of perpetual spouting from T25.

Shane Fryer and Rhonda Pfaff taking a temperature measurement at **Geyser T25**. (Photo by Alan Glennon)

GROUP U–IV

Below a 60–centimeter tall, 1–meter wide elevated hot spring pool, lies a series of small craters arranged linearly. Typically vertical perforations in the sinter, 40 centimeters in diameter and 30 centimeters deep, these craters are aligned primarily along three different trends. Each of the lineaments originates at the elevated hot spring pool and radiate outward. The first trend is approximately aligned toward the east. Only one or two craters exist along the trend, but they head toward a dilapidated, broad geyserite cone 20 meters away. Two geysers are located at the worn geyser cone. The second trend stretches southeast toward T25. Along this trend are numerous craters. Nearly all of the small craters emit steam and boil vigorously in the subsurface. Several of these craters periodically erupt to short heights as geysers. The third lineament trends to the southwest. Several steaming craters and small vents are present, but only one's boiling would periodically reach above the ground level. The trend continues outward toward a region of small vents. The vents trend roughly toward T36 and include numerous multi–colored warm springs with tiny vents (less than 5 centimeters in diameter), several steaming 20–centimeter deep craters, and tiny boiling springs.

T27 (Geyser)

T27 is a geyser that plays from a broad, heavily worn cone, 60 centimeters tall and a meter wide at its top. The top of the geyser cone funnels down 40 centimeters to a circular vent 15 centimeters wide. Most of the vent is clogged with pointy rocks and dry gravel, although a gap along one side of the vent provides an opening for eruptions. Eruptions play as angled surges splashing to 40 centimeters. The eruption rarely plays water outside of the cone's funnel and only a small area of the total geyser vent is wetted by the eruption. One eruptive duration lasted 5 minutes with a minute pause in activity. Other observations found the feature to be perpetual.

T34 (Geyser)

At the northwest base of T27's cone is a small geyser that typically plays to 10 centimeters, but occasionally splashes to six times that height. The geyser plays from a shallow, dark–colored funnel on the ground level amongst sinter gravel. The funnel itself appears worn and some of its sinter is broken. The play is nearly perpetual with momentary pauses. During a typical eruption, very little water flows away from the cone; however, during occasional 60–centimeter tall splashes, water often lands beyond its sinter funnel and onto the nearby gravel. The geyser's runoff channel is an area of moist gravel, but the wet area extends at least 6 meters from the little geyser. From its appearance, the feature occasionally sends significant but short–lived washes of overflow down its channel.

T28 (Geyser)

T28 lies along the southern base of the elevated cone of a 1.5–meter wide, non–erupting, steaming hot spring. The elongated vent creates a jagged cut laterally along the base of the cone. The vent is a meter long and 30 centimeters wide. A primary vent plays often and sends splashes up to a meter. Two satellite vents occasionally play in concert to 10 centimeters or more. The feature appears erratic but almost perpetual, with seconds to a minute of nearly continuous eruption followed by a pause of up to 20 seconds. The vent is angular and jagged, possibly indicating that the feature is relatively new, had a particularly explosive genesis, or has long periods of quiescence.

T29 (Geyser)

T29 lies along the lineament of craters toward T25 approximately three meters from southeast of the elevated hot spring. The steaming jagged crater, approximately 30 centimeters wide and deep, plays to 50 centimeters above ground level. Several observed closed intervals showed the play to last 30 seconds with an interval of approximately 2 minutes. The crater steams gently throughout its quiet period.

T30 (Geyser)

Six craters in a 3–by–3 meter area include several small, apparently erratic geysers (T30, T31, and T33). The largest of the group is T30. T30 possesses a 50–centimeter wide, 30–centimeter deep crater. Similar to the other features in the immediate vicinity, the crater drops off at ground level with vertical walls and has an irregular shape. During three closed intervals, T30 played to 30 to 40 centimeters above ground level with a 5 second duration and an interval between 15 and 25 seconds. Very little water is discharged by the eruption.

T31 (Weak Geyser)

T31 is a very small and apparently erratic geyser playing from a narrow, 1–meter long vent. Though boiling can be heard constantly in the vent, an occasional splash to 20 centimeters may occur. During our observation of the area, a single weak splash would occur from the southern portion of the vent not more than once per minute. Overall, compared to the nearby activity, the eruption is very easy to miss. Normally, the geyser is a gently steaming crater.

T33 (Weak Geyser)

T33 is another very small and apparently erratic geyser. It plays from a 30–centimeter in diameter, erratically shaped vent along the lineament between T28 and T25. A single splash, lasting no more than a second occurs every 30 seconds or more. The weak splash commonly plays to 20 centimeters above ground level.

T33b (Fumarole)

Although not seen in eruption, this feature may be more important than the several other minor features in the area. T33B is an elongated vent sub–parallel with the T28/T25 lineament. The 20–centimeter deep crack has a tiny vent that hisses a 5–centimeter spray. The misty spray's height remains well below the ground surface. Although not as impressive as the other features in the immediate vicinity, T33B has a small, but distinct, runoff channel. A layer of small gravel lies ten centimeters from the vent in the upstream direction. It appears to be a high water mark for the feature. Though it may have eruptive potential, for now, it is classified as a small fumarole or dormant vent.

T32 (Geyser)

T32 is fan–shaped depression that slopes down to a point 30 centimeters below the ground surface. The vent is 20 centimeters wide at the bottom of the depression. Rocks have been jammed into the vent such that the small eruptions occur only through openings in the obstruction. The eruptions barely splash above the rock jam, with none observed to splash above ground level. Eruptions occurred during occasional rises in water level that reveal highly convective boiling leading to weak splashing to 10 centimeters. The activity appeared relatively erratic with rising and lowering of water to occur over several minutes and splashing to last only several seconds.

Small **Geyser T29** (middle left) plays in Spring Group U–IV. An afternoon storm hides the hills behind a weak, steamy eruption of **Geyser T25** (background). (Photo by Shane Fryer)

T26 (Geyser)

T26 is a fountain–type geyser that erupts from an L–shaped pool, 1.5 meters in length. The pool is 5 centimeters deep, with a gray mud bottom. The rim of the pool is lined with reddish–orange bacteria. Play to 40 centimeters comes from two primary vents, which are 10 centimeters in diameter. The splashes are formed as the clear water rhythmically surges in and out of the vents every second. A third vent forming the bottom leg of the "L" is separated from the main area of the pool by a small natural bridge at the water level. Water in this 20–centimeter wide vent rhythmically surges. A tiny fourth vent lies 2 meters north of the pool and erupts in concert with the other vents (to heights of 20 centimeters). The eruption goes for a few minutes with periods of quiescence occurring in all vents lasting only a couple of seconds. In short, the spring is active nearly all the time.

GROUP U–V

T35 (Geyser)

T35 is one of the more significant geysers in the basin. It appears to be a consistent player with a well–developed, often–used runoff channel, consistent durations and predictable intervals. T35 erupts as a fountain from a vent flush to the ground 50 centimeters wide. The geyser reaches heights of 1.5 meters during its 1–minute eruption that occurs every 2 minutes. The eruption reaches full strength within 10 seconds with no pre–play. The eruption height overall is sustained in a series of splashy bursts throughout the eruption. After 50 seconds, the height of the eruption starts to decline and 10 seconds later the eruption has completely ended. It takes less than 10 more seconds for water to drain from the vent. The primary vent is located among a series of other smaller vents. The geyser erupts from only one vent, but it overflows and spills into several of the surrounding small holes.

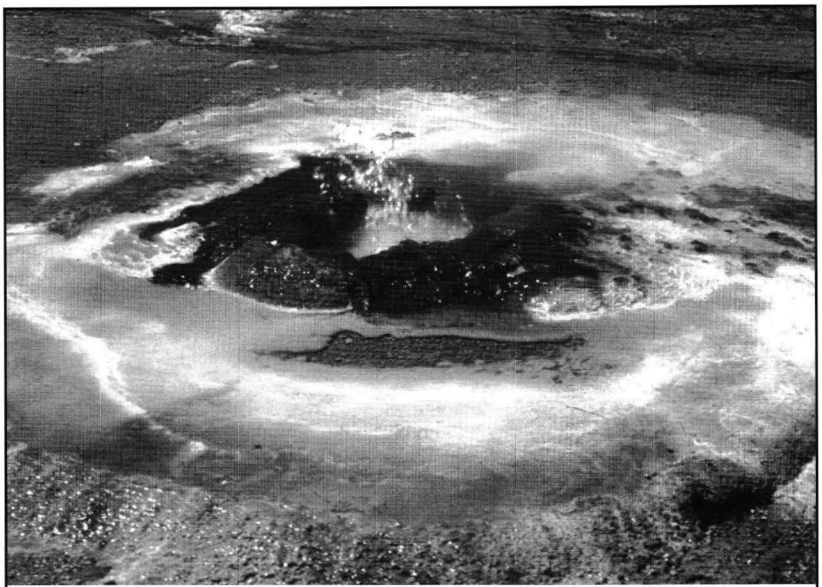
T36 (Perpetual Spouter)

T36 is an attractive spouter whose play (up to 50 centimeters) emerges from a 40–centimeter wide, dark brown–colored cone in the middle of a 10–centimeter high, white, flat sinter–mound. The lower mound, which is nearly circular, is approximately 1.5 meters in diameter. The lower mound is very wet from splashes. Orange and dark brown bacteria are growing in some areas of the lower mound, primarily around the outer rim of the flat mound. A small pool (30 centimeters in length and less than 2 centimeters deep) has formed over a portion of the lower mound. There are many geyser pearls and other small silica deposits in the pool.

Spring T35. (Photo by Shane Fryer)

T37 (Geyser)

T37 is located near the road along the northern side of the Main Terrace. Several small perpetual spouters are located in the vicinity, but only T37 was seen to have intermittent activity. The gurgling play is up to 10 centimeters high and is nearly perpetual. Quiet pauses last only



Spring T36. (Photo by Shane Fryer)

a few seconds. During the momentary pause, the water level in the feature drops before gurgling and splashing begins again.

T38 (Geyser)

T38 is a muddy, oval–shaped pool level to the ground. Four linear vents are present in the small pool. The pool measures less than a meter in length and is about 5 centimeters deep. T38 is near the main road that runs through the upper basin. All the vents splatter to 20 centimeters for about 30 seconds. When in eruption, the splashes of clear water occur from different vents while the pool is overflowing. At the conclusion of the eruption, the pool drains completely. Its interval is about 2 minutes.

T67 (Geyser)

T67 is a spring with a 10–centimeter deep pool at the vent. The vent was clogged with rocks that had probably been placed in the vent by tourists. The rock nearest the surface oscillated with the splashing of the water during the eruption. When two rocks were removed, the pool drained. After inventorying several other features, we noticed the vent had begun splashing to 40 centimeters. In addition, it had started to overflow and wet its small runoff channel. The eruption lasted for at least 10 minutes, but nothing is known about its interval. A ring of platy, rough gray sinter is present around the pool. Beyond that, the ground is composed of reddish–sandy deposits. A couple meters away, two tiny features spurt to a centimeter.

T67b (Geyser)

T67B plays from a 20–centimeter deep pool that is about a meter wide. A meter to the west, a 5–centimeter hole acts as a satellite vent. The geyser itself is located immediately north of the road that many tourist vans take into the basin. Only cursory observations of the geyser were made, but the activity was quite intriguing. The activity starts from a gently boiling pool and small splashes begin along the pool's northern side. The side of pool muffles the splashes and they reach only about 10 centimeters. After a minute of this activity, the splashing ends with a weak, but agitated, rocking of the pool. Over the next 30 seconds, boiling begins along the pool's southern side. The southern side of the pool has a ragged, overhanging sinter ledge that begins enduring most of the boiling. After several vigorous boils, a steeply angled splash begins jetting 30 to 40 centimeters from under the sinter ledge and tangent to the pool. The splashing increases in intensity for several seconds before the satellite vent begins a constant boil to 10 centimeters. The activity sends a thin overflow of water across the road. The eruption lasts around 4 minutes before returning to a somewhat agitated boiling along the pool's northern edge. Nothing is known about its interval other than the activity was not repeated within 5 minutes of observation.

T39 (Geyser)

T39 is a sediment–filled geyser that, unfortunately, lies in the middle of tire tracks on the main road through the upper terrace. The vent and pool together are 50 centimeters across and are completely choked with small gravels and pebbles. The small feature spouts to 10 centimeters for several seconds with an interval of less than a minute. When in eruption, activity in a series of frying pans 50 centimeters away intensifies.

T40 (Perpetual Spouter)

T40 is a small spouter that splashes from a 20–centimeter wide vent. The pool splashes perpetually up to 10 centimeters.

T41 (Geyser)

T41 is a small geyser that spurts to 40 centimeters (at least 20 centimeters above ground level) from a hole that is 20 centimeters in diameter. There is a dry sinter–encrusted circular area reaching a meter from the vent, indicating that the geyser could possibly erupt higher than observed. The vent and splash ring are encrusted in beaded sinter. T41 splashes for approximately 2 minutes, with an interval of greater than 5 minutes. The vent dries in between eruptions, although the splash ring remains wet. The geyser is located 1 meter away from the crater of an old, large (1 meter in diameter, nearly 1 meter tall) dormant, reddish–colored cone.

T42 (Intermittent Spring)

T42 overflows and gurgles from a hole 25 centimeters across for 30 seconds. Another vent a meter away has similar behavior every 3 minutes.

T43 (Geyser)

T43 is a crater level to the ground coated in dark green and black algae. The coloration was unusual among the other spouters. Splashing reaches heights of a meter for several minutes with a very short (only seconds long) interval. The surrounding splash area extends a meter out from the vent, with similar dark–colored bacteria growing in all directions. There are no gravels or sediments located within the splash area, possibly indicating a high water mark. The outer rim of the splash area has some orange bacteria. A small, round hole located within the splash area occasionally spurts a few centimeters.

T44 (Geyser)

From above, T44 resembles a gray, open–faced seashell. The inner vent is nearly black. The top of the vent is flush to the ground, although the opening extends 20 centimeters beneath ground level. Frothy water surges once every few seconds from the 30–centimeter long sinter–covered vent with a sound that is reminiscent of rhythmic ocean waves breaking on the seashore. One side of the vent gently and smoothly slopes downward, while the opposite side is jagged like a half–conch shell. The bottom of the vent is full of fist–sized rocks and pebbles blocking the geyser's full eruption power. The surrounding splash area and reddish–colored sandy sediments are dry. The frothy eruption reaches to 10 centimeters and lasts more than a minute. The interval is greater than 5 minutes. A 10–centimeter in diameter hole—a satellite vent—adjacent to the main opening, occasionally splashes as well.

T45 (Geyser)

T45 is a geyser on a meter–tall, gently sloped, white sinter mound. Sinter beads are present on the mound. Several small rocks that were choking the 5–centimeter wide, round vent were removed, but several still remain. The eruption has an angled component and reaches laterally 70 centimeters. The east side of the geyser is wet, while the west side remains dry. A splash area at ground level has a coating of dark film. The geyser erupts for 1 minute at intervals of greater than 2 minutes.

GROUP U–VI

T46 (Geyser)

T46 is a geyser that produced a vigorous eruption after we removed ten rocks and pebbles that had been stuffed by vandals into its 10–centimeter in diameter vent. The vent and splash area were slightly damp and there was little activity (play to less than 10 centimeters). Cleared of blockage, the geyser plays to 1 meter, with an angled eruption emanating from an opening on the side of a low, gray sinter mound. Water from the geyser's eruption spills over into a lower splash area. Light and dark gray beaded sinter is present, with little or no coloration in either the vent or splash pools. The eruption lasts a minute or more with a 15+ minute interval.

T47 (Geyser)

T47 is a small geyser that erupts with weak splashing to 10 centimeters. Only one eruptive episode was observed. The duration was less than 10 seconds. Its small, wet splash cone implies that the interval is relatively short.

T48 (Geyser)

T48 has a smooth, 10–centimeter in diameter vent that extends 10 centimeters beneath the ground before being obstructed by several rocks. The rocks appear to have been artificially placed in the vent, so we attempted to clear them (most could not safely be removed). The geyser erupts up to 20 centimeters. There is a light gray sinter splash ring around the vent and a handful of pebbles scattered about it. The geyser has periods of quiescence minutes long. Eruptions observed consisted of a series of splashes every few seconds.

T49 (Geyser)

T49 is a somewhat–round pool 50 centimeters in diameter. The pool's western edge is bounded by a low, lumpy sinter accumulation that overhangs the pool and creates an irregularly shaped western shore. The pool's vent is located below the irregular side 10 centimeters underwater. Eruptive activity is typically weak and consists of small surges to 5 centimeters. Otherwise, during its quiet period, boiling at depth creates small ripples along the pool's surface. Orange bacteria line the eastern rim of the pool. A tiny runoff channel flows from T49 into T50.

T50 (Geyser)

T50 is a fountain–type geyser that splashes from two distinct vents. The vents share the same small pool. The shallow pool, which is oval–shaped and 1 meter across, has a dark green tint, with orange bacteria around the rim. Both vents commonly splash to 50 centimeters. Two frying pans splatter in T50's overflow channel. The intensity of boiling rises and falls and brief total pauses were observed. The duration is greater than 1 minute with an interval of seconds.

T51 (Geyser)

T51 is a geyser located immediately south of the road through the upper terrace. Its eruption consists of a continual gush of water, with heights up to 1 meter. Compared to the other small geysers of the basin, its eruption creates considerable discharge. Its pool and splash area, which is about 1 meter across, is full of small rocks. The pool is level to the ground. When the geyser is not in eruption, the pool is drained and its vent gently steams. The duration is less than 5 minutes and the interval is less than 15 minutes.

T53 (Geyser)

T53 is a small geyser that splashes to 15 centimeters from a 7–centimeter vent. The vent is covered in dark gray sinter. Adjacent to the geyser is a low, white sinter mound. Three small rocks were removed from the vent while it was not in eruption. The interval is approximately 10 minutes.

T54 (Weak Geyser)

T54 is an obscure vent on an area of flat sinter pavement. The 3–centimeter wide vent was noticed when it suddenly began splashing and bubbling water to 5 centimeters. The weak splashing only lasted a few seconds before ending. No runoff was produced. Further observation found the feature to erupt at intervals of less than a minute.

T55 (Two Geysers)

T55 is a geyser that intensely splashes to 10 centimeters from a crack vent 3 centimeters across. The crack, encircled by a smooth sinter splash zone, is ringed by an apparent high water mark radiating 20 centimeters from the vent. Another small, wet crack with an elongated sinter splash zone is located 20 centimeters east. Its duration is less than 10 seconds. The interval is unknown, but the feature was seen in eruption again within 15 minutes. With such a small geyser, any intervening eruptions could have easily gone unnoticed.

T56 (Geyser)

T56 is a fountain–type spouter whose pool is lightly scalloped around the edges. The pool is dark gray and 10 centimeters deep. Fifty–centimeter high splashing occurs from a vent in the center of the pool. The geyser's duration is short with long quiet pauses of gentle boiling. The runoff channel has bright orange bacteria present.

T57 (Geyser)

T57 is a small spouter that splashes to 5 centimeters from a hole 5 centimeters across. Located in an area of flat sinter crust, its vent is obscure until it erupts. Eruptions only last a few seconds with an interval close to a minute.

T58 (Hot Spring)

T58 is a hot spring with a 1–meter long depression that is 20 centimeters deep. Two vents containing 72°C water were seen to be rising during 15 minutes of observation. The elongated depression has a thin coating of orange sinter.

GROUP U–VII

T59 (Geyser)

T59 was observed erupting up to 30 centimeters from its 30–centimeter tall, light–colored sinter cone. The round geyser vent is level with the ground, but is encircled by a short geyser cone. A wet area of dark gray deposits or bacteria encircles the geyser. Weak, brief splashes occur every 30 seconds. During 15 minutes of observation, occasional puffs of steam and intermittent rising and lowering of water levels in the crater were observed. From the size of the cone and nearby well–maintained sinter apron, the geyser may have a history of more vigorous activity. Given that two other large geysers exist nearby (T63 and T51) with relatively long intervals, perhaps this geyser also possesses a long interval between majors. In all, the observed activity of T59 was frustrating. Several times, when it appeared the water, steam, and activity rose enough to preface an eruption, the water level dropped, and the geyser became quiet.

T60 (Warm Spring)

T60 is a spring that may have been used by guides to cook for tourists. T60's calm water was greenish–brown–colored with a heavy film on its surface and there was some trash scattered about the spring. The pool's temperature was measured at 43.8°C, with an adjoining smaller pool measured at 25° C. These temperatures are at least 30°C lower than other surrounding, non–erupting springs.

T61 (Geyser)

T61 is a rectangular pool that vigorously laps back and forth, eventually surging and splashing up to 60 centimeters from its orange–colored crater. The pool is sunk 10 centimeters from the surface. A smaller vent one meter away emits weak splashes to 10 centimeters. As the eruption ends, the intensity of the surging in the main vent decreases and the water level lowers. A relatively dry sinter–splash area encircles the vents. While always agitated, the spring definitely displayed minutes of stronger splashing and overflowing activity (and increased activity in its satellite vent). This activity is followed by minutes of weak rocking of water within its pool and small splashes to 5 centimeters.

T62 (Perpetual Spouters)

T62 erratically splashes to 10 centimeters. Quiescent periods several seconds long were noted, but not convincing enough to classify it as a geyser. The hill northwest of T63 creates a 60–meter wide alcove with several perpetual spouters, mudpots, and fumaroles. T62's irregularly shaped, 2–meter wide pool is scalloped and undercut around the sinter–encrusted rim. Its runoff temperature was measured at 84.6°C. The primary vent is obstructed by rocks, which likely reduces its eruption height to 30 centimeters. Two perpetual spouters that erupt to 10 to 30 centimeters are located within 20 meters to the north and west. T62 lies on the northern side of the main terrace primary road, opposite T63 and the majority of the main terrace geysers. About 10 meters up the slope east of T62, an interesting bright red–orange pool has several splashing frying pans along a slump on its uphill side. The pool's water shares the same red color. Above this pool and 50 meters farther to the east lies a lone, loud fumarole on a gentle slope. From the fumarole along the hillside, most of the main terrace can be seen.

Dormant **Vent T64** (foreground) and **Spring T63**. (Photo by Shane Fryer)

T63 (Geyser)

T63 is one of the major geysers of El Tatio Geyser Basin. It erupts to 3+ meters for 15 minutes with an interval greater than 2.5 hours. Steam increases from the vent and the cone begins to splash before an eruption begins. There are only about 10 seconds of splashing outside the cone before the water reaches its full height. The cone, which stands 60 centimeters tall, is dry at the beginning of the eruption. During the eruption, water gradually spills over the cone and into the surrounding splash pool. The runoff spills north, west, and east. Water also drains into a nearby hole at ground level (T64). Tourist postcards of T63 show what appear to be bacteria covering its cone and splash area. The bacteria range in color from tans and browns close to the orifice and deep reds, oranges, and near–blacks a meter or more from the vent. Although the play shown on the postcards is similar to what we observed, some type of change in activity or water chemistry has occurred.

T64 (Dormant Vent)

T64 is a dormant vent that is 2 meters east of T63. The vent is level to the ground, such that runoff from T63's eruption drains into it. A well–maintained sinter apron, a short splash cone rim, and intricate beading suggest that this feature may have eruptive episodes.

Looking west at **Spring T63** in eruption. (Photo by Shane Fryer)

T65 (Geyser)

T65 is a geyser that splashes to 15 centimeters from a series of three vents that lie in a 1.5–meter line. Rocks fill one of the vents.

T66 (Geyser)

T66 is a large pool, approximately 7 meters wide that has quick surges to 3 meters. The water is clear and there is a brown, sandy mound a meter tall on its northern side. The durations of the surges are only several seconds long with an observed interval of more than an hour. During our visit, we noticed the pool constantly steaming. Occasionally the pool exhibits particularly intense, heavy steaming. During one of these periods, we noticed a low, white boiling surge in the pool. As we watched, the boiling surge rose to 3 meters. A few seconds of smaller surges were noted, as well as very heavy steam, before the pool went back to its normal boiling state. We walked to the pool in hopes of further activity, but no other similar surges occurred. The pool is located 100 meters south of T63.

T67c (Geyser)

T67c plays from a 1–meter wide, round, meter–deep pool. The pool has several different types of activity that appear erratic, but are nearly perpetual. The spring has momentary quiet modes. At those times, the pool is about a centimeter below overflow. These times of quiescence are short–lived. The typical eruption consists of either splashing with overflow, splashing without overflow, or overflow without splashing. Splashes occur from the center of the pool and typically reach 30 centimeters. Larger splashes reach a meter. Runoff from the spring spills down two runoff channels, but a lower runoff channel flows more often. The pool is located immediately north of the tourist road on the Main Terrace; its runoff channel crosses the road. Longer eruptive episodes can play uninterrupted up to a minute. The longest period of quiescence was only about 30 seconds. Most eruptions consist of a couple of splashes followed by a short 10 second pause.

UPPER GEYSER BASIN, OTHER PORTIONS

GROUP U–VIII (FAR UPPER GROUP)

Separated from main Upper Geyser Basin activity 500 meters up the valley to the northeast, the Far Upper Group features several kinds of landscapes. Rolling foothills surround the broad, flat area. A great deal of the thermal area is covered in green moss and scrub brush, much like a thermal marsh. Small, shallow, often bubbling, hot springs and runoff channels break up the patches of moss, although some areas of moss are brown and dying. Other areas of the Far Upper Group are characterized by a desolate landscape void of vegetation, with volcanic boulders the sizes of cars strewn about the area.

A few geysers exist in the Far Upper Group, although most of the play observed reached heights much less than a meter. There are, however, several intense mud volcanoes. Two of them are located on a hillside. The larger of the two continuously and vigorously boils watery, light brown mud up to 1 meter from a steaming crater 5 meters long, 3 meters wide, and 3.5 meters deep. The smaller mud volcano (about 1 meter in diameter and 1 meter deep) has formed in a hole downhill from the larger volcano. The vigorous splashing nearly reached the ground surface and had formed reddish–brown mud stalactites under the rim.

There were also several mudpots located within the area. An oblong–shaped, dark–gray 5–meter long mudpot was nearly dry; mud cracks were present throughout the depression. The only "plopping" was found in a watery spot in its center. Many of the hot springs and hot streams had patches of cream–colored, sudsy foam on their surfaces. The small springs of this area often had scalloped sinter encrustations around their pool rims. Very little bacteria mat growth was observed within the Far Upper Group, although a few pools did have runoff channels with red and orange bacteria present.

Inventorying the Far Upper Group in detail, due to the possibly unstable nature of the soggy moss and marsh, was dangerous. Therefore, only a portion of the area was visited up close on foot. Much of the basin was viewed at a distance from the hillsides.

T3 (Geyser)

T3 erupts up to 1 meter approximately every 4 minutes for 15 seconds from a series of three small, reddish–colored vents. The largest and primary vent is 20 centimeters across, with water splashing from a 10–centimeter tall, rough, white and dark gray sinter mound. The eruption begins with simultaneous splashes from the primary vent and a smaller adjacent vent on a shorter, although still connected, mound. Water spills down the mound from the secondary vent. Splashing begins 15 seconds later from a third vent, which is an elongated rift tangent to the mound. The eruption creates an overflow stream about 1 meter in length. The geyser is located in an area several meters long comprised of rough, gravelly white and gray sinter. Two other mounds (one up to 50 centimeters tall) are present, although no eruptive activity was observed from these nearby features. The sinter area is surrounded by green moss and short, stubby grasses.

T4 (Geyser)

This geyser consists of a main vent and a secondary vent. From a distance, we saw a meter eruption from the main vent, possibly a major. Up close, we observed intense, 20–centimeter bursts from the main vent. The main vent is a rounded, crater–like pool that is 50– centimeters deep. The geyser has a well–developed, smooth–bottomed runoff channel, which, like the rim of the main pool, is encrusted with scalloped, gray sinter. There are also thin runoff lines radiating from the pool. One side of the pool has a 20–centimeter tall, overhanging sponge–like sinter deposit that is reddish–colored in locations where water splashes against it. The secondary vent alternates activity with the main vent. The pools undergo a series of filling and emptying in an 8–minute (possibly minor) eruption duration. The interval is greater than 14 minutes.

GROUP U–IX (MIDDLE VALLEY GROUP)

A spring cluster 700 meters east of the Main Terrace was not visited. At least twenty hydrothermal manifestations are represented on the Trujillo *et al.* [1969] map. At least a dozen more features are noted downstream of this group in the portion of the valley south of the Main Terrace. Both of these vicinities can be seen in the distance from the Main Terrace, but appreciable steam was not observed.

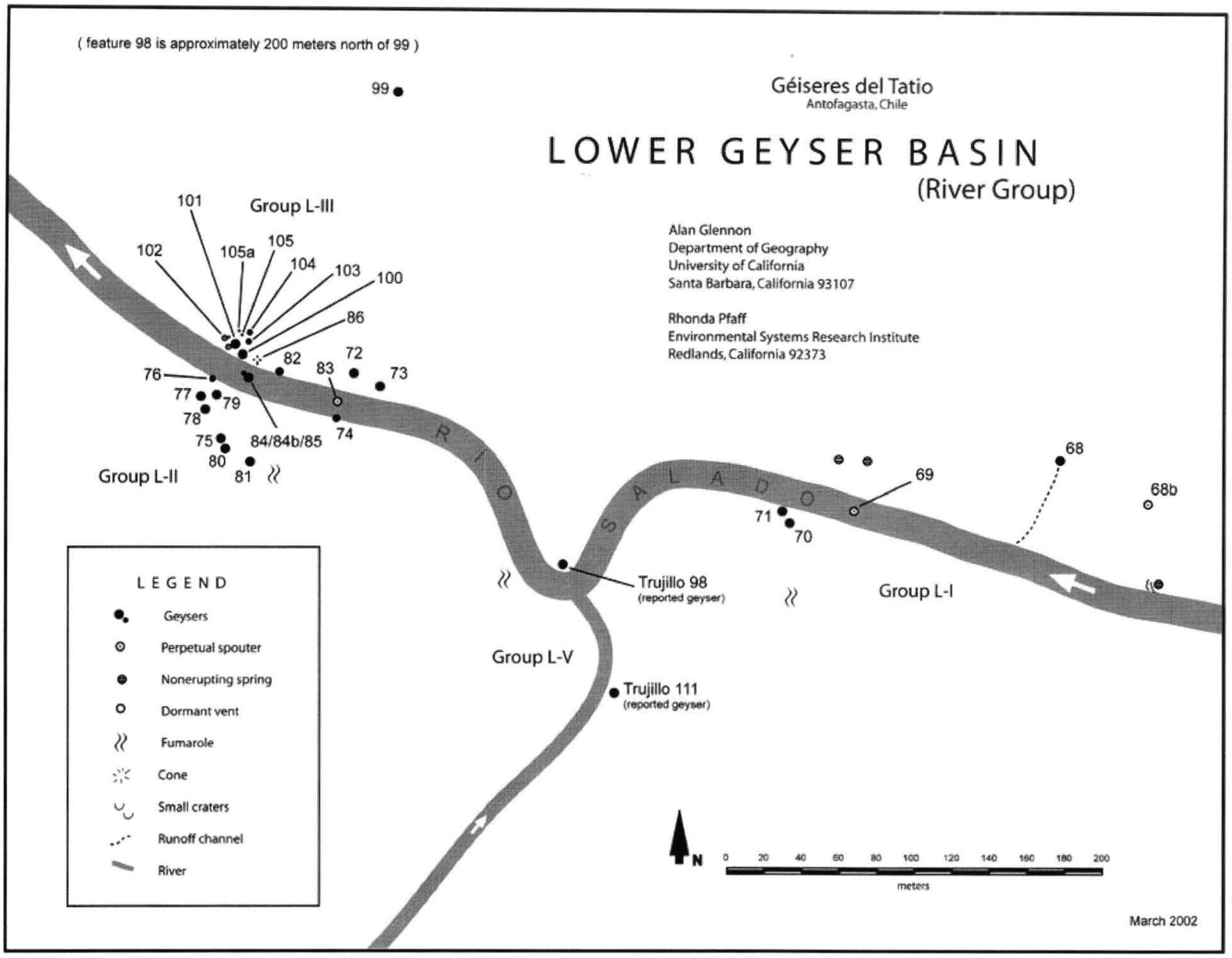
LOWER GEYSER BASIN OVERVIEW

The Lower Geyser Basin (or River Group) lies along the banks of the Río Salado, approximately 2 kilometers downstream from Middle Basin (Map C; see also Map A). In all, at least 20 true geysers are located in the area. Following downstream from the Middle Basin, the river becomes increasingly channelized between steep hills. The river throughout the group flows with a gray–colored bed. The river's color contrasts with the red soils of the hillsides, white and yellow hydrothermally altered ground, and many colors of the hot springs. At wide points, the river reflects the surrounding hills and sky.

For the first kilometer, the river remains a wide, braided stream. Only a half–dozen features exist in this zone, but they are of significant size (T68, T70, T71). An additional 500 meters downstream, the river takes a sharp southern meander loop. Along the banks of this southern loop, a spring group exists that we did not visit. Steam and fumaroles are visible in the distance. After the loop makes its northern curve, it flows northwest. As it flows northwest, a tightly packed grouping of spouting springs exists. The area of vigorous activity lies within a 100–by–100 meter area. Several springs erupt in and near the river to heights of 1 to 3 meters. Numerous springs in the Lower Basin flow or erupt from within the flow channels of the river itself, including several underwater geysers whose boiling deposits sediment on the riverbank. Two of the larger geysers (T72/73) erupt at steep angles. Very little sinter accumulation has occurred in this downstream river group; many of the geysers appear to be erupting from fractures and fissures in the bedrock itself. In this area, the Río Salado is a much narrower stream, but still maintains a braided character. Except when very close to a boiling spring, the sound of the river overwhelms many of the sounds of hissing, steaming, and splashing.

From the Lower Geyser Basin, the surrounding hills dominate the view to the south, west, and north. Their reddish–brown soil is dotted with low green and yellow scrub. Reddish boulders are strewn about along many of the slopes. Above similar low hills to the east, the same tall, dark snow–capped Andes stretch toward the north and south.

Map C — Lower Geyser Basin (River Group)



LOWER GEYSER BASIN, RIVER GROUP

GROUP L–I

T68 (Geyser)

T68 erupts from three ragged, red sinter–coated vents comprising a complex approximately 8 meters long and 5 meters wide. A nearby fourth vent is filled with cloudy hot water and did not respond to the geyser's eruption. The geyser is located at the intersection of a gulley draining from the north toward the Río Salado valley. Immediately above the vent complex, a contact between a conglomerate and white silicic rock exists. The white rock unit contains small flecks of garnets. Eruptions appear to occur in series at the geyser, with both minors (less than 1 meter) and majors (about 1 meter) noted. However, with only six eruptions observed, the geyser's true behavior is unknown. Eruptions consist of simultaneous splashing of frothy water from each of the three vents for approximately 1 minute. The interval during several closed intervals was timed at 3 minutes. The eruption ends with all three vents draining completely with only slight steam being emitted. Within 30 seconds, the steaming ends. Steaming begins again about a minute before an eruption.

T68b (Perpetual Spouter and Well–Developed Sinter Terrace)

Located 30 meters east of T68 near the bottom of the valley slope, a perpetual spouter (T68B) erupts frothy, but clear, water. The splashdown area surrounding the spouter is covered in dark green (nearly black) bacteria, with some bright oranges along the outer rim and runoff channels. A grapefruit–sized rock covered in dark bacteria blocks part of the vent's opening. A small, bubbling vent lies within the dark green runoff channel 50 centimeters downstream of the main vent. Fifty meters south, a white and gray, 1–meter high, 2–meter wide silica terrace is located on the northern bank of the Río Salado.

T69 (Perpetual Spouter)

T69 is a perpetual spouter located just barely above water on a small island in the Río Salado. The vent is, at most, a few centimeters above river level, and would be submerged during wet periods. Activity occurs from a small vent at the level of the island. The spouter's activity can be most easily seen from the banks of the river on the path downstream from T68. Clear water fountains a consistent 30 centimeters.

T70/T71 (Two Geysers)

T70 and T71 geysers are located along the river bank on the south side of the Río Salado immediately before the river takes a southern bend. T71 is closest to the river and erupts as a surging fountain to a meter or more for a minute. Its height, interval, and duration are all greater than T70, which is located on a red–sinter bank about one meter to the southeast. While T71 remains quiescent between eruptions, minor activity seems to be occurring continuously at T70. Small splashes to 10 centimeters occur erratically, but eventually activity increases until the activity reaches a meter or more. The increase in activity at T70 appears to induce T71 to eruption. Although closely related, the geysers also exhibit independent activity. A small area of hydrothermally altered soil lies immediately to the south of the geysers. A large fumarole can be seen steaming from a red soil–lined crater that lies about 50 meters up the hill south of the two geysers.

GROUP L–II

T72 (Geyser)

T72 is a geyser located on the slope of the northern bank of the Río Salado about 10 meters north of the observed river flow. Water shoots from a ragged, red rocked vent. Outside the splash zone, the soil near the vent is white and light red. Continuous jetting, up to 2 to 3 meters, is angled (about 30° from vertical) east and south toward T73. T72 has a more defined spray than does T73. Dark bacteria cover the wet areas. T72 has a smaller pool than does T73, although its flow becomes channelized before it reaches the primary Río Salado flow (approximately 10 meters away during the observed flow conditions). Considering the long duration of eruptions, the geyser discharges a large volume of water.

Looking west toward **Group L–II**. (Photo by Shane Fryer)

T73 (Geyser and Several Perpetual Spouters)

Quick splash pulses from T73 gush at an angle 45° from the vertical southerly toward the Río Salado. These blasts of water splash from a 30–centimeter wide vent on the hill slope; the splashes commonly reach 2 meters. Several large rocks deflect some of the splash-

Geyser T73 (left foreground) and **Geyser T72** (right background). (Photo by Shane Fryer)

center of the cauldron. The eruption appears to be perpetual.

T77 (Geyser)

T77 is a large fountain geyser that erupts to heights of greater than 1 meter. The pool is located on the edge of an exploded geyser cone. The eruption lasts 1 to 3 minutes, with an interval of 5 minutes.

T78 (Geyser)

T78 is a pool approximately 50 centimeters in diameter. The pool is at ground level, but debris piles 10 to 20 centimeters high are located near the pool. During its eruption, water surges and splashes to 40 centimeters. No closed intervals were carefully observed, but field video recorded the feature to have an interval of at least several minutes, with an eruption lasting more than 1 minute. The intervals and durations may, in fact, be erratic.

ing, but the volume of water typically inundates them. The eruptions have formed a 3–meter wide splash pool that channelizes the flow 20 meters south into the Río Salado. A thin red sinter crust is around the geyser vent and all the way down its flow channel. The crust appears to be at least 10 centimeters thick in some areas. During some of the particularly powerful pulses, the geyser fans water from 90° from the vertical to the south to 30° to the north. As a result, these occasional splashes were observed to a meter or more outside the geyser's northern sinter lining. Several small perpetual spouters erupting to 10 centimeters were noted immediately southeast of T73.

T74 (Perpetual Spouter)

T74 erupts from a sinter–lined cauldron about 20 centimeters above the Río Salado's southern bank. A sinter crust creates a slight overhanging edge above its crater. One side of the rounded crater is open and flows into the Río Salado. Eruption heights approach the level of the ground surface, about 40 centimeters above the vent, with occasional droplets reaching a meter. The splashes mostly are vertical and slightly angled toward the

T79 (Geyser)

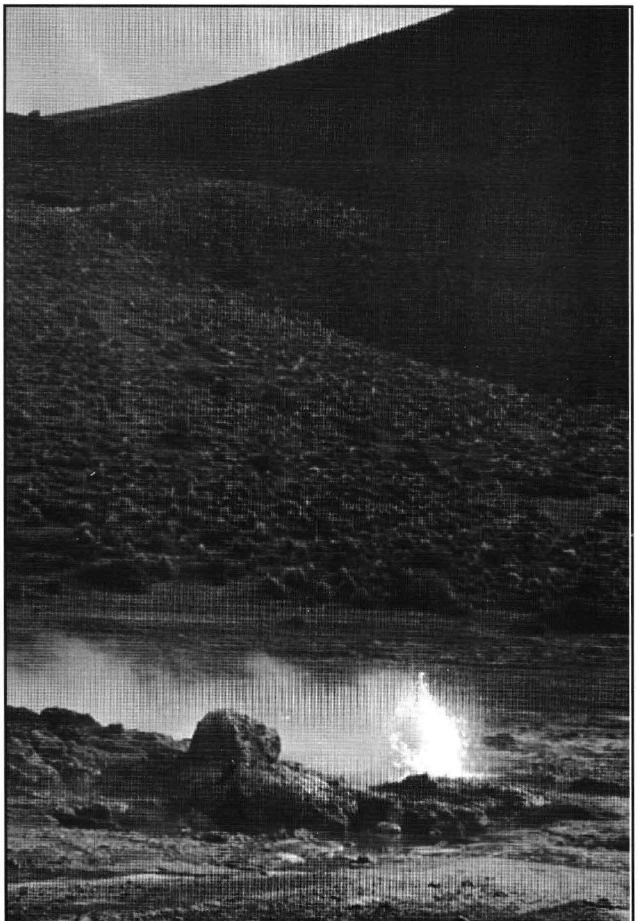
T79 is a small fountain geyser that plays from a pool that had dead frogs around it. The eruption reaches heights of 50 centimeters. The geyser continued playing while the nearby T77 underwent several closed intervals. T79's play continued for at least 15 minutes, and noticeably weakened through the duration. The geyser has a 10 minute quiet interval.

T76 (Four Perpetual Spouters)

Numerous apparent perpetual spouters lie near the southern shore of the Río Salado north of T79. At least four were noted splashing or causing surges into an elongated discharge pool from 10 and 50 centimeters high. Almost all of these features have unique, colorful sinter mounds or overhangs. Their close relationship to the river undeniably affects their development and eruptive activity. A careful inventory of these features would undoubtedly yield additional small perpetual spouters, and likely small geysers.

T80 (Geyser)

T80 is a geyser that sprays a thin stream of water up to 2 meters high. The activity quickly subsides into a steam phase lasting at least 20 minutes. Similar to its observed eruption, the geyser's steam phase consists of a thin column of steam being forcefully ejected for about 2 meters before dissipating into a less organized form. The geyser's vent, which is level to the ground, is surrounded by a circle of gray and red softball to basketball–sized rocks, with some much larger. These rocks possibly are the result of a hydrothermal explosion related to the geyser. The immediate ground is flat, barren, gray and red. Two meters from the vent, beyond the thermally altered ground, are patches of yellow–green moss.



Spring T78. (Photo by Shane Fryer)

T75 (Geyser)

Nearly adjacent to T80, a small splashing geyser erupts to 20 centimeters. It is immediately northwest of the T80 vent. Similar to T80, the area around the vent is strewn with softball–sized gray and red rocks. When this geyser was first noticed, it was vigorously splashing from a small pool. This was concurrent with the steam phase of T80. An inspection from a distance of 70 meters 30 minutes later noted no activity and no steam. Nothing further is known about its activity.

T81 (Fumarole and Perpetual Spouter)

Approximately 10 meters east of T80, a red soil slump area contains a gentle fumarole. At the base of the fumarole, a 50–centimeter high perpetual spouter was observed.

T82 (Geyser)

T82 is an underwater geyser that gently boils in a shallow, gray, murky pool next to the bank of the Río Salado. A few handfuls of black and cream–colored pebbles have been stirred up from the riverbed and deposited on the surrounding reddish–brown sinter crust. The main Río Salado flow has been cut off from this area. Boiling reaches up to 10 centimeters. When T82 is not in eruption, the water is still. The interval is at least 20 minutes and the duration is at least several minutes.

T83 (Perpetual Spouter)

T83 is located near the upstream tip of the island in the middle of the Río Salado. It is likely a perpetual spouter, with its eruption partially submerged in the river. The eruption gushes a mix of water, gravel, and sand to 15 centimeters. Though the spouter is in one of the two main channels of the river, the geyser is located on a sandbar. The water is only a couple of centimeters deep over its vent. The spouter is located very close to the location that T72's runoff channel enters the Río Salado.

T84 (Geyser)

T84 is a completely underwater geyser. Intense surging, which was observed as high as 1 meter over the river's water level, deposits pebbles from the riverbed onto the surrounding shore crust. The geyser is located near the northwestern corner of the island in the middle of the Río Salado. The pellet–sized sediments are typically black or cream–colored and form a 5–centimeter deep layer that extends on the bank up to 1 meter from the boiling pool. The geyser's water is typically murky, due to the pebbles and particles it is carrying. Two other adjacent underwater geysers (including T85) are located within several meters of T84 in the same deep pool.

T84b (Very Small Geyser)

One meter southeast of T84's splash area, a small geyser erupts with weak splashing to 10 centimeters for 10 seconds from two small vents. The geyser was not observed directly in the field, but noticed during examination of T84's videotape. In fact, during its quiet interval, we actually stepped right over the geyser without noticing it. T85b's vent is one of numerous unremarkable fractures and small holes spread throughout the island in this spring area. It is possible that other small geysers exist in the vicinity, but were not observed. The geyser's activity appears to be independent of T84. Only a single eruptive episode was observed; however, given the vigorous activity of the area, its interval is likely no more than several minutes.

T85 (Geyser)

T85 is a completely underwater geyser whose boiling picks up pebbles from the river bottom and deposits them on the bank. Located 2 meters northwest of T84 and within the same deep spot in the river, T85 periodically boils to 10 centimeters. One splash to 30 centimeters water was seen.

Group L–III

In the northwest portion of the Group II springs lies a concentration of'features in a 20–by–20 meter area. The small area, part of the Río Salado's flood plain, is pockmarked with small craters and mudpots. These craters are typically 10 to 20 centimeters in diameter and about as deep. Two perpetual spouters and a number of geysers erupt from the craters.

T86 (Mud Volcano)

The most distinctive feature in the group is a 50–centimeter tall, 50–centimeter wide mud volcano along the northern shore of the Río Salado. Mud has been deposited forming a cylinder with walls about 10 centimeters thick. A small cauldron of mud boils 70 centimeters down inside the cylinder, occasionally splashing mud 10 centimeters or more out of the cone. A smaller mudpot adjoins the little volcano, but for some reason has not developed a cone of its own.

T100 (Geyser)

T100 is comprised of three small 10–centimeter deep craters. The craters coalesce to form an elongated feature that makes a highly distorted "T"–shape. The entire "T" is no more than a meter across. Each of the three craters contains a tiny pool of agitated water. The middle pool is the most active, with occasional erratic splashes to 10 centimeters. The middle pool occasionally offered larger eruptions. When this occurs, the erratic splashing increases its frequency and force until it is nearly constant. The angled play throws water laterally at least 50 centimeters. The vertical height reaches no more than 50 centimeters. The duration of the eruption was erratic, but commonly lasted over a minute.

T101 (Geyser and Perpetual Spouter)

T101 erupts from a small elongated crater no more than 80 centimeters long and 50 centimeters wide. Similar to other craters in the immediate vicinity, it is no more than 20 centimeters deep. The crater is slightly narrower in the middle and is somewhat shaped like a "Figure 8." The geyser was not approached too closely due to dangerous ground, but water appears to be relatively calm in its crater during its quiet period. The geyser begins eruption with an increase in boiling and water level in its crater. The activity builds for 10 seconds or more until the pulsing splashes reach a meter in height.

The play occurs from nearly the entire crater, so the splashes are typically 50 centimeters in diameter. A glaze of water is sent toward the nearby Río Salado. Several closed intervals were timed to between 100 to 220 seconds. Adjacent to T101, toward the river, a perpetual spouter erupts from a 10–centimeter wide crater. Its 30–centimeter high play looks like a smaller version of the T101 eruption. A few red–lined craters are present to the east of T101. Of these, the one closest to T101 appears to occasionally splash within its crater. However, no water rose above ground level. The next red–lined crater had a 4–centimeter layer of wet red mud downstream of its rim. During our observations, only steam was emitted from its crater.

T102 (Very Small Geyser and Perpetual Spouter)

Barely a geyser, a small feature exists in close proximity to a much more impressive perpetual spouter. The spouter maintains a frothy play to 10 centimeters. Of the two perpetual spouters in the L–III Spring Group, it is the farther downstream of the two. Mossy green material is located on a 10–centimeter mound on the spouter's southeast side. A tiny feature was noted 50 centimeters north of the spouter's main play. Every 10 to 15 seconds, a tiny vent throws a single, quick splash to 5 centimeters. The nearby ground is composed of light–colored sand and gravel.

T103 (Geyser)

T103 plays from a shallow meter–wide crater. It is effectively a twin feature with T104. Tilted bedrock is visible at the bottom of the crater at the geyser's vent. A thin coating of gray sinter gives the geyser a dark color. The geyser is nearly always erupting. Pauses were infrequent and lasted no more than 10 seconds. When not erupting, the crater is completely drained of water. The play consists of frothy, but clear water splashing 30 to 60 centimeters high. The activity of the geyser appears erratic.

T104 (Geyser)

T104 plays from a shallow meter–wide crater. The crater is similar in shape and appearance as T103, except that T104's sinter is red. Bedrock can also be seen near its vent at the bottom of the crater. The geyser plays almost continuously, but several complete stops were noted. When not erupting, its crater is completely drained, with steam coming from its vent. The play consists of erratic splashes of frothy, but clear water 60 centimeters to a meter high. Its duration lasted several minutes or more between pauses. Quiet periods usually only lasted several seconds, but a couple of 10 second pauses were also noted. Similar to its neighboring springs, the activity appears erratic.

T105 (Geyser)

T105 lies in an obscure area of craters west of T103. The crater could not be approached due to unstable ground, but appears to be about 30 centimeters across and about 10 to 20 centimeters deep. The play sends one or two splashes of water to 20 centimeters above the ground surface. Only about a liter of water is airborne during a single splash and very little discharge leaves the crater.

T105a (Geyser)

Dwarfed by its larger neighbors, T105a occasionally sends a single, weak splash of water to 10 centimeters above ground level. The small play occurs from an obscure crater 30 centimeters wide. The interval is less than a minute. Numerous similar craters lie within several meters of T105 and 105a.

LOWER GEYSER BASIN, OTHER SPRING GROUPS

Group L–IV

Another spring group lies north of the vigorous activity of main Lower River Group. From a quick trip to the group, Shane Fryer reported a geyser (T98), a suspected geyser (T99), and a pool complex.

T98 (Geyser)

T98 is a 20–meter wide complex of three springs, with at least one geyser that erupts from a 2–meter wide vent under a cliff face. Water shoots

1 meter before it hits a ledge. Momentary pauses were noted in the otherwise continuous play, otherwise nothing else is known about its duration and interval.

T99 (Hot Spring/Reported Geyser)

T99 is an 8–meter long pool that is about 1 meter deep. The spring has at least ten underwater vents. Vigorous boiling and fluctuating water levels were observed, but no eruptions seen. This feature has previously been reported as a geyser [Trujillo *et al.* (1969) feature 195]. Near T99, Shane also reported a deep, meter–wide shaft. During his quick visit to the area, the water level in the shaft dropped several meters. No other information is known about its activity.

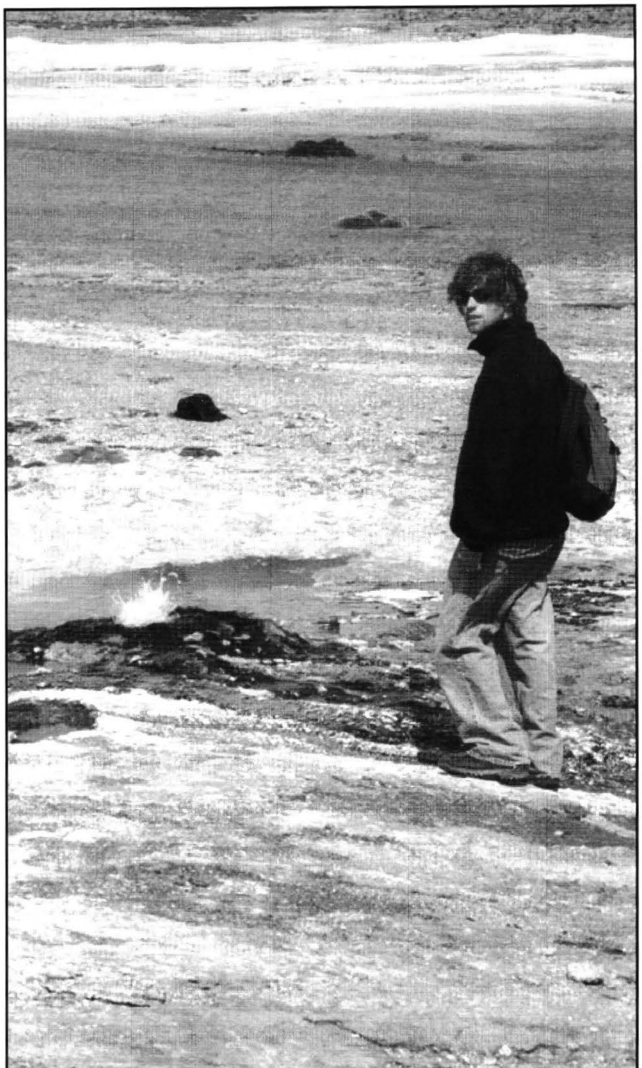
Group L–V (Two Reported Geysers)

A spring group reportedly containing geysers [Trujillo *et al.* features 98 and 111] is located on a southern bend of Río Salado, downstream of T70/71. From T70/71, fumaroles and intermittent steam were seen. The group was not visited due to time constraints. Since much of the activity appears to be south of the river, approach from the southern bank of the Río Salado may be the best strategy.

Feature 98 on the Trujillo *et al.* map was reported to be a geyser [Trujillo *et al.*, 1969]. It is located downstream of T70/71 on the Río Salado. Approximately 50 meters south of Trujillo *et al.* feature 98, is another reported geyser. This spring is number 111 on the Trujillo *et al.* map. Both of these reported geysers were not visited on the March 2002 trip.

Group L–VI (Three Reported Geysers)

In the upstream areas of the Lower Basin lies another spring group that has been known to contain geysers. The group lies roughly between the Upper, Middle, and Lower geyser basins. Due to time constraints, we were able to visit only a small portion of the spring group. The group is located above a 10– to 20–meter high escarpment that prevented us from viewing the group from the Río Salado. Three features, numbered 168, 181, and 184 on the Trujillo *et al.* map, have been reported as geysers. The spring group extends southeast and down the short escarpment. This small portion of the group is along the road entering the geyser field.



Shane Fryer at **Spring T2**.
(Photo by Rhonda Pfaff)

T1 (Hot Spring Pool)

T1 is a 70–centimeter deep pool next to an upended rock 30 meters north of a branch of the Río Salado. The clear, shallow pool is 5.5 meters wide, scalloped and undercut with temperatures measured from the bubbling vent at 60.7°C. Several bubbles float on the surface of the pool. The pool has a tan–beige–colored bottom with a narrow band of red algae where the deeper pool meets its runoff channel. The runoff channel has dark brown and orange bacteria present, but the pool has relatively little discharge.

T2 (Perpetual Spouter)

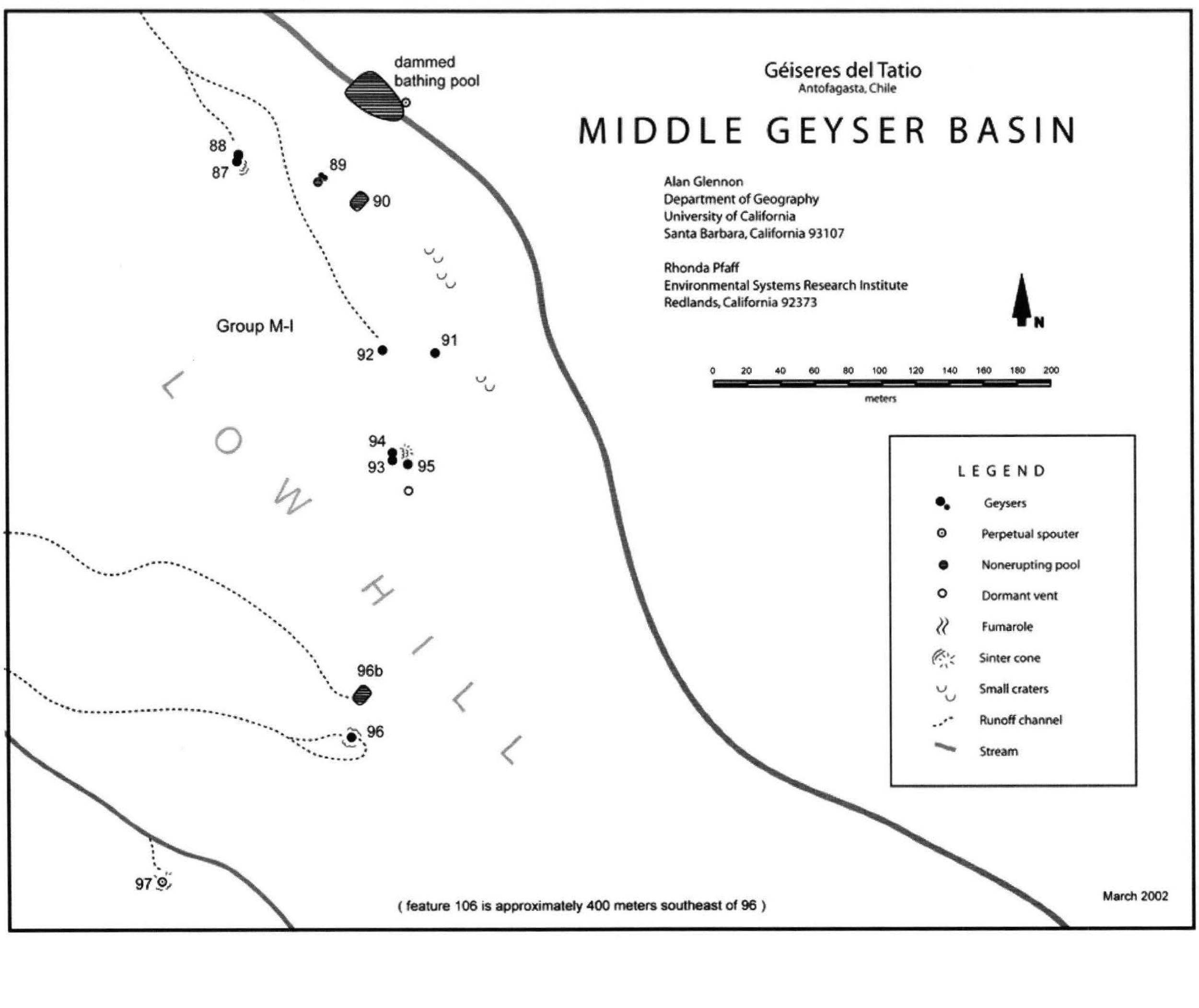
T2 plays perpetually to 50 centimeters from a 10–centimeter tall cone on a 1–meter high sinter mound. Orange bacteria are present on the sinter runoff apron. The apron stretches in a semicircle, with a radius of greater than 2 meters. The temperature at the orifice was measured at 80.5°C. Two nearby vents on 8–centimeter high sinter mounds boil up to several centimeters in height. The discharge trickles down the mound and into a tributary of the Río Salado.

MIDDLE GEYSER BASIN OVERVIEW

The Middle Geyser Basin lies immediately to the south of Upper Basin and is a stark, flat sinter plane. The geyser activity of the Middle Basin lies in a zone 400 meters long and 100 meters wide (Map D; see also Map A). The basin contains at least ten true geysers. The area of geyser activity is bounded on the west by a low, flat–topped hill and a creek on the east; the creek is a major upstream branch of the Río Salado. Along the creek, a small dam has been created to form a soaking pool for tourists. The pool is approximately 30 meters long and 15 meters wide, with a few perpetual spouters erupting within a few meters of the pool.

The most prominent thermal features of the Middle Basin are six deep pools. Only one of these pools (T90) was not seen to erupt. The other pools average 3 meters deep and have frothy, fountain–type eruptions. The intervals and durations for the pools appear erratic. The area also contains numerous small examples of fumaroles, mudpots, and perpetual spouters between the pools and creek. Some of these features may be geysers. One of the features (T89) exhibited intermittent spouting as a true geyser. Numerous parallel shallow runoff channels flow to the north from the pools. A low, long hill follows to the west of the thermal flat.

Map D — Middle Geyser Basin



Besides the six pools, a widespread region of thermal activity lies upstream along the main creek and to the west (over the low hill, in a parallel creek). These other areas contain numerous hydrothermal features, but few geysers. The environs of these remaining geysers are described with their individual descriptions.

GROUP M–I

T87 (Geyser)

T87 is a frothy pool with a 1–meter tall exploded cone on its southern end. The eruptions occur from an overhung pool. The fountain, which measures 5 meters across, produces frothy, "Jacuzzi–like" surges up to 1 meter with an interval of less than a minute. Nearly the entire pool is frothy at some times in its eruption. The pool appears superheated and is rarely completely calm.

T88 (Geyser)

T88 is a pool adjacent to the north of T87 that is separated from T87 by a 1 meter bridge of overhanging crust. Its overflow flows northward in a wide runoff channel. Its surging is likely related to the activity of T87. Small splashing (up to 30 centimeters) that appears to be independent of activity within T87 occurs along the overhanging ledge on the pool's northern edge.

Spring T92. Despite its sudsy, frothy appearance, there is no evidence that Spring T92's activity was induced. (Photo by Shane Fryer)

T89 (Geyser)

T89 is a group of small sputtering, boiling springs. A shallow pool 50 centimeters across vigorously boils and two vents a meter east erupt to 20 centimeters. During observation, the southernmost spouter erupted for at least 2 minutes with splashing to 20 centimeters before stopping. When it stopped, a vent 40 centimeters to the north began erupting to 20 centimeters. Play continued on the northern vent for more than a minute. Further information about its interval and duration are unknown.

T90 (Hot Spring Pool)

T90 is a handsome 2–by–2 meter pool that was not seen in eruption, although it is suspected to be a geyser because of its well developed, wide runoff channel. In addition, a sinter–lined splash area surrounds the pool and implies, if not eruptive activity, at least intermittent rises in water level. Continuous boiling occurs along the pool's southeast edge.

T91 (Geyser)

T91 is a pool 2 meters across with half of its perimeter encircled by white, bumpy sinter deposits that radiate out 1.5 meters from the pool's edge. The active vent is located on the eastern corner of the pool. The rim of the sinter next to the pool has orange and dark–brown bacteria growing along it. The pool had no distinct runoff channel. The geyser produces frothy surges up to 2 meters in height for a few seconds on an interval of about a minute.

T92 (Geyser)

T92 erratically produces frothy surges up to 2 meters from an elongated pool. The undercut pool is 2.5 meters across. Its abundant discharge flows north through a well–developed, meandering runoff channel. The area surrounding the pool is bright orange and wet to a distance of 1 meter. The temperature during quiescence was measured at 83.6°C.

Spring T91. (Photo by Cyril Cavadore)

T93/T94/T95 (Three Closely Related Geysers)

T93–95 is a group of three fountain geysers that surround an exploded cone at the base of the western hill. These geysers now act independently, although they may at one time have been one geyser. The remnant of the cone is about 1.5 meters in height and 3 meters in diameter. The cone is golden brown in color, with some white patches. T94 is the northern geyser, which splashes near perpetually to 1 meter from its bluish–colored pool. Its discharge is channeled northward. The runoff channel, with scalloped sinter encrustations along its borders, is about 50 centimeters wide and several meters in length. The channel has rusty orange deposits (possibly bacteria, although the colors do not vary along the channel), with some cream–colored patches along the upper rim. The entire pool occasionally appears to use a wide, wet overflow zone with brown, rusty orange and cream–colored deposits. T93 is the eastern geyser, which surges near almost perpetually to 2 meters. The overflow pool around T93 had a temperature of 83.5° C. T95 is the southernmost geyser, with near perpetual surges to 1 meter.

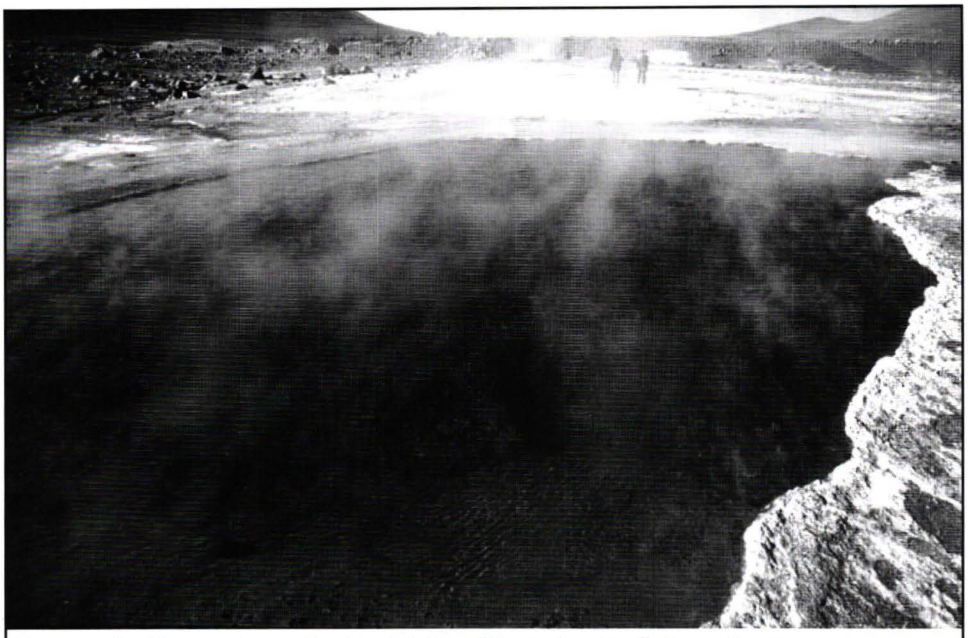
Immediately south of the geyser complex is a steaming rock–filled depression. Many of the rocks in the depression are concreted together by a fine layer of reddish–orange sinter. The sound of boiling water can be heard under the rocks. It is possible that the feature has eruptive behavior, but none was seen.

T96 (Geyser)

T96 is a 25–centimeter tall cone with an irregularly shaped meter–long cauldron. It is located near the top of the hill and its overflow is radial from the elevated cone. Water inside the cone appears to be 2 or more meters deep. This feature was not observed in eruption. However, a visitor's (Cyril Cavadore) February 2000 photograph shows a small eruption of the feature. The eruption appears to be a vigorous boiling overflow with a splash to 20 centimeters. During March 2002, a wide, wet zone surrounding the vent was noted, implying that the geyser is active. A combination of shallow water, mineral deposition, and bacteria create a colorful mosaic of dark reds and greens away from the elevated vent. Its interval is greater than 15 minutes. This region has dark ashy soils and volcanic rocks, ranging from baseball– to car–sized, spewed everywhere. Yellow scrub grasses are interspersed throughout the area.

T96b (Intermittent Spring Pool)

About 30 meters to the northeast of T96 is one of the largest pools in the basin. The 9–by–6 meter rectangular pool is filled with dark blue water on the edge of boiling. Parts of the spring have an overhanging geyserite crust, but otherwise, the bed of the pool descends as a cone to a meter–wide vent at the pool's bottom. At its deepest, the pool is at least 6 meters deep. We observed the pool to be approximately 1 centimeter below overflow. However, its shallow runoff channel was wet with scat-



The pool of intermittent **Spring T96b**. (Photo by Cyril Cavadore)

tered moisture and tiny pools. Whether the spring erupts is unknown, but the spring apparently has some type of intermittent discharge activity.

GROUP M–II

T97 (Perpetual Spouter, Hot Springs, and Sinter Terraces)

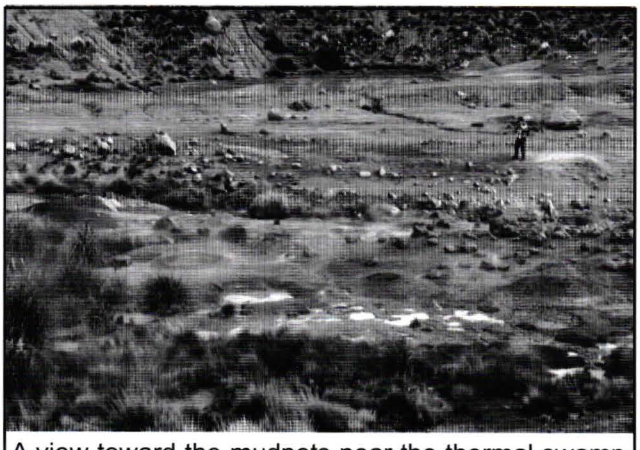
T97 is a red, iron–colored cone that is located on a mound. The feature is about 100 meters south of the Terrace Spring Group along a slope west of a small stream. This spouter erupts nearly perpetually to 30 centimeters with an erratic duration. Several similar boiling springs were noted on the same western slope; several are small perpetual spouters. This feature and one or two others are likely to be actual geysers.

Downstream of T97 lies an extensive area of short, white, brown, and orange terraces developed from non–boiling springs. Several of the taller terraces are composed of multiple 10–centimeter high tiers, combining to a height of no more than a meter. Though short, the terraces are widespread. The area follows down the small creek for at least 100 meters with a width exceeding 20 meters along the way. The terraces appear to be sinter.

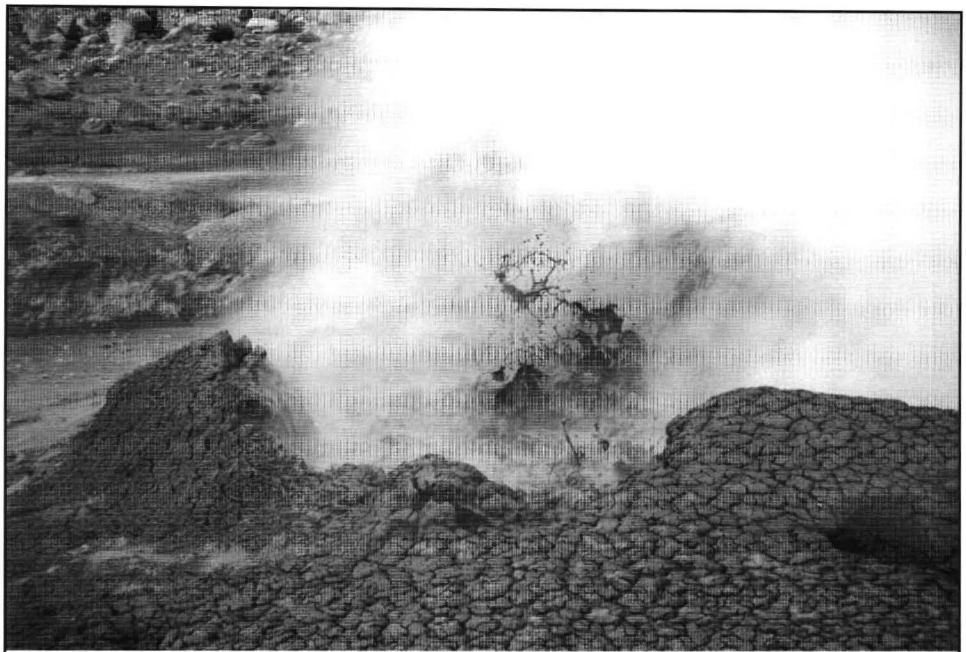
GROUP M–III

A thermal marsh with two distinct mudpot areas and at least one perpetual spouter lies about 2 kilometers southeast of the Middle River Group. The marsh is approximately 100 meters long, 50 meters wide and situated in a ravine. Geothermal well drilling surrounds the area. Mudpots that consist of either entirely black mud or reddish orange mud are interspersed throughout the vicinity. In the upstream and northern portion of the swamp, an area of flooded mudpots is surrounded by tall grass and green moss. Along the southeast end of the thermal marsh lies a perpetual spouter that erupts clear water to a meter. It is located along the bank of a small stream flowing through the swamp. Its 30–centimeter deep crater–like vent is surrounded on one side by a leafy green moss. The other side is open to the nearby creek. Pebbles and gravel lie on its flat crater floor.

A large vigorous mudpot lies about 500 meters west of the thermal swamp. The feature is located south of the road in the same valley as the marsh. Numerous geothermal wells are visible from the



A view toward the mudpots near the thermal swamp of **Group M–III**. (Photo by Alan Glennon)


Mudpots within **Group M–III**. (Photo by Alan Glennon)

mudpot. The far southern end of the Middle Geyser Group can be seen from the mudpots. By far the most vigorous mudpot in the basin, the main area of activity occurs in a 3–by–3 meter cauldron. Watery red mud is splashed between 50 centimeters and 2 meters everywhere in the cauldron. A couple of meters to the north of the cauldron, an elongated pool 10 meters long and 4 meters wide boils gently with a less watery variety of the red mud. Fifty meters west of these mudpots, a fumarole belches steam from a 2–meter deep explosion crater.

T106 (Geyser and Reported Geyser)

A geyser (probably Trujillo *et al.* [1969] feature 35) is located 400 meters southeast of the primary Middle Group. Its vent is well–hidden within an area scattered with small ravines, small scrub brush, gravel, and boulders. The geyser erupts a stream of water 2 meters high at an angle about 30° from the vertical. The eruption lasts less than a minute. We originally saw this geyser while driving from the middle group to the thermal marsh area. Taking a well–drilling road, we noticed the geyser erupting, approximately 50 meters from our truck. By the time we stopped the truck and made it over to the geyser, the eruption had ended. In fact, when we arrived at the geyser, not even a trace of steam remained. Without using the eruption itself as a guide, the vent would be very difficult to find. The small vent looks like a small animal's burrow near a large rock. Similar rocks and small ravines make the location quite nondescript. Luckily, from the middle group, steam from the eruption is easily visible. From the middle group, having seen approximately three eruptions in the distance, the geyser's interval was estimated at 15 minutes or more.

The immediate vicinity of this geyser is intriguing, but we did not have the time to investigate. The area between the middle group and the thermal marsh has the appearance of a long–dormant geyser area. Several low, broad mounds appeared to be dilapidated spring terraces.

Spring number 36 on the Trujillo *et al.* [1969] map is a reported geyser. We did not visit the feature. The road into the basin from the south crosses a steep–sided ravine where several small springs can be seen from the road. The reported geyser is located upstream in the stream valley and access appears straightforward.


A perpetual spouter (unnumbered) in **Group M–III**. (Photo by Alan Glennon)

Appendix I
The Geysers and Springs of El Tatio
Observations of March 8–24, 2002

	Latitude	Longitude	Height	Duration	Interval	Description
GROUP U-I						
T5a	see map	see map		-	-	fumarole
T5b	see map	see map	0.10	1 minute	10 minutes	weak geyser
T5c	-22.32985000	-68.00951667	1.00	perpetual	perpetual	perpetual spouter
T5	-22.32988333	-68.00976667	0.05	perpetual	perpetual	perpetual spouter
T6	-22.32993333	-68.00970000	0.10	5 seconds	erratic	geyser
T7	-22.32993333	-68.00970000	0.05	perpetual	perpetual	perpetual spouter
T18	-22.32993333	-68.00988333	0.40	>1 minute	15-20 minutes	geyser
T9	-22.32975000	-68.01006667	0.20	perpetual	perpetual	perpetual spouter
T10	-22.32971667	-68.01010000	0.10	perpetual	perpetual	perpetual spouter
GROUP U-II						
T12	-22.33006667	-68.01030000	1.50	1.25 - 2 minutes	<15 minutes	geyser
T13	-22.33006667	-68.01030000	0.20	2.5 minutes	<14.75 minutes	geyser
T14	-22.33011667	-68.01033333	0.50	1.5 minutes	3 - 15 minutes	geyser
T15/16	-22.33015000	-68.01035000	0.10	minutes	4 minutes	geyser
T17	-22.33000000	-68.01020000	0.50	9 minutes	>5 minutes	geyser
T19	-22.33023333	-68.01023333	1.50	3 minutes	20-23 minutes	geyser
T20	-22.33016667	-68.01021667	0.10	perpetual	perpetual	perpetual spouter
T21	-22.33023333	-68.01016667	0.05	perpetual	perpetual	perpetual spouter
T22	-22.33045000	-68.01013333	0.30	2 minutes	5 minutes+	geyser
GROUP U-III						
T23	-22.33058333	-68.01040000	0.40	days	days	geyser
T23a	see map	see map	0.50	days	days	geyser
T24	-22.33095000	-68.01061667	1.00	35 minutes	>3 minutes	geyser
T25	-22.33105000	-68.01115000	5.00	15 minutes	2 hours +	geyser
GROUP U-IV						
T27	see map	see map	0.40	5 minutes	>1 minute	geyser
T34	see map	see map	0.10	seconds	seconds	geyser
T28	-22.33090000	-68.01168333	1.00	<1 minute	seconds	geyser
T29	-22.33090000	-68.01165000	0.50	30 seconds	2 minutes	geyser
T30	-22.33106667	-68.01163333	0.40	5 seconds	15-25 seconds	geyser
T31	-22.33093333	-68.01161667	0.20	seconds	> 1 minute	weak geyser
T33	-22.33003333	-68.00968333	0.20	seconds	30 seconds	weak geyser
T33b	-22.33033333	-68.00968333		-	-	fumarole
T32	-22.33093333	-68.01161667	0.10	seconds	> 2 minutes	weak geyser
T26	-22.33116667	-68.01133333	0.20	minutes	seconds	geyser
GROUP U-V						
T35	-22.33123333	-68.01176667	1.50	1 minute	2 minutes	geyser
T36	-22.33143333	-68.01180000	0.50	perpetual	perpetual	perpetual spouter
T37	-22.33106667	-68.01193333	0.10	seconds	seconds	geyser
T38	-22.33121667	-68.01221667	0.20	< 30 seconds	2 minutes	geyser
T67	-22.33140000	-68.01255000	0.30	10 minutes +	unknown	geyser
T67b	see map	see map	0.40	4 minutes	> 1 minute	geyser

T39	-22.33116667	-68.01223333	0.10	seconds	<1 minute	geyser
T40	-22.33130000	-68.01210000	0.10	perpetual	perpetual	perpetual spouter
T41	-22.33138333	-68.01210000	0.40	2 minutes	> 5 minutes	geyser
T42	-22.33140000	-68.01183333		30 seconds	3 minutes	intermittent overflow
T43	-22.33156667	-68.01215000	1.00	minutes	seconds	geyser
T44	-22.33160000	-68.01216667	0.10	> 1 minute	> 5 minutes	geyser
T45	-22.33158333	-68.01225000	0.70	1 minute	> 2 minutes	geyser
GROUP U-VI						
T46	-22.33173333	-68.01213333	1.00	>1 minute	>15 minutes	geyser
T47	-22.33176667	-68.01221667	0.10	seconds	unknown	geyser
T48	-22.33170000	-68.01238333	0.20	seconds	minutes	geyser
T49	-22.33175000	-68.01246667	0.05	seconds	seconds	geyser
T50	-22.33175000	-68.01243333	0.50	> 1 minute	seconds	geyser
T51	-22.33155000	-68.01276667	1.00	< 5 minutes	<15 minutes	geyser
T53	-22.33190000	-68.01256667	0.15	unknown	10 minutes	geyser
T54	-22.33175000	-68.01248333	0.05	seconds	seconds	weak geyser
T55	-22.33168333	-68.01251667	0.10	< 10 seconds	unknown	geyser
T56	-22.33191667	-68.01231667	0.50	seconds	> 1 minute	geyser
T57	-22.33171667	-68.01251667	0.05	seconds	1 minute	geyser
T58	-22.33171667	-68.01250000		-	-	hot spring
GROUP U-VII						
T59	-22.33195000	-68.01276667	0.30	1 second	< 30 seconds	geyser
T60	-22.33185000	-68.01288333		-	-	warm spring
T61	-22.33203333	-68.01275000	0.60	5+ minutes	seconds	geyser
T62	-22.33208333	-68.01345000	0.10	perpetual	perpetual	perpetual spouter
T63	-22.33216667	-68.01303333	3.00	15 minutes	2.5 hours+	geyser
T64	-22.33215000	-68.01290000		-	-	dormant vent
T65	-22.33220000	-68.01293333	0.15	seconds	seconds	geyser
T66	-22.33320000	-68.01300000	3.00	seconds	> 1 hour	geyser
T67c	see map	see map	1.00	1 minute	seconds	geyser
GROUP U-VIII						
T3	-22.32728333	-68.00568333	1.00	15 seconds	4 minutes	geyser
T4	-22.32813333	-68.00623333	0.20	8 minutes	14 minutes+	geyser
GROUP L-I						
T68	-22.34088333	-68.02275000	1.00	1 minute	3 minutes+	geyser
T68b	-22.34145000	-68.02235000	0.20	perpetual	perpetual	perpetual spouter
T69	-22.34106667	-68.02396667	0.30	perpetual	perpetual	perpetual spouter
T70	-22.34116667	-68.02421667	1.00	< 1 minute	~2 minutes	geyser
T71	-22.34108333	-68.02423333	1.00	~ 1 minute	~ 5 minutes	geyser
GROUP L-II						
T72	-22.34038333	-68.02635000	5.00	>30 minutes	minutes	geyser
T73	-22.34043333	-68.02621667	2.50	>30 minutes	seconds	geyser
T74	-22.34068333	-68.02655000	0.40	perpetual	perpetual	perpetual spouter
T77	-22.34050000	-68.02708333	1.00	3 minutes	5 minutes	geyser
T78	-22.34058333	-68.02710000	0.40	> 1 minute	minutes	geyser
T79	-22.34050000	-68.02705000	0.50	~15 minutes	10 minutes	geyser
T76	-22.34041667	-68.02705000	0.50	perpetual	perpetual	perpetual spouter
T80	-22.34075000	-68.02700000	2.00	25 minutes	unknown	geyser

T75	-22.34071667	-68.02700000	0.20	seconds	seconds	geyser
T81	-22.34081667	-68.02686667	0.50	perpetual	perpetual	perpetual spouter
T82	-22.34038333	-68.02673333	0.10	minutes	20+ minutes	geyser
T83	-22.34050000	-68.02650000	0.15	perpetual	perpetual	perpetual spouter
T84	-22.34038333	-68.02686667	1.00	minutes	seconds	geyser
T84b	see map	see map	0.10	10 seconds	minutes	weak geyser
T85	see map	see map	0.30	seconds	seconds	geyser
GROUP L-III						
T86	-22.34028333	-68.02690000	1.00	erratic	erratic	mud volcano
T100	see map	see map	0.50	1 minute	erratic	geyser
T101	see map	see map	1.00	1 minute	3 minutes	geyser
T102	see map	see map	0.05	1 second	10-15 seconds	weak geyser
T103	see map	see map	0.60	minutes	seconds	geyser
T104	see map	see map	0.60	minutes	seconds	geyser
T105	see map	see map	0.20	seconds	seconds	geyser
T105a	see map	see map	0.10	seconds	< 1 minute	geyser
GROUP L-IV						
T98	-22.33715000	-68.02640000	1.00	near perpetual	seconds	geyser
T99	-22.33898333	-68.02615000		-	-	hot spring pool
GROUP L-VI						
T1	-22.33955000	-68.01898333		-	-	hot spring pool
T2	-22.33958333	-68.01855000	0.50	perpetual	perpetual	perpetual spouter
GROUP M-I						
T87	-22.34241667	-68.01283333	1.00	near perpetual	< 1 minute	geyser
T88	-22.34240000	-68.01283333	0.30	seconds	> 1 minute	geyser
T89	-22.34255000	-68.01233333	0.20	2 minutes	1 minute	geyser
T90	-22.34265000	-68.01216667		-	-	hot spring pool
T91	-22.34348333	-68.01175000	2.00	seconds	~ 1 minute	geyser
T92	-22.34346667	-68.01203333	2.00	seconds	seconds	geyser
T93	-22.34408333	-68.01198333	2.00	near perpetual	seconds	geyser
T94	-22.34405000	-68.01198333	1.00	near perpetual	seconds	geyser
T95	-22.34410000	-68.01190000	1.00	near perpetual	seconds	geyser
T96	-22.34558333	-68.01221667	0.20	unknown	>15 minutes	geyser
T96b	see map	see map		-	-	hot spring pool
GROUP M-II						
T97	-22.34638333	-68.01326667	0.30	perpetual	perpetual	perpetual spouter
GROUP M-III						
T106	see map	see map	2.00	<1 minute	>15 minutes	geyser
Sol de Manana	-22.42545000	-67.76178333		-	-	Bolivian field

APPENDIX II: Expedition Log

Inception — Before the trip in March 2002, Alan Glennon had been talking about making a South American geyser trip for nearly a year. Along the way, his rambling about geysers high in the Andes Mountains piqued the interest of several friends. Rhonda Pfaff, a graduate student, had gained an interest in geysers while working at the Yellowstone Center for Resources at Yellowstone National Park during the summer of 2001. On one trip to visit her, Alan brought along geology student Weldon Hawkins. To show Weldon something different, Alan took him to Geyser Creek. After several hours in the backcountry thermal area, Weldon was hooked. Shane Fryer, a geography student and avid traveler, was our fourth participant.

Since, we were all associated with Western Kentucky University (WKU), we had the same spring break holiday. In addition, Shane's father works for an airline serving Santiago, Chile and was able to obtain discount passes. We left from Louisville, Kentucky, for Chile on March 13, 2002. We wanted to see the geyser field at El Tatio, and other thermal fields, too, if we could arrange the travel.

Flying standby from Louisville, we scheduled a "buffer day" in Santiago, Chile's capital and home of 5 million inhabitants, before our 2,000–kilometer domestic flight to Calama. We spent the day in Santiago walking around downtown, visiting the University of Chile, and obtaining maps at the Instituto Geográfico Militar (IGM). We purchased 1:50,000 scale topographic maps of the Chilean geyser fields of El Tatio and Puchultisa. The IGM employees spoke some English, although much of the conversation of selecting the particular map sheets occurred in Spanish. Rhonda and Weldon both speak Spanish. Their Spanish was particularly useful in obtaining food, lodging, and the rental car.

From Santiago to the Atacama Desert — From Santiago, we flew LanChile—Línea Aérea Nacional, the government airline of Chile—north to Calama, with a stop in Antofagasta. The Calama airport had roll–up steps for deplaning and a single baggage claim carousel inside. As we stepped off the airplane, we saw a vast, wide–open landscape voided of all vegetation and dotted with chunks of rock. At the Calama airport gift shop, we purchased a Spanish guidebook with road maps of northern Chile, published by the telecommunications company CTC Chile [Zúñiga, 2001].

A line of rental car agents from primarily American companies greeted the flight. We obtained our vehicle from the Chilean company Econorent without having confirmed reservations. We rented a Toyota Hilux (similar to a Tacoma), which was a double–cab, 4x4 sport utility truck with a 5–speed manual transmission, roll bar, and room for five people. We were sure to rent a truck that was tuned for driving off–road and at high altitudes. It came equipped with a flag on a 3–meter pole and a flashing blue light for driving in the large open pit copper mines near Calama. With unlimited kilometers, two drivers, and insurance, a week's rental was about US$500. An International Driver's Permit is required to drive in Chile.

Paved roads become dirt paths in San Pedro de Atacama, an oasis town of about a thousand permanent residents located about 60 kilometers southeast of Calama. San Pedro is a tourist town, with small hotels, quaint cafes and restaurants. The town has an outdoor market, archaeological museum, charming adobe church with a cactus–wood ceiling, and an interesting cemetery. There are also many Internet cafes, with an hour of access for as little as US$1.50. Most of the visitors we saw in San Pedro were German or Australian eco–tourists; Americans were scarce. The town has electricity from 8 or 9 a.m. to midnight and most hotels we found throughout northern Chile only have hot water when tourists request it.

We arrived in San Pedro after 10 p.m., which, without reservations, made it difficult to find a hotel. Since the first hotel we checked had a sign warning, "*Peligro! Cholera*," we took our search elsewhere (the sign was leftover from an outbreak several years ago). We ended up spending the week at the Hostal Sumaj–Jallpa, a hotel just outside of the "downtown." The small hotel had an inner courtyard and about five rooms. Our room cost about US$30 per night for four people. Weather during the day in San Pedro, at nearly half the elevation of El Tatio, was typically hot at around 27°C. However, temperatures decreased enough each night to make sleeping comfortable.

The majority of our meals in San Pedro were at Petro Pizza, a small restaurant run by a German–turned–Chilean hippy that, of course, served pizza. He also served empanadas and other traditional Chilean dishes. A pizza *marguerita* (cheese pizza) was about US$1.50 there. We found that only chain restaurants (like the Calama Domino's Pizza) served the typical American–style pizza. The local restaurants skipped the sauce and placed the cheese (often Roquefort) on wafer–like crusts. San Pedro grocery stores have water jugs, snacks, and beverages. Supplies had to be purchased in either San Pedro or Calama, since the area between San Pedro and the geysers is effectively wilderness.

As a general note, a Hepatitis A (and Hepatitis B) immunization is recommended for the trip. We visited travel doctors before the trip and received prescription medication for diarrhea, nausea, elevation sickness, and other travel–related unpleasantness. While some travelers said that much of Chile's water is potable, we drank only bottled water. Some villages near Calama have water supplies that have been contaminated by copper mine drainage. Alan became very sick on the trip (he left the United States with a terrible cold, which did not mix well with elevation), and almost had to cut his trip short. Because of lost time from his sickness, we were unable travel to Puchultisa, although we spent three days at El Tatio and one day in Bolivia.

San Pedro was our base for our El Tatio and Bolivia excursions. We spent two nights in San Pedro in order to acclimate to the high elevation (2,440 meters at San Pedro). Just a few kilometers outside of San Pedro is Valle de la Luna (Valley of the Moon) within the Reserva Nacional Los Flamencos (National Flamingo Reserve). Valle de la Luna has widespread salt deposits, caves, pits, heavily folded rocks, and sand dunes over 100 meters tall. However, in the area, we also passed several former land mine fields with signs warning visitors to remain on the road. Mines are a real danger in Chile; in 2001, a group visiting El Tatio found a mine along the main road [*La Estrella de Loa*, 2001].

To Bolivia — After a few days in San Pedro, everyone but Alan took a day–trip to Bolivia. The stops along the tour were Laguna Blanca, Salvador Dalí's Rocks, Aguas Termales (warm springs), Sol De Mañana thermal field, Laguna Colorada, and Laguna Verde. Tour companies in San Pedro primarily offered trips to Bolivia that lasted three days and concluded at Uyuni, Bolivia; Pamela Tours was the only company that we found that offered a single–day–long trip to Bolivia. Since a three–day trip to Uyuni is US$70 (plus an extra US$50 to return to San Pedro), our single–day excursion, with a minimum four people and a maximum of six people, was considered very expensive at US$50 per person. The tour left at 8:30 a.m. and dropped us off at our hotel at 8 p.m.

The trip began at the tour company's office, with the first stop at Chilean customs and immigration just a few kilometers outside San Pedro. An officer stamped us out of the country and collected our yellow landing slips from our arrival at the Santiago airport. The true border with Bolivia was approximately another hour away on a road that was paved for much of the way. At Bolivia, the van driver dropped us off as a new driver in a beaten–up Toyota Land Cruiser Sport Utility Vehicle (SUV) met us. At Bolivian customs and immigration, a shack with abandoned vehicles strewn about around the property, we each paid a US$5 entrance fee for the Reserva Nacional de Fauna Andina Eduardo Avaroa (a national wildlife refuge) and received a passport stamp valid for up to a 30–day stay.

The Bolivian dirt roads were very bumpy and heavily "wash–boarded." The first stop along the tour was a few kilometers from the border, at Laguna Blanca (White Lake). It is a clear, shallow, reflective lake surrounded by mountains. There were a few flamingos wading in the water. Laguna Blanca appeared to be a meeting point for several tours, since there were many backpackers sitting on the steps of a series of hostel rooms that faced the lake. There, our driver checked over the SUV; at one point, he was using a welder to repair something under the hood. This was also the last opportunity to use a flushing toilet, which cost 100 Chilean pesos (about US$0.15).

From Laguna Blanca, the next stop was Salvador Dalí's Rocks, a series of jagged outcrops that are reminiscent of a Dalí painting. Some tours drive up to the rocks, although ours remained a kilometer or so away. The 20 minutes of hiking out to the rocks spent time that could have instead been applied to the geysers.

About 20 minutes later, we reached Aguas Termales, a lake with a series of hot springs around the shore. At least five other tour groups were already at Aguas Termales. We measured the primary spring at 37°C. One of the other tour SUVs had a stereo and was blaring 1980s American dance music, as many of the youthful, European tourists bathed in the shallow waters or kicked a soccer ball amongst each other. We saw some tourists submerging themselves in the spring water, which we, as students of water quality, deemed an unhealthy decision.

At Aguas Termales, the tour company provided "lunch," which consisted of fresh cucumbers and tomatoes, and Bolivian bologna (we think) with pink and white fatty speckles. The "mystery meat" had been in a basket—not a cooler—in the back of the truck, in the sun, for several hours. Shane and Weldon ate the meat and became ill that day, while Rhonda, who brought a jar of peanut butter and made her own sandwich, remained healthy. Therefore, we suggest bringing your own lunch and gracefully declining the tour company meal. The tour operator also rinsed the dishes and knives from lunch in one of the thermal springs. During the dishwashing, we discovered that our vehicle had a flat tire, which the driver changed in about ten minutes. In all, about two hours was spent at Aguas Termales; a ten–minute stop is about all that is needed.

After another 45 minutes of driving, we reached Sol de Mañana thermal field (at elevations around 4,800–5,000 meters). At the field, there were already four tour SUVs. The air temperature was warm and the sun was bright, although a chilly wind blew across the altiplano. We drove across the hydrothermally altered ground and parked at an area of intense activity. As the driver stopped the truck, he turned around and said, "Diez minutos," which meant that we were leaving Sol de Mañana in ten minutes. Frustrated, we offered to pay him extra to skip the rest of the tour and remain longer at the thermal area. He repeated, "Diez minutos." Shane ran as far as he could from the truck to provide us with more time. In total, we spent about 25 minutes at the field; in the allotted time, we believe we saw only a quarter of the area.

The hydrothermally altered, barren soils ranged from reds and oranges to grays and whites. As we stepped out of the truck, the ground was whistling with steam and we felt thumps underfoot from intense subterranean activity. Faded, wooden, red signs warned us, "Peligro de muerte": danger of death. We saw tourists walking haphazardly through many risky areas. None of the tourists appeared to be in the field with their guides; indeed, our driver (as he did at all the stops), leaned his seat back, covered his eyes with his hat brim, and took a short nap.

Trying to see as much hydrothermal activity at Sol de Mañana as possible, we ran around the field (as quickly as we could at high elevations and in unstable terrain). The main area is about 10 km^2, although hydrothermal manifestations occur throughout a much larger region. In the short time that we were there, we saw one perpetual spouter sputtering a fine spray a meter high within its crater. Because other features in the area appeared to be watery, it is likely that there are other perpetual spouters and possibly geysers. The area we visited seemed to be part of the field's higher elevations; there is also a potential for eruptive features in the lower elevations of the basin. Nonetheless, Sol de Mañana has incredible mudpots that splash gray to deep–brown mud up to 2 meters. Many of the waterlogged pots splashed more than "plopped." Closely spaced depressions 3 meters deep and some nearly 7 meters wide dominated the field, with each splattering mud. Plumes of steam could be seen in the distance and on hills lining one side of the field. A strong fumarole vented steam 10 meters and higher. Angular, volcanic rocks, many larger than our truck, dotted the hillside and altiplano. Within 2 kilometers of the field, we noticed at least two geothermal wells.

The final two stops along the tour were Laguna Colorada and Laguna Verde. Laguna Colorada is a pink–colored lake that had flamingos wading in it. Mountains and volcanoes surround the thermally fed lake. As we neared Laguna Verde, a brilliant, emerald green lake, the weather turned windy, cold, and rainy. At Laguna Verde, we stopped only long enough to snap a few photographs of the lake and a rainbow behind us. We soon arrived again at the Bolivian border, where we paid a "departure tax" of 1,500 Chilean pesos each (about US$2) and received exit stamps in our passports.

On the return trip to San Pedro, we passed through a storm that dropped more than a centimeter of snow. Every few minutes, the front seat passenger had to wipe the driver's continuously fogging windshield. As we descended to San Pedro, the storm passed. At Chilean customs and immigration on the outskirts of town, a narcotics dog sniffed the van and our personal items. Inside customs, we had to empty our bags and were hand–searched for drugs, fruits, and vegetables. Before long, we were back at our hotel and regaling Alan with stories about the tour. For the lakes, Andean views, and miscellaneous hot springs, seeing southern Bolivia is worthwhile, even with only 25 minutes at Sol de Mañana.

To El Tatio — After the day trip to Bolivia, we spent our next three days at El Tatio. We drove ourselves to and from El Tatio daily, again using San Pedro as our base. The 86–kilometer drive from San Pedro to El Tatio took between two and two–and–a–half hours. The route was along a rocky and heavily wash–boarded dirt road with occasional stream crossings and detours at washed–out bridges. The road to El Tatio is well–marked and easy to follow. Traversing unimproved roads, volcanic rocks, sand, and gravel proves hard on car tires. We were sure to bring the tools necessary to change a tire — including a good spare. In fact, the locals recommend having two spares. We also filled our gas tank daily, just in case weather or unexpected washouts forced us to return via the alternate route. The alternate road to El Tatio via Calama is about 130 kilometers long. Gas in Calama was reasonably priced, but was expensive in San Pedro. The single gas station in San Pedro is at Hostería San Pedro, where it cost as much as US$80 for a fill–up. We also took camping gear with us, in case we had major car troubles. It was reassuring that a load of tourist buses would be driving the road each morning.

Although the owner of our hotel in San Pedro questioned us for heading to El Tatio when there was supposedly no activity, we set out for El Tatio each day in the mid–morning. We passed tour vans returning to San Pedro, but we arrived at El Tatio after all the tourist buses had left. For the three days of our visit, we were alone in the basin.

At elevations close to 4,500 meters at the geysers, the decreased oxygen level slowed our physical activities. We spent the days recording the activity in a field notebook and collecting map coordinates using a handheld Global Positioning System unit. We took still photographs and used a video camera to document the activity. However, after two days, the camcorder malfunctioned. The combination of rough roads, dust, and steam proved too much for the camera.

The afternoon temperatures at El Tatio in March were chilly, primarily from mountain winds. As if preparing for a cool day in Yellowstone and at high elevations, we wore sunblock, sunglasses, blue jeans, floppy hats, jackets and fleece liners, and gloves. We also experienced a thunderstorm one day at the basin. Though the clouds made the sky dark, only a trace of rain fell.

We generally left El Tatio just before dark (at around 6 or 7 p.m.), so we would at least be on the road before night fell. We saw many chinchillas and other small nocturnal animals bounding across the road. By the time we arrived in San Pedro each night and took a quick shower, the town had already slowed down. By 10 p.m., most of the tourists had eaten and were wandering the streets returning to their hotels. We usually hit a restaurant as they closed and made a last supply run to one of the small general stores.

APPENDIX III: HAZARDS

Numerous hazards exist while traveling abroad in general. However, the following are some of the hazards and cautions specifically relating to travel to El Tatio Geyser Field.

The Thermal Area

Although the El Tatio Geysers have become increasingly accessible by tour and rented vehicle, visitors should be aware of numerous hazards involved in traveling to and within this thermal area. Guides in San Pedro told us that burn accidents are routine and several people have died by falling into boiling pools. Unconfirmed accounts have reported that a body was not recovered at El Tatio and that several bodies may remain in the mudpots of Sol de Mañana. In October 2002, a Spanish tourist to El Tatio stepped backward into a hot spring—with a temperature estimated at 90°C—and received burns to 80 percent of his body [*La Estrella de Loa*, 2002]. As a result, a $35,000 trail and parking project are underway to enhance visitor safety [*La Estrella de Loa*, 2003]. Regardless, as with all geyser areas, extreme care must be taken while walking throughout the basin. Thin crusts may conceal underlying pools of boiling water and mud. Unseen fragile rims may overhang deep boiling pools, while seemingly innocuous dry cones and rifts areas can violently eject boiling water with little or no notice. One remarkable characteristic of the El Tatio basin is that a number of thermal features are submerged in the Río Salado. These features look like deep spots in the otherwise shallow river, although these locations actually discharge boiling water. Visitors unaccustomed to the perils of backcountry geyser travel should be careful to stay with competent guides. Considerate travel through the basin not only is safer, but also helps protect the thermal features themselves.

Volcanoes

The geyser field is ringed by active volcanoes. On the drive to El Tatio, we noticed two volcanic vents. From San Pedro de Atacama we saw that Volcán Lascar, about 100 kilometers to the south, was having constant hydrothermal eruptions. These occurred throughout our seven–day visit. Volcán Lascar is one of the most active volcanoes in the central Andes. Violent eruptions in July 2000 sent ash streaming 4,000 to 5,000 meters above its summit. In addition, near Volcán Lascar, renewed activity has appeared at Volcán Chilique. The activity was first noted on NASA Aster satellite imagery in January 2002. During our last day at El Tatio, Volcán Putana, which is 25 kilometers southeast of the basin, began spewing 200–meter–high columns of steam from its crater. Visitors should be constantly aware of their surroundings and ask locals about ongoing volcanic activity.

Roads

The dirt roads to El Tatio from San Pedro and Calama are well marked, but there are several points to consider before traveling. First, make sure to have a vehicle tuned to high elevation travel. While El Tatio itself is at 4,200 meters, the road steadily climbs from these cities and traverses altitudes of greater than 4,700 meters. Elevation gain is accomplished through a series of occasionally sharp switchbacks. Numerous memorial crosses have been placed along the side of the road marking locations where vehicles have driven off the road and down the steep hillsides. On a return trip from the basin one evening, we encountered a truck that had taken a turn too fast and was now resting upside down with its windows shattered. We stopped to investigate since the overhead light in the truck was on, although there were no passengers inside when we found the vehicle. The wreck had occurred sometime while we were at El Tatio, since it was not there on our way to the basin. By our trip to the basin the next day, the vehicle had been towed to San Pedro.

Several large road washouts exist along the main route, too, but are not problematic with slow, attentive driving. The locals, possibly the tour companies, have created alternate winding routes around each washout. The road from San Pedro to the geysers also crosses a number of creeks that were up to sixty centimeters deep. The creeks could be dangerous if approached too quickly or if a recent rain had raised the water levels. Flash floods can create impassable muddy deluges during thunderstorms and sudden snow melts. During normal conditions, other than occasional streams and mud puddles, the route is dry. With a four–wheel drive vehicle, having a flat tire (since the dirt roads tend to be made of gravels and sharp volcanic basalts) is the most likely problem to occur along the road. Getting stuck at the geyser basin itself is possible, though. Besides crossing the Río Salado, the road through the basin travels around and literally over numerous thermal features. Drivers should be extremely cautious. We originally planned to park at the edge of the basin and walk to the features. However, we found ourselves using our truck as a ferry to keep ourselves dry, since the Río Salado flows throughout much of the basin as a wide, braided stream requiring frequent fording.

Plans appear to be underway to create a paved road from San Pedro to the basin. Numerous government signs near San Pedro provide information about the road project, but probably also portend the beginning of geothermal electricity development. We noticed flagged survey stakes along the side of the road for a majority of the route.

Elevation Sickness

At elevations of 4,200 meters and greater, El Tatio Geyser Field is one of the highest geyser fields on earth. The road from San Pedro to the geyser basin often exceeds 4,700 meters. At the basin's altitude, elevation sickness is common. Allow time to acclimate slowly to the high elevations. Our team stayed in San Pedro de Atacama (2,440 meters) two nights before traveling to the higher elevations. When we arrived at the basin, we each felt at least some effect of the altitude. We found that the best way to cope with the high altitude was to walk slowly and minimize exertion (hiking and climbing was very slow as well). Fortunately, most of the geysers lie on gentle slopes or level ground. The kilometer or two walk to the Lower Basin (River Group) put everyone in our group out of breath; Alan and Rhonda both got headaches, but an ibuprofen solved the problem within an hour. Of course, being well–hydrated and getting plenty of sleep the night before lowers the risk of altitude problems. Tourist accounts of the basin seemed to come in two varieties: either the people loved the tour or they became sick. Since it is a good idea to consult a doctor about various immunizations before international travel anyway, ask about coping with high altitudes.

Landmines

Politically, Chile is a civilized, modern destination for travelers and scientists. Social and legal order are similar to Europe, Australia, and North America. Nevertheless, from 1974 to 1978, tensions between Chile and its neighbors Bolivia, Peru, and Argentina were the basis for a program of minefield creation. At least 293 separate minefields, between 250,000 and 1,000,000 landmines were laid in northern Chile. Although Chile now opposes the use of landmines and, in 2001, ratified an international treaty banning their use, minefields still exist in northern Chile. Particularly at Valle de Luna and along the road between Calama and San Pedro de Atacama, signs denote areas where minefields still pose a danger. Although there is no indication that mines were laid at the geysers themselves, tourists in January 2001 reported an antipersonnel mine on the way to El Tatio and notified local authorities. Mine clearance personnel from Calama were mobilized, but were unable to find any mines [*La Estrella de Loa*, 2001]. In 1999, the Chilean Government began an 11–year mine clearing program that will reduce the landmine threat.

Weather–related Hazards

With its location that spans the Andes Mountains and the Atacama Desert, the weather at the basin could be life–threatening for unprepared visitors. Be sure to carry plenty of water; the Atacama is known for being one of the driest places on earth. Water quality varies widely in the thermal basin; drinking the water is not recommended. Throughout the year, weather typically gets near or below freezing at night. Many tourist photos, which are generally taken at sunrise, show ice patches around the geyser cones. During the day, temperatures can be warm. However, snow above 4,000 meters is common. Although we did not encounter any dust storms, they are apparently quite dangerous in the area, particularly in the lower elevations at San Pedro and Calama. We were told that when dust storms occur, all travel, including tour operations, halts.

REFERENCES

Allen, E.T., and Day, A.L., 1935, *Hot Springs of the Yellowstone National Park, Publ. 466.* Carnegie Institution of Washington: Washington, D.C., 525 pp.

Allis, R.G., 1981, Changes in heat flow associated with exploitation of Wairakei geothermal field, New Zealand. *New Zealand Journal of Geology and Geophysics, 24*, 1–19.

Andres, L.R., Raul, M.R., and Hugh, R.V., 1998, Energía Eólica y Geotérmica en Chile: Evaluación de su potencial y desarrollo (unpublished paper on wind and geothermal energy in Chile). Pontificia Universidad Católica de Chile: Chile, 30 pp.

Bernhardson, W, 2000, *Chile & Easter Island.* 5th edition. Lonely Planet Publications: Melbourne, Australia, 599 pp.

Bertrand, A., 1885, *Memoria sobre las cordilleras del desierto de Atacama y regiónes limítrofes*, presentada al señor ministro del interior. Imprenta nacional: Santiago, Chile, 304pp.

Brueggen, J., 1943, Los geisers de los volcanes del Tatio. *Rev. Chil. Hist. Geogr.* 101, 236.

Bryan, T.S., 2001, *The Geysers of Yellowstone.* 3rd edition. Colorado University Press: Boulder, Colorado, 472 pp.

Collar, R.J., 1990, *Causes for the decline of hot spring and geyser activity, Steamboat Springs, Nevada.* Master's Thesis. San Diego State University: San Diego, California, 327 pp.

Cusicanqui, H., Mahon, W.A., and Ellis, A.J., 1976, The geochemistry of the El Tatio Geothermal Field, northern Chile. In *Proceedings of the 2nd United Nations Symposium on Geothermal Fields*, Berkeley, California, pp. 703–711.

de Silva, S.L., and Francis, P.W., 1991, *Volcanoes of the Central Andes*. Springer–Verlag: New York, 216 pp.

ENTEL Antofagasta, 2002, *Misterios del Tatio*. Santiago, Chile, 1 p. www.puntoantofagasta.cl/.

Farmer, J.D., 2000, Hydrothermal systems: doorways to early biosphere evolution. *GSA Today 10*, 7, 1–2.

Farmer, J.D., and Des Marais, D.J., 1994, Biological versus inorganic processes in stromatolite morphogenesis: observations from mineralizing systems. In L.J. Stal and P. Caumette (Eds.), *Microbial mats: structure, development, and environmental significance*. Springer–Verlag: Berlin, pp. 61–68.

Filipponi, A., 1953, Energía geotérmica del Tatio chileno. *Scientia* Año XX, 74.

Filipponi, A., 1960, Electrifación del norte con energía geotérmica del Tatio chileno (2 parts), Universidad de Chile Boletín, I part no. 16, p. 4; II part no. 17–18, p. 42.

Graham, M., Sainsbury, C., and Danbury, R., 1999, *Chile: The Rough Guide*. Rough Guides Ltd: London, UK, 488 pp.

Healy, J., and Hochstein, M.P., 1973, Horizontal flow in hydrothermal systems. *Journal of Hydrology (New Zealand)* 12, 71–82.

Hroarsson, B., and Jonsson, S.S., 1992, *Geysers and Hot Springs in Iceland.* Mal og Menning: Reykjavik, Iceland, 158pp.

Instituto Geográfico Militar, 1985, *Cerros de Tocorpuri 2215–6745* [map]. 1st edition. 1:50,000 scale. Instituto Geográfico Militar: Santiago, Chile.

Instituto Geográfico Militar, 2001a, *Mauque A–045* [map]. 2nd edition. 1:50,000 scale. Instituto Geográfico Militar: Santiago, Chile.

Instituto Geográfico Militar, 2001b, *Toconce 2215–6800* [map]. 1st edition. 1:50,000 scale. Instituto Geográfico Militar: Santiago, Chile.

Jones, B., and Renaut, R.W., 1997, Formation of silica oncoids around geysers and hot springs at El Tatio, northern Chile. *Sedimentology* 44, 287–304.

La Estrella de Loa, 12 January 2001, "Alarma por supuesta bomba en El Tatio."

La Estrella de Loa, 7 October 2002, "Turista español se quemó en los Géisers del Tatio."

La Estrella de Loa, 16 July 2003, "Géiser ofrecieron espectáculo único."

Lahsen, A., and Trujillo, P., 1976, El Tatio Geothermal Field. In *Proceedings of the 2nd United Nations Symposium on Geothermal Fields*. Berkeley, California, pp. 157–158.

Rinehart, J.S., 1980, *Geysers and Geothermal Energy.* Springer–Verlag: New York, 223 pp.

Rye, R.O. and Truesdell, A.H., 1993, *The question of recharge to the geysers and hot springs of Yellowstone National Park.* U.S. Geological Survey, Open–File Report 93–384, 40 pp.

Sorey, M.L., 2000, Geothermal development and changes in surficial features: examples from the Western United States. In *Proceedings of the World Geothermal Conference, Kyushu – Tohuku, Japan, May 28 – June 10, 2000*, p. 705–711.

Sundt, L., 1909, Estudios geológicos y topográficos del Desierto y Puna de Atacama. Two parts. Santiago de Chile, 212 pp.

Tocchi, E., 1923, Studio geologico e geotermico del Tatio cileno. Reserved report to Larderello S.A.: Italy.

Trujillo, P., 1969, Estudio para el desarollo geotermico en el norte de Chile – Manifestaciónes termales de El Tatio, Provencia de Antofagasta: CORFO Project Report.

Trujillo, P., Lahsen, A., and Varar, J., 1969, *Estudio Geotermico Manifestaciones Termales Superficiales de El Tatio* [map]. 1:10,000 scale. Photocopy, approximately 60–by–60 centimeters.

Walter, M.R., and Des Marais, D.J., 1993, Preservation of biological information in thermal spring deposits: developing a strategy for the search for fossil life on Mars. *Icarus, 101*, 129–143.

White, D.E., 1968, *Hydrology, activity, and heat flow of the Steamboat Springs thermal system, Washoe County, Nevada.* U.S. Geological Survey Professional Paper 458–C, 109 pp.

White, D.E., 1998, *The Beowawe Geysers, Nevada, before geothermal development.* U.S. Geological Survey Bulletin 998, 25 pp.

Zeil, W., 1956, *Theoretical and experimental study of the possible use of geothermal energy provided by the geysers and fumaroles of El Tatio.* In Siegel [thesis]: Universidad de Chile: Santiago.

Zeil, W., 1959, *Das Fumarolen– und Geysir–Feld westlich der Vulkangruppe des Tatio (Provinz Antofagasta, Chile).* Bayerische Akademie der Wissenschaften, Abhandlung der Mathematisch–Naturwissenschaftliche Klasse: Muenchen, Deutschland, n. 96, 22 pp.

Zúñiga, C.M. (CTC generente general), 2001, *TURISTEL Norte Guia Turistica de Chile.* Telefónica CTC Chile: Santiago, Chile, 240 pp.

Alan Glennon has visited several of the world's geyser areas. This photo, taken in 2003, shows a small geyser at **Hveravellir, Iceland.**

GOSA

A Statistical Analysis and Comparison of the Activity of Old Faithful Geyser

September–October 1996 and June–July 1997

by William P. Moats

Abstract

Many large and spectacular geysers at Yellowstone's Upper Geyser Basin increased their eruptive activity between late–1996 and mid–1997, but whether or not Old Faithful Geyser participated in this change has not been considered. A statistical study of Old Faithful's eruption height, interval and duration was undertaken to investigate possible changes. In summary, although other geysers in the Upper Geyser Basin may have increased their activity over this time frame, Old Faithful did not.

Introduction

In the summer of 1997, it was widely accepted among many observers that thermal activity had increased basin–wide at Upper Geyser Basin relative to previous years. Although no rigorous scientific proof is offered, this conclusion was based on observations of decreased intervals for some geysers (e.g. Beehive), and reactivation (e.g. Splendid) or greatly increased activity of other geysers (e.g. Giant). While some geysers received considerable attention during this time, Old Faithful Geyser was largely ignored. Thus, it is interesting to speculate whether Old Faithful also increased its activity in the summer of 1997. To answer this question, a statistical study was undertaken to evaluate the activity of Old Faithful Geyser prior to and during this time. The results of this study are presented here.

Method

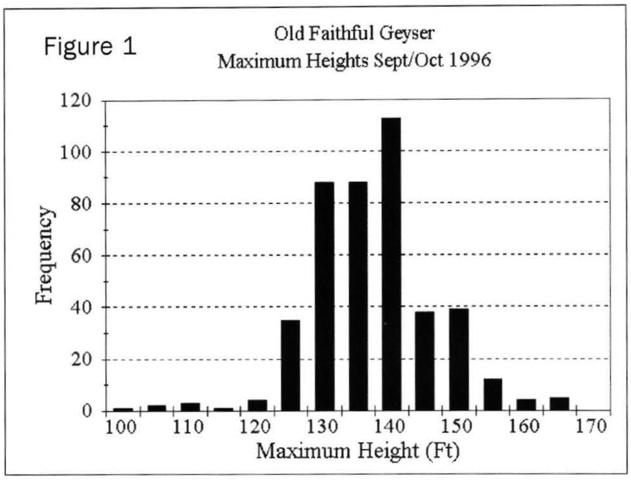
Three of the most important characteristics of a geyser's eruptions are maximum height, interval and duration. Any significant difference in the mean values of these eruption characteristics is taken herein as evidence of a change in eruption behavior. A significant increase in height or duration, or a decrease in interval would imply a positive correlation between the activity of Old Faithful Geyser and the 1997 event of increased thermal activity at Upper Geyser Basin.

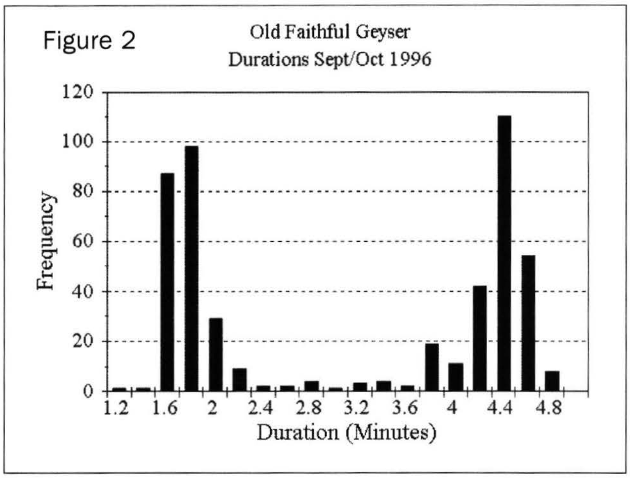
To evaluate any possible changes in the activity of Old Faithful Geyser, data for those three eruption characteristics (height, duration, and interval) were analyzed by statistical methods and compared for two discrete time periods. More specifically, data for September–October 1996 (fall 1996) were selected because they should represent the behavior of Old Faithful Geyser *prior* to the beginning of the increased thermal activity at Upper Geyser Basin. For comparison, data for June–July 1997 (summer 1997) were chosen because they reflect the behavior of Old Faithful Geyser *during* the time period of interest.

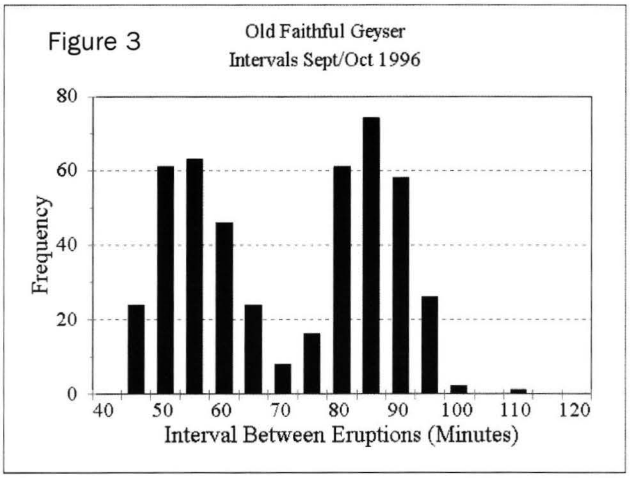
It may be difficult to recognize whether small differences in any of the three eruption characteristics are significant. For this reason, F-tests and Student t-tests were employed where possible in this study because they are often used to help make statistically supported decisions. The F-test was used to determine if the variances of two data sets differ significantly at a 95% level of confidence. Once the variances were evaluated, the Student t-test was used to determine if the means of the eruption characteristics differ significantly between the fall of 1996 and the summer of 1997, again at a 95% confidence level. The calculations for a Student t-test are done in different ways depending on whether the variances of two data sets are statistically equivalent; the reader is referred to Taylor [1990] for more details.

Eruption Characteristics for September–October 1996

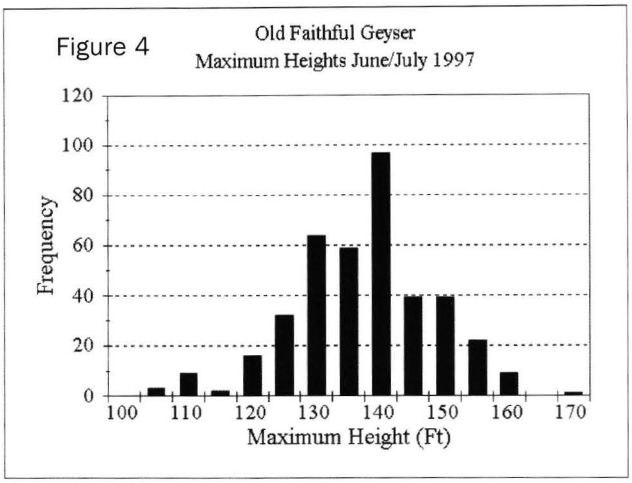
Figures 1–3 are histograms showing frequencies of maximum height, duration, and interval between eruptions (herein referred to as interval), respectively, for the time period September–October 1996. All data used in this study are from the National Park Service (NPS) logbook, made avail-

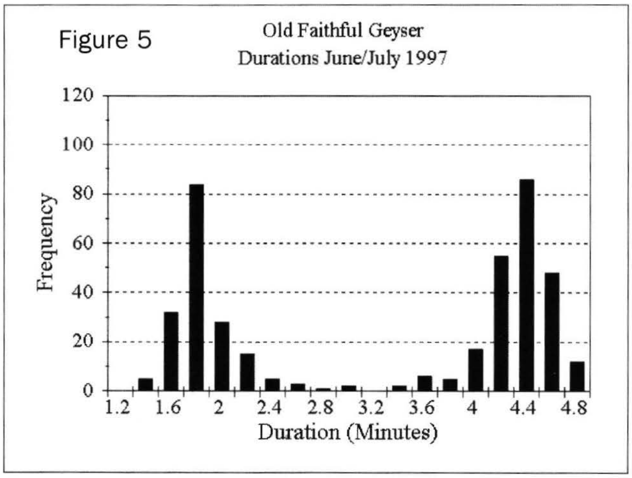


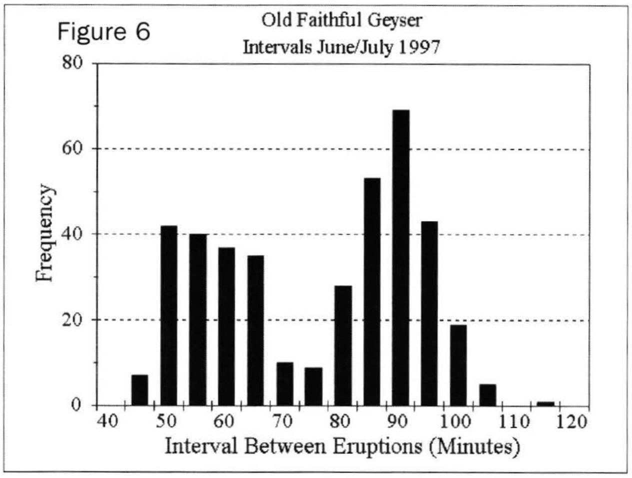




Figures 1–3. Histograms showing the frequencies of maximum height, duration and interval of Old Faithful Geyser in September–October, 1996.







Figures 4–6. Histograms showing the frequencies of maximum height, duration and interval of Old Faithful Geyser in June–July, 1997.

able electronically. As shown in Figures 2 and 3, the data sets for both duration and interval have bimodal distributions; this is consistent with previous observations for Old Faithful Geyser at least prior to 1994 [Bryan, 1994].

Because the distributions are bimodal, data were separated into short ($\leq$180 seconds) and long durations (>180 seconds), and short ($\leq$73 minutes) and long intervals (>73 minutes). Rejection of data was minimal; four values for height and three high values for interval were rejected (possible copying errors). Statistical descriptors for the fall 1996 data are presented in Tables 1–3.

Eruption Characteristics for June–July 1997

Figures 4–6 are histograms showing the eruption characteristics for Old Faithful Geyser for the time period June–July 1997. As the distributions for duration and interval are again bimodal (Figures 5 and 6), data were separated into short ($\leq$ 180 seconds) and long durations (>180 seconds), and short ($\leq$73 minutes) and long intervals (>73 minutes). Four data points were rejected for interval (again, possible copying errors); none was rejected for height or duration. Statistical descriptors for the June–July 1997 data sets are also presented in Tables 1–3.

Tests for Normality

The distribution of each data set for each eruption characteristic was evaluated for normality by plotting the expected boundary for a standardized normal distribution against their ranked data values, as measured in units of standard deviation (Figures 7–12). The graphs depicted in these figures are used in the same way as traditional probability plots, in that a given data set will plot as a straight line if normally distributed. The advantage of this method over traditional probability plots is that special graph paper is not needed.

The step–like configuration apparent in the first graph (Figure 7) is caused by the presence of numerous subsets of equivalent data values, which in turn, is related to the manner in which the data were recorded. For example, in this case of short intervals, values are derived from eruption times that have been truncated to the minute of the hour in compliance with NPS policy, giving rise to many data points of equal value. Similar step–like patterns are also apparent at some degree in all the other plots. As with Figure 7, these step–like patterns are caused by subsets of equivalent data points.

The plots shown in Figures 7–12 are roughly linear, suggesting that the data sets for height and interval (short and long) for both time periods can be reasonably approximated as normal distributions. With respect to the data sets for short and long durations, the means differ by only 3.1 and 1.1 seconds, respectively, for the two time periods (Table 2). From a practical standpoint, such changes are certainly not marked. Furthermore, the magnitudes of these differences are easily in the range of routine measurement errors, including that associated with the time needed for an observer to identify and record the end of the water phase of an eruption of Old Faithful Geyser. For these reasons, the application of normality and statistical tests is deemed inappropriate for the data setrs for short and long durations.

Comparison of the Eruption Characteristics

On cursory examination, the corresponding means for height, duration and interval in Tables 1–3 appear similar for the two time periods. However, F-tests and the Student t-tests were employed to make statistically supported decisions regarding eruption heights and intervals. F-test results are presented in Table 4, based on a 95% confidence level (F_c); whereas, Student t-test results are presented in Table 5 (t is based on a 95% confidence level).

As seen in Table 4, height is the only case where the variances differed significantly between the two time periods; however, the mean heights did not (Tables 1 and 5). For both the fall 1996 and summer 1997, the mean maximum height of Old Faithful Geyser remained consistent at 138 feet. The height of an Old Faithful eruption is estimated by NPS personnel by comparing the top of the water column to various branches on a tree that have been "calibrated" to represent certain eruption heights. Given this crude method of measurement, estimations of height would be expected to vary depend-

Figure 7

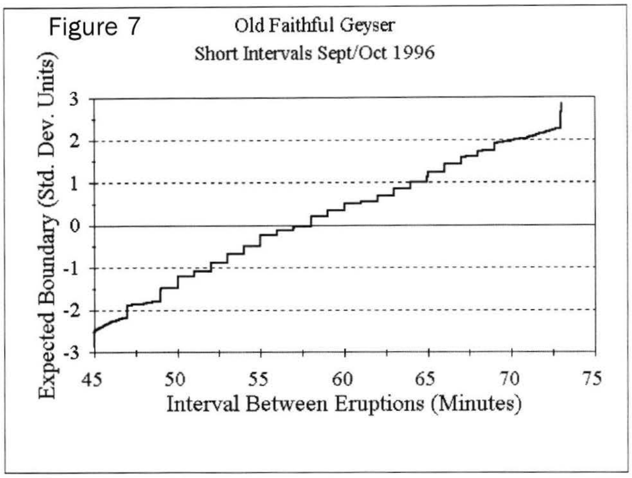


Figure 8

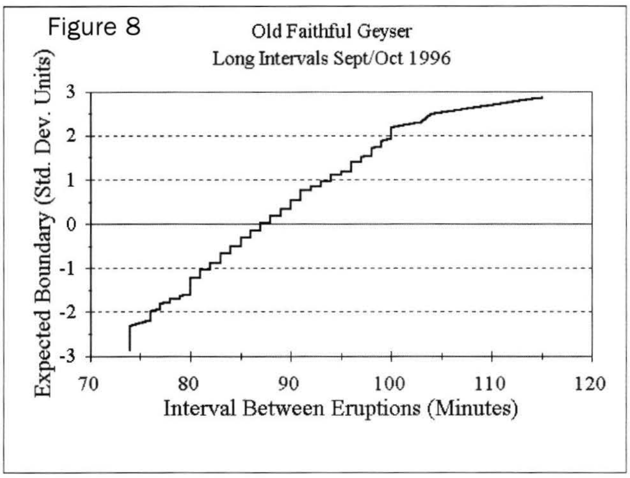


Figure 9

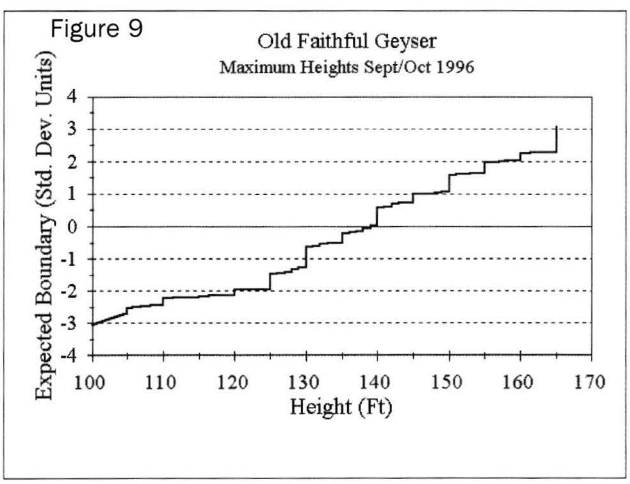


Figure 10

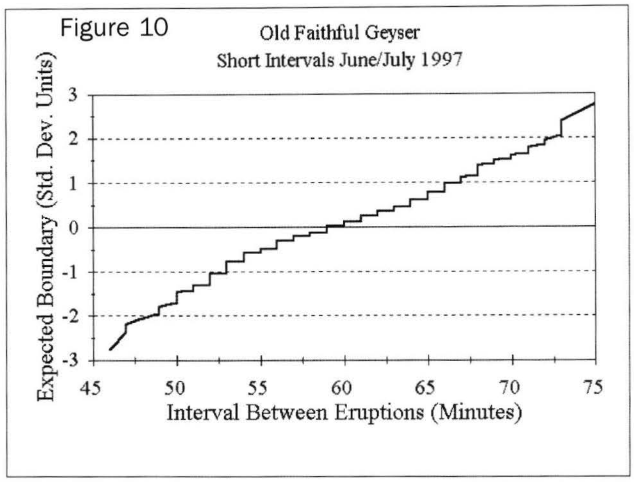


Figure 11

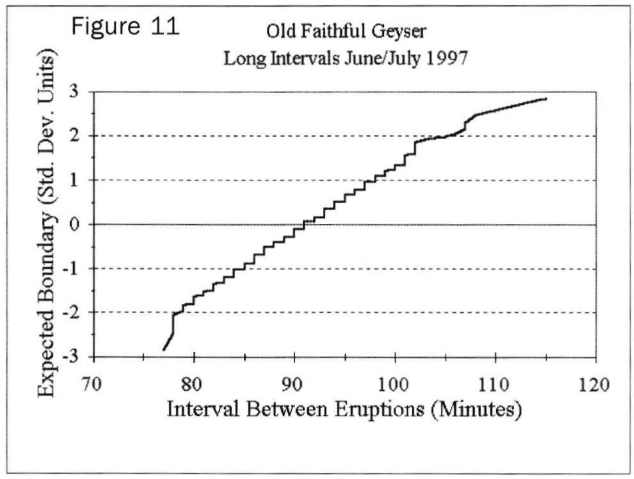
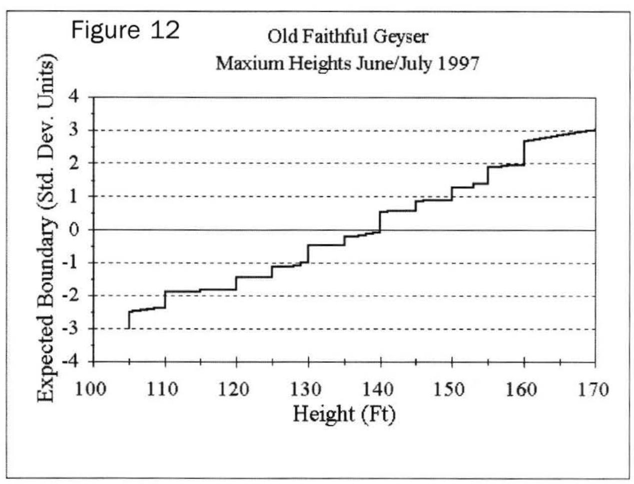


Figure 12



Tests for Normality between the two data sets.
Figures 7–9 (left column) show tests for short intervals, long intervals and maximum heights in September-October 1996, while Figures 10–12 (right column) show tests for short intervals, long intervals and maximum heights in June–July 1997. In each case, the graph is a plot of the expected boundary for a standardized normal distribution versus the ranked data values.

ing on the eye height of different observers, which affects the angle of the line of sight. Therefore, the difference between the variances of the two time periods was likely caused at least in part by the measurement method, which is unstable because it depends on the individual making the measurements. The presence of steam obscuring the top of the water column would also be expected to have an effect on the consistency of the measurement process.

As discussed above, there is no practical and perhaps verifiable difference between the data sets for short and long durations.

The mean short interval was 57.8 and 59.5 minutes for the fall 1996 and summer 1997, respectively; whereas, the mean long interval was 87.7 and 91.2 minutes for the fall 1996 and summer 1997, respectively (Table 3). As indicated by the Student t-tests (Table 5), the means for short and long intervals differ significantly between the two time periods, showing increases of 1.7 and 3.5 min, respectively, for the time period June/July 1997. Unlike those for short and long durations, these differences are not easily dismissed. The average increase is 2.72 minutes (weighted relative to the number of short and long intervals). For comparison, the average difference between NPS–predicted intervals and actual intervals during the same time period was -2.75 minutes. The latter suggests that the NPS was not aware of the increased intervals during the summer of 1997, generally underestimating eruption start times for Old Faithful Geyser by nearly 3 minutes.

Conclusion

The weighted mean interval of Old Faithful Geyser during June–July 1997 is 2.72 minutes larger than that for September–October 1996; whereas, height and duration remained essentially the same. Although other large and spectacular geysers at Upper Geyser Basin may have increased their activity in the summer of 1997, Old Faithful Geyser did not.

Acknowledgements

Data are from the National Park Service, made available to the public in electronic format by the extraordinary efforts of Lynn Stephens. Anne Moats, T. Scott Bryan, Holly Zullo and Paul Strasser made helpful suggestions.

This paper is dedicated to the memory of Richard Kilbury (1952–2003) and his many contributions in support of wilderness and environment.

References

Bryan, T. S., 1994, *The Geysers of Yellowstone*, 3rd Edition; University Press of Colorado, Niwot, CO, 463 p.

Taylor, J. K., 1990, *Statistical Techniques for Data Analysis*; Lewis Publishers, Inc., Chelsea, MI, 200 p.

Table 1. Eruption Height — Statistical descriptors for maximum eruption height for Old Faithful Geyser, September–October 1996 and June–July 1997.

	Maximum Height	
Descriptor	**September/ October 1996**	**June/July 1997**
Mean (ft)	138	138
Median (ft)	139	140
Mode (ft)	140	140
Standard deviation (ft)	9.15	10.85
Minimum (ft)	100	105
Maximum (ft)	165	170
Number of observations	433	392

Table 2. Eruption Duration — Statistical descriptors of eruption duration for Old Faithful Geyser, September–October 1996 and June–July 1997.

	Short Duration		Long Duration	
Descriptor	**September/ October 1996**	**June/July 1997**	**September/ October 1996**	**June/July 1997**
Mean (seconds)	113.3	116.4	265.3	266.4
Median (seconds)	110	113	269	269
Mode (seconds)	105	111	270	260
Standard deviation (seconds)	13.5	13.92	17.6	16.86
Minimum (seconds)	80	92	184	181
Maximum (seconds)	180	180	297	300
Number of observations	233	173	254	233

Table 3. Eruption Interval — Statistical descriptors of eruption interval for Old Faithful Geyser, September–October 1996 and June–July 1997.

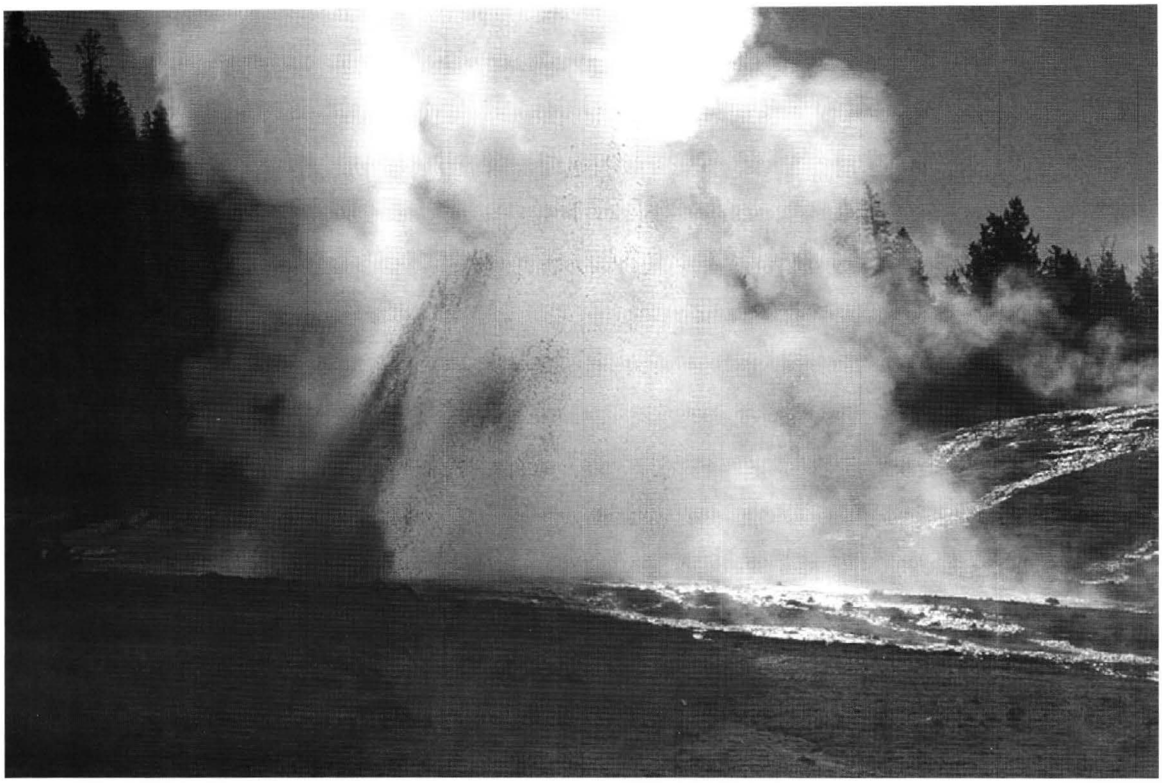
	Short Interval		Long Interval	
Descriptor	**September/ October 1996**	**June/July 1997**	**September/ October 1996**	**June/July 1997**
Mean (minutes)	57.8	59.5	87.7	91.2
Median (minutes)	58	59	87	91
Mode (minutes)	54	53	87	93
Standard deviation (minutes)	6	6.54	6.1	6.59
Minimum (minutes)	45	46	74	77
Maximum (minutes)	73	75	115	115
Number of observations	223	172	241	226

Table 4. F–test Results — F–test results for eruption height and interval for Old Faithful Geyser, September–October 1996 and June–July 1997. Results are based on a 95% confidence level.

Characteristic	**F**	**F_c**	**Difference?**
Height	1.406	1.213	Yes
Short Interval	1.188	1.323	No
Long Interval	1.167	1.293	No

Table 5. Student t–test Results — Student t–test results for eruption height and interval for Old Faithful Geyser, September–October 1996 and June–July 1997. Results are based on a 95% confidence level.

Characteristic	**Equal Variances?**	**Difference**	**Degrees Freedom**	**t**	**t_c**	**Means Differ?**
Height	No	0 ft	769	1.963	1.378	No
Short Interval	Yes	1.7 minutes	393	1.966	1.245	Yes
Long Interval	Yes	3.5 minutes	465	1.965	1.154	Yes



Butterfly Spring, May 27, 2003. (Photo by Pat Snyder; see also page 88)

Butterfly Spring, May 4, 2003. (Photo by Tara Cross; see also facing page)

Water from the larger eruptions by Butterfly Spring (those estimated to be 40 to 50 feet high) reached as far as halfway up the geyserite mound of Dome Geyser, the formation to the right in both of the above photos.

Butterfly Spring —

The major eruptions of May 2003

photos by Mike Newcomb, Tara Cross, Pat Snyder and F. Jay Haynes; historical summary by Scott Bryan


Butterfly Spring by F. Jay Haynes, perhaps as early as the 1890s. Haynes Photo #10144.

Butterfly Spring was first described by A. C. Peale in 1878 as a "fissure 4 feet long, yellow sputterer." That sounds nothing like the description given by Walter Weed in 1888, when he named it and referred to it as "Two noisy splashers." So begins some controversy about the identity and history of this spring.

Any further description of activity in the 1880s is apparently unknown. In 1894 park visitor J. S. Saltus discussed the butterfly–like appearance, which he said was due not to the shape of the crater but rather because of the "sediment and coloring matter" that had been deposited for several feet around the spring. Saltus also said that the vent was "full of dark brown water" — a point possibly important when considering the action in 2003.

Butterfly might have had an on again–off again record of action in the early days of the park. It certainly was active in 1894 and before, but it was said to have been "out of business" in 1895, then a "beautiful geyser" in 1900, and dormant in 1914. No further action was reported until 1936, when play 6 to 10 feet high was described in park naturalists' reports.

Occasional visitor reports stated that the spring received its name of "Butterfly" because of the form of the erupted water, but this was probably more imagination than fact. Prior to the major eruptions of 2003, Butterfly in fact bore two connected craters, each containing a small vent. Relatively little imagination was needed to see the formation's resemblance to a butterfly's wings (see Haynes' photo). That appearance no longer exists.

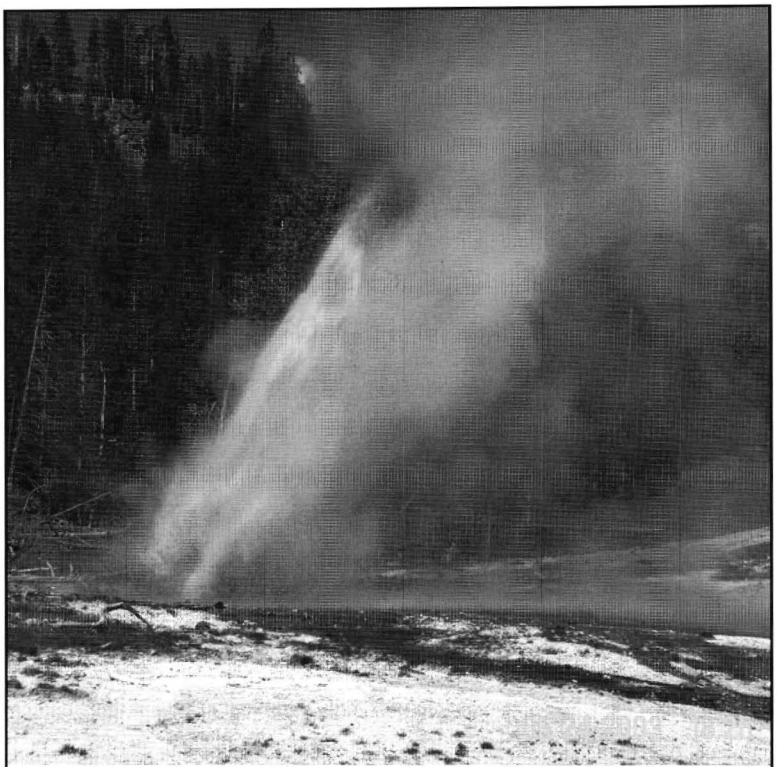
In recent years, Butterfly's vents have been dry more often than they contained visible water, and no actual eruptions are known to have occurred


Butterfly Spring in eruption on May 4, 2003. Note the dark appearance of the water. (Photo by Tara Cross)

between 1936 and 2003 — periods of activity, if any, must have been weak and brief. No runoff channel is visible in the Haynes photo, and this writer cannot recall seeing any in recent years.

The first 2003 activity was observed on May 1, when a muddy minor eruption was reported that evening. Butterfly reached major dimensions by the next day. This major activity continued through the month of May; the last known major eruption occurred in the afternoon of May 31, 2003 (see Table 1).

The angled spray of the better eruptions frequently reached over 40 feet high, and some play in excess of 50 feet probably took place. Closed intervals between the eruptions varied quite widely, ranging from 4h 36m to 10h 40m. Durations were from about 2 to 3½ minutes long.



Butterfly Spring in the afternoon of May 24, 2003. Note that the water bore much less of a muddy appearance. (Photo by Mike Newcomb)

The water discharged by these eruptions had a dark, chocolate–brown color, probably similar to that described in 1894. Gradually, the water cleared somewhat and by the end of May it was more pale gray than dark brown. The small, twin–vented spring had become a jagged crater, and all traces of the butterfly shape were gone. The heavy discharge of water carved two deep and one broad runoff channels where there had been none before. It seems likely that the major eruptions of 2003 were the first ever in Butterfly Spring's existence.

Minor eruptions, just a few feet high and lasting only seconds, were common during the intervals between the major eruptions. Most produced no runoff and, in fact, they no doubt resembled the action reported in 1936 and before. As of this writing (mid–September 2003), the minor activity was continuing.

Butterfly Spring backlit by the early morning sun on May 27, 2003. (Photo by Pat Snyder)

Reference

All historical information cited here has been extracted from:

Whittlesey, L. H., 1988, *Wonderland Nomenclature: A History of the Place Names of Yellowstone National Park*: The Geyser Observation and Study Association *after* he Montana Historical Society, Helena, Montana.

Table 1 – The Major Eruptions of Butterfly Spring, May 2003

Date	Time	Interval	Comment
May 1	(1925)		Minor; first report, muddy to 1–2 feet
May 2	1253		FIRST KNOWN MAJOR ERUPTION?
May 3	1327 ie		
	1848	~5h 21m	
May 4	1059		
	1725	6h 26m	
May 5	1151		
	1941	7h 50m	
May 6	0840		d = 2m07s
	1502	6h 22m	d = 2m20s
May 7	1520		
May 8	1512 ie		
May 9	no report		
May 10	1633		
May 11	no report		
May 12	1221		
May 13	no report		
May 14	no report		
May 15	0713		
	1222	5h 09m	
	1821	5h 59m	
May 16	no report		
May 17	0848		
	1752	9h 04m	
May 18	no report		
May 19	no report		
May 20	no report		
May 21	1103		
	2020	9h 17m	
	"nite"		meaning next calendar day?
May 22	1237		
	1713	4h 36m	
May 23	0735		
	1511	7h 36m	
	2004	4h 53m	
May 24	~0550		runoff heavily steaming at 0600
	1103	~5h 10m	
	1625	5h 22m	
May 25	0817		
	1405	5h 48m	
	1927	5h 22m	
May 26	0102	5h 35m	
	0611	5h 09m	d ~ 3¼ min
	1149	5h 38m	
May 27	0824		
	1330	5h 06m	
	2042	7h 12m	d > 2½ min
May 28	0916		
	1429	5h 13m	
	2015	5h 46m	
May 29	0823		
	1903	10h 40m	definitely a single, closed interval
May 30	0534		
	1153	6h 19m	d > 3 min
	1852	6h 59m	
May 31	0838		
	1555	7h 17m	LAST MAJOR ERUPTION (per use of markers)

The Geyser Hill Wave, April 9 to June 9, 2003 A Timeline Chart

by T. Scott Bryan

Introduction

The Geyser Hill Wave ("GHW") is a cyclic process that causes water levels to rise and geyser activity to become more frequent among a number of thermal features on Geyser Hill. All of Geyser Hill is involved, but these changes are most obvious within selected springs on the southern portion of Geyser Hill. The timing of the cycle can most readily be judged by eruptions of Little Squirt Geyser, the time known as "SMax."

The GHW was fully described by my article (*Cyclic Geyser Activity on Geyser Hill...*) in Volume IV of *The GOSA Transactions*. This brief analysis updates information about the GHW for the period of April 9 through June 9, 2003 when the action was complicated by extraordinarily frequent GHW cycle intervals, an eruption by Giantess Geyser, and a dormancy in Plume Geyser accompanied by a possibly–corresponding rejuvenation of Butterfly Spring.

The data is visually represented by the timeline chart on the following page.

Explanations

In summary, the geyser activity observed for this study is as follows:

• **Giantess Geyser** erupted on April 22, its first since December 5, 2002. So far as is known, there was nothing unusual about this eruption that might have "caused" subsequent events.

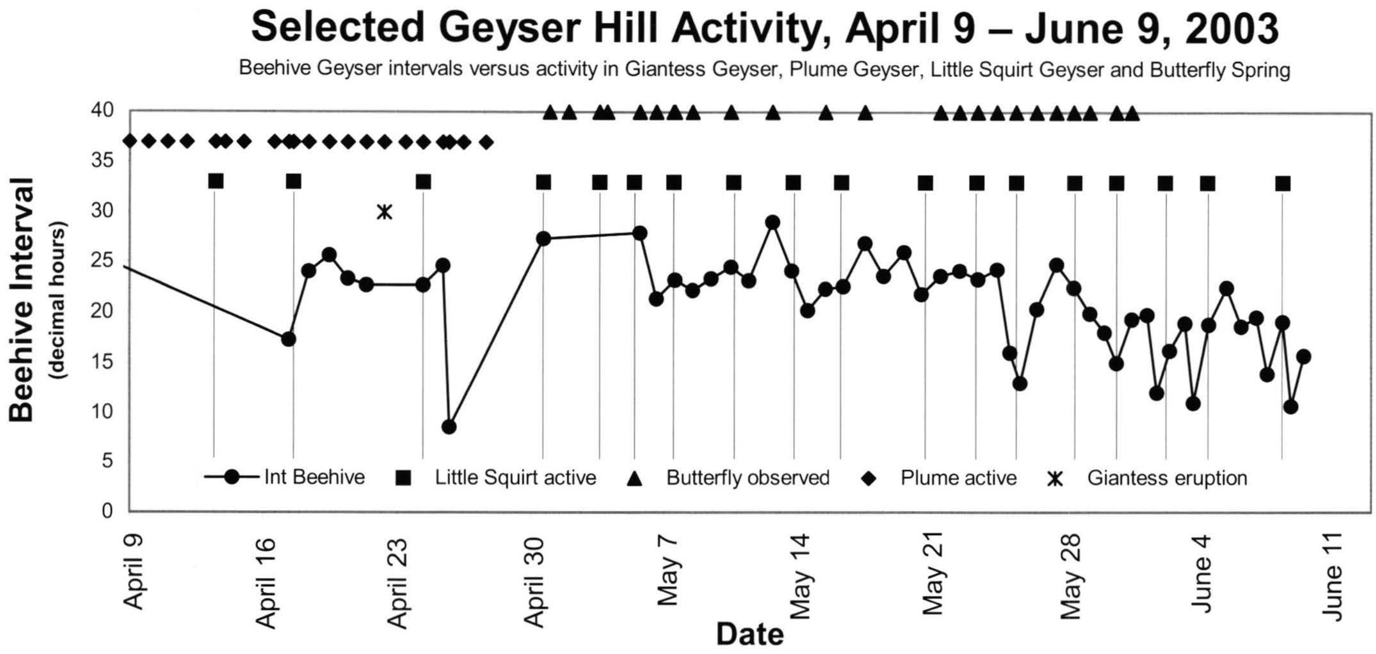
• **Plume Geyser** was active with intervals typically between 50 and 60 minutes, from the start of observations on April 9 until it began a dormancy on April 27. This active phase is plotted along the "37–hour" level of the chart. During the last two days before the dormancy, some intervals were substantially longer than normal, exceeding 120 minutes in some cases. The last eruption prior to the dormacy occurred at 15:54 on April 27. Plume resumed eruptions on June 19 (after the time frame of this report).

• **Butterfly Spring**, which in prior Park history had episodes of minor eruptions just 6 to 10 feet high observed only in the 1800s and 1936, began erupting on a major scale. The active phase started on May 1, less than three days after the beginning of dormancy in Plume Geyser. Some eruptions reached over 40 feet high, repeating with durations of 2 to 3 minutes at intervals of 4 to 9 hours (see photo next page). The last known major eruption occurred at 15:55 on May 31. This major episode is plotted on the "40–hour" line of the chart. Minor action continued throughout June, including after the reactivation of Plume Geyser.

• **Infant Geyser** (not plotted on the chart) generally stood at a higher water level during the major activity of Butterfly Spring. The level began to drop slightly as Butterfly grew less frequent near the end of its major activity.

• **Little Squirt Geyser** showed eruption (therefore, GHW) intervals of a "normal" 4 to 7 days through April, the longest interval being the first full interval following the April 22 eruption by Giantess Geyser. Thereafter and continuing through this reporting period, it had extraordinarily short intervals of only 2 to 4 days. Dates on which Little Squirt was observed are plotted on the "33–hour" level of the chart. At no previously observed time did the GHW exhibit such consistently short cycles. That this corresponded to the dormancy in Plume and the activity in Butterfly is "intriguing."

• **Beehive Geyser** is known to respond to the GHW by frequently having intervals much shorter than average at about the time of Little Squirt activity.



This pattern held true during this study, as shown on the chart. Each data point for Little Squirt has been appended with a dropline and, while it does not clearly show for all eruption intervals, Beehive indeed showed a tendency toward short intervals at or just after the start of Little Squirt. This correspondence was, admittedly, not as strong as seen in previous seasons. However, too, in those other years the GHW cycle was longer and Beehive then showed a clear need to "adjust" itself to the cycle's state.

On about May 30, Beehive's overall intervals became substantially shorter, the running average decreasing by perhaps 7 hours. That this change occurred just as Butterfly Spring was ending its major eruptions must be significant.

Analysis

Following the April 22 eruption by Giantess Geyser, Plume Geyser underwent a seemingly–normal "Giantess Effect" response, with shorter and then longer intervals. Somehow, it did not recover to more ordinary activity. Instead, it entered a dormant period that lasted 53 days. At about the same time, Butterfly Spring began unprecedented activity and Little Squirt Geyser/Geyser Hill Wave began a series of extraordinarily short intervals. Beehive Geyser responded to the GHW by often exhibiting short intervals near the time of GHW culmination (SMax), and it showed consistently shorter intervals when Butterfly ceased its major activity.

The causes of these changes are as unknown as before, but a summary analysis indicates that the Geyser Hill Wave remained active with effects similar to those previously observed.

Butterfly Spring, May 24, 2003. (Photo by Scott Bryan)

The Major Activity of Link Geyser in 2002

by Tara Cross

Abstract

Major eruptions by Link Geyser, the most significant geyser within the "Chain Lakes Complex" of springs, have generally been rare. This article provides a brief background history of Link, and describes its activity of 2002.

Introduction

Major eruptions of Link Geyser have always been rare. Link has had few active phases in the known history of Yellowstone National Park. Isolated major eruptions have taken place over the years, but these eruptions have been very infrequent and completely unpredictable. Eruption accounts uniformly describe Link's major activity as sudden, short, and impressive.

Link has historically had two different types of activity: In 1956, 1974, and 1983, Link had series of major eruptions, with several plays recurring on intervals of roughly 1 to 3 hours. The remainder of its known major activity has consisted of erratic, individual eruptions, even during more active years such as 1936, 1954, and 2002.

When Link is not in a series, its major eruptions occur with almost no warning. There is a sudden upwelling of water in Link's crater, followed by doming boils to 10 to 15 feet. Then violent jets of water push forcefully out of the crater, sending a massive wave of runoff across the broad sinter platform between Link and the old road. This wave has been known to sweep all the way across the asphalt bicycle trail (formerly the main road through the Upper Geyser Basin), picking up any loose debris in its path and ripping up chunks of algae from its runoff channel. The water then plunges into the Firehole River, causing it to flow muddy for at least several minutes after the eruption.

Between 1983 and 2002, there were only nine confirmed major eruptions of Link Geyser. The best year during that time was 1993, when Link had three known major eruptions. Reports indicate that there may have been one to three additional eruptions in October of 1993. There was a single eruption of Link in 1994 followed by a dormancy caused by an increase in temperature in the nearby Chain Lakes. During this time Link had no major or minor eruptions and did not even overflow. The dormancy ended with a major eruption in May of 1998. Then, after three years of nothing but minor eruptions, Link had two major eruptions in 2001. Twelve major eruptions followed in 2002, a total far exceeding any year since 1983.

Since at least 1926 and for a majority of its history, Link has had frequent minor eruptions. These eruptions have historically come 1 to 4 hours apart, lasted 5 minutes to an hour, and consisted of heavy boiling to 3 to 5 feet. These minor eruptions

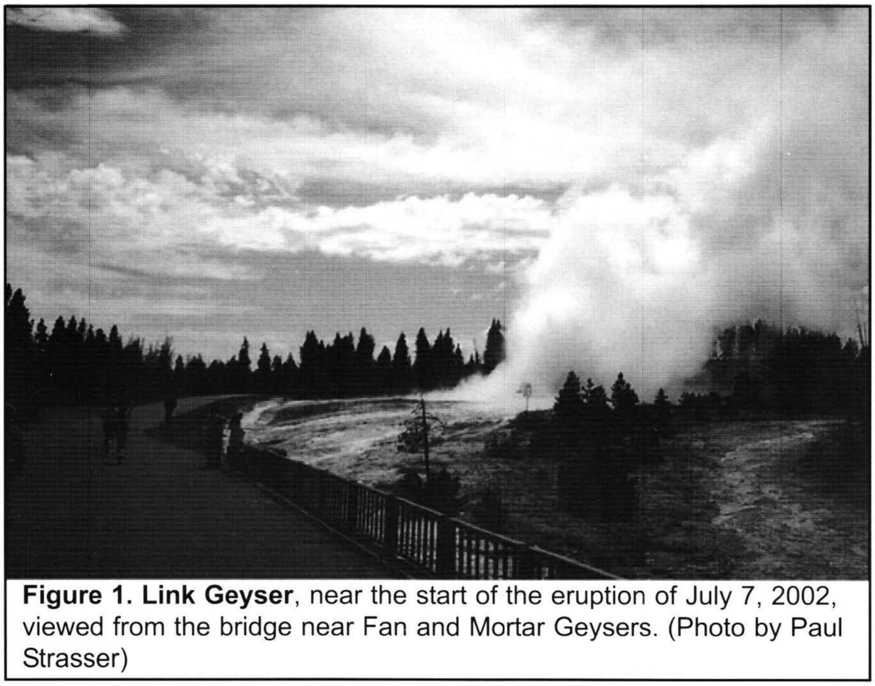


Figure 1. Link Geyser, near the start of the eruption of July 7, 2002, viewed from the bridge near Fan and Mortar Geysers. (Photo by Paul Strasser)

Table 1
Major Eruptions of Link Geyser in 2002

Date	Time	Interval	Comments
February 23	0920 v.r.		Visitor report confirmed by wash
April 26-27	overnight	~59½ days	Inferred by wash
May 14	1404	~17½ days	Seen by Steve Eide
June 16-17	overnight	~32½ days	Inferred by wash
June 28	1921	~11½ days	Seen by Lew and Jan Johns
July 6	~1730	~7d22h	Confirmed by empty crater and wash
July 7	1339	~20 hours	Seen by large group of geyser gazers
July 11	daytime	~4 days	Inferred by washed marker
July 14	daytime	~3 days	Inferred by washed marker
July 25	1602	~11 days	Seen by Mario Durrant
August 30	0008	35d8h06m	Seen by T. Cross and A. Bunning
September 6-7	overnight	~8 days	Inferred by washed marker

continued to occur between the major eruptions of Link in 2002.

Link Geyser was named for its important connection to the nearby Chain Lakes. At times in its history, an increase in their activity has caused a corresponding decrease in the temperature and activity of Link. On rare occasions, features in the Chain Lakes complex have erupted along with major eruptions of Link. In all observed cases during 2002 the water levels in the Chain Lakes rapidly dropped several feet immediately following a major eruption of Link. However, the Chain Lakes did not erupt at any time during 2002 and no other unusual behavior was observed.

The Major Activity of 2002

The first eruption in 2002 occurred on February 23. A visitor report of a Link major was confirmed by Interpretive staff at Old Faithful [Old Faithful Visitor Center logbook]. The eruption tore up a large amount of cyanobacteria and melted all of the snow in the area of Link [Lang, 2002]. After this, Link had only minor eruptions for over two months. However, geyser gazers noticed wash and large chunks of bacteria on the asphalt path near Link at about noon on April 27, indicating an eruption some time overnight. Link was already full and having minors, and the water levels in the Chain Lakes had recovered by that time [personal observation, April 27, 2002].

Link had its third major eruption on May 14 at 1404. This eruption was witnessed by geyser gazer Steve Eide, who was standing near Square Spring when the eruption started. He described the eruption as beginning with bursting to 10 to 15 feet before rapidly building to about 60 feet high. The column was obscured by steam for most of the duration, estimated at less than one minute. The eruption appeared to have occurred without any preplay [Goldberg, 2002].

On June 17, geyser gazers noticed wash and disturbed bacteria at Link, indicating another eruption overnight June 16–17 [personal observation, June 17, 2002].

A major eruption of Link was seen on June 28 at 1921 by Lew and Jan Johns, who had stopped to look at Fan and Mortar Geysers. Jan noted that Link was not overflowing when she passed by, but it was boiling around the edges of its pool. A few minutes later as Lew crossed the Firehole River bridge, he saw a huge steam cloud and realized that Link was having a major eruption. Both Lew and Jan watched as a wave of muddy water poured into the runoff channel and a massive steam cloud blew in their direction. When they emerged from the steam cloud, they estimated the height at 35 to 40 feet. The eruption came as such a surprise that neither was able to determine the duration, but in keeping with virtually all reports of Link majors, it was short [Johns and Johns, 2002].

There were many geyser gazers in the Upper Geyser Basin on July 6, but somehow they all missed the steam cloud from Link's major eruption. When gazers came past Link in the evening, they found that the marker was washed and Link's crater was still empty. Based on when the crater refilled[1] and the times when it was known that no one was in the immediate vicinity of Link, the time of the eruption was estimated at about 1730 [personal observation, July 6, 2002].

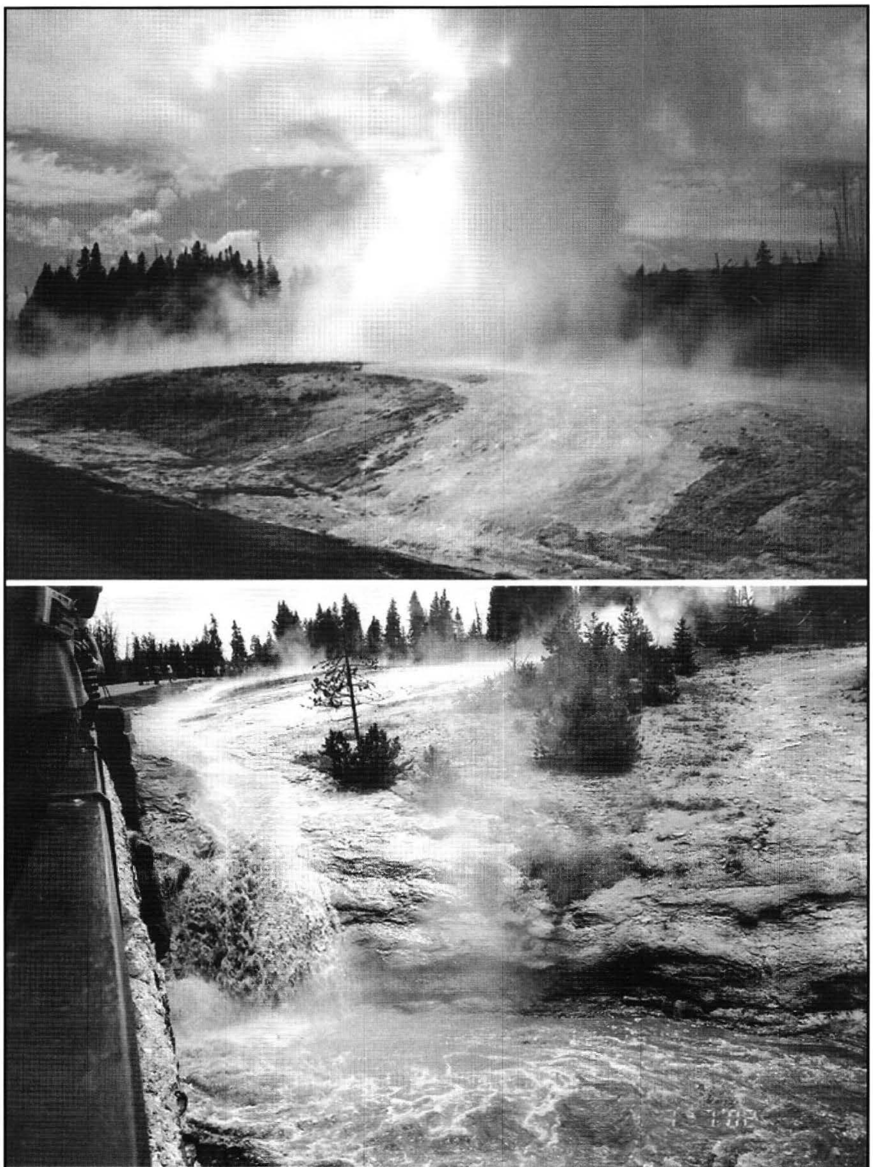


Figure 2. Link Geyser, July 7, 2002.
Figure 2a (top). A closer view of Link Geyser, showing a portion of the heavy runoff it produces. (Photo by Paul Strasser)
Figure 2b (bottom). The runoff, pouring into the Firehole River adjacent to the bridge near Fan and Mortar Geysers. (Photo by Kit Barger)

A large group of geyser gazers was waiting at Fan and Mortar when Link had a major eruption at 1339 on July 7. The eruption occurred on an interval of approximately 20 hours, by far the shortest since 1983. The eruption began with boiling to about 10 feet and then built into bursting which grew from 20 to 30 feet within seconds. The highest bursts were estimated at about 45 feet. The eruption consisted of violently thrashing muddy water. As the eruption reached peak height, a 3–inch wave of water swept across the wide sinter platform leading to Link's runoff channel, carrying algae chunks, gravel, and sinter debris with it. The duration of the eruption was estimated at about 100 seconds. After the eruption ended a chugging sound could be heard within the vent though nothing could be seen from the trail [personal observation, July 7, 2002].

Major eruptions of Link also occurred in the daytime on July 11 and again on July 14 [Old Faithful Visitor Center logbook]. Neither of these eruptions was seen, but were inferred by washed markers. In both cases, Link was checked in the evening and was already having minor eruptions again. Minor eruptions typically resumed about 5 to 6 hours after a major eruption of Link. During July, minors came in pairs with intervals of about 35 minutes separated by 3 hour intervals [Goldberg, 2002]. Unfortunately, no observations connecting Link's minor and major activity were made.

Geyser gazer Mario Durrant witnessed Link in eruption on July 25 at 1602. Mario had been watching Riverside erupt when he felt warm spray land-

[1] Other observations in 2002 indicated that Link took about 2 hours to refill after a major eruption.

ing on him and turned around to see a huge steam cloud in the direction of Link. Mario quickly abandoned Riverside and ran towards Link, arriving just as the eruption was ending. Muddy water spilled out of the runoff channel and onto the paved trail, and the entire area was wet from spray. The duration was estimated as a little over a minute [Durrant, 2002].

The author was fortunate enough to witness the next eruption, which took place at 0008 on August 30. I was standing on the bridge facing Riverside Geyser when I heard what I thought was wind rushing through the trees. A few moments later I realized that there was no wind and turned around to see that the noise had actually been water flooding across Link's platform.

In the very pale moonlight I could see that the steam cloud had suddenly grown and was spreading out as the runoff poured across the platform. I could hear the sound of roiling water coming from Link, but it was almost covered by the sound of rushing water from the runoff. Then the steam cloud quickly grew and I could hear water bursting and jetting from Link. It was impossible to tell how high the bursts were, but based on the steam cloud and very limited visibility, it was at least 30 feet tall. After this, a second, larger wave swept across the platform and plunged into the gutter. The runoff had the sound of a swift mountain stream and created a small waterfall that crashed into the Firehole River.

Though I did not catch the very beginning of the eruption, the duration seemed comparable to the eruption I witnessed on July 7, 2002, which was approximately 100 seconds. Once the bursting had subsided, water could be heard churning within Link's crater for about 15 minutes after the eruption. The Firehole River flowed muddy from the runoff for about 15 minutes following the eruption [personal observation, August 30, 2002].

The final eruption of 2002 occurred overnight September 6–7 and was inferred by a washed marker [personal observation, September 7, 2002]. This ended a fine year for Link during which many people had an opportunity to see this rare geyser.

Acknowledgments

Thank you to Mike Lang, Steve Eide, David Goldberg, Mary Beth Schwarz, Jan and Lew Johns and Mario Durrant for sharing information about Link, to Paul Strasser and Kit Barger for the use of their photos, and to Lee Whittlesey, Rocco Paperiello, Nancy Cross and Carlton Cross for offering helpful editorial suggestions on this article.

References

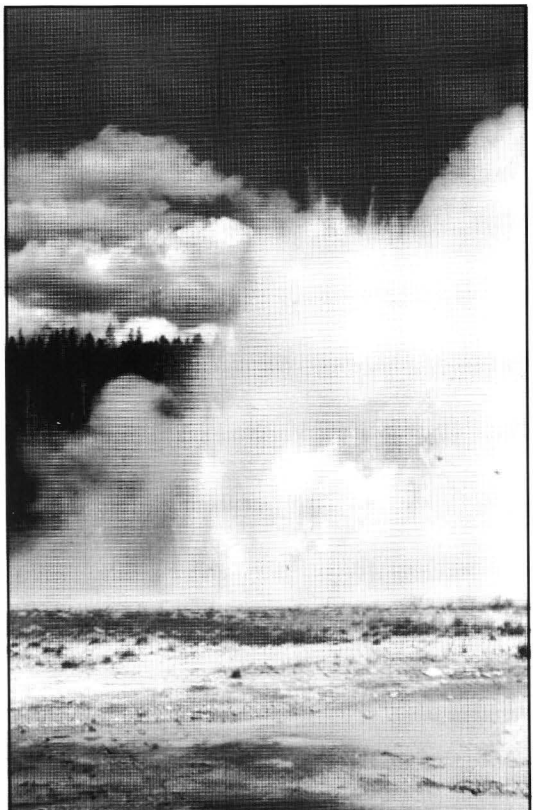
Durrant, Mario, 2002, Unpublished geyser report, in Box K-130, YNP Archives.

Goldberg, David, 2002, "Spring 2002 Geyser Activity," The Geyser Gazer Sput, v. 16, no. 3, p. 23.

Goldberg, David, 2002, "Late Summer 2002 Geyser Activity," The Geyser Gazer Sput, v. 16, no. 5, p. 18.

Johns, Jan and Johns, Lew, 2002, Unpublished geyser report, in Box K-130, YNP Archives.

Lang, Michael, 2002, Unpublished geyser report, in Box K-130, YNP Archives.



Link Geyser, August 29, 1974. On that single day, Link underwent a series of seven (possibly eight) major eruptions, at observed intervals ranging from 87 to 186 minutes. This photo shows the eruption that took place at 11:32 that morning. (Photo by Scott Bryan)

Fan and Mortar Geysers in the Summer of 2002, April 20 to November 3

by Tara Cross

Abstract

During 2002, Fan and Mortar Geysers erupted at intervals ranging from about 2.5 days to about 10 days. Cyclical minor activity between major eruptions was studied in an attempt to better predict eruptions. These observations showed some new behavior, while the basic pattern of activity remained consistent with that seen in previous years.

Introduction

After highly erratic behavior in the spring and early summer of 2001, Fan and Mortar settled into more regular intervals in the fall and winter. Intervals remained steady for the early months of 2002. When the park opened in April, however, observers found that Fan and Mortar had become more irregular. As the season progressed, Fan and Mortar settled into a pattern of behavior that allowed observers to see 32 of the 44 eruptions that took place while the park was open. This article details these behavior patterns and discusses the major differences in activity between 2001 and 2002.

The vents of Fan and Mortar

The vents of Fan: In order south to north: River, High, Gold, Angle, Main, and East. The vents of Mortar: Upper Mortar, Lower Mortar, Bottom Vent[1], Frying Pan.

River, High, Gold, and Angle comprise the "minor vents."

Main Vent, East Vent, and Lower Mortar comprise the "main system."

Other vents within the complex are Back Vent, Crack Vent, Beach Springs, Tile Vent, Spiteful Geyser, Norris Pool, Backwater Spring.

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

[1] Bottom Vent has also been called "Arch Vent" by some observers in year past.

Changes in the vents of the Fan and Mortar complex

For the most part, the morphology of Fan and Mortar's vents did not change between 2001 and 2002. However, there were several notable developments.

Bottom Vent greatly increased the size of its vent and eruptions over the winter of 2001–2002. During this time the sinter around the vent opened up several inches wider and the height of its eruptions increased to 5 to 10 feet.

A small complex of vents associated with Frying Pan were first seen in 1999 and informally named "Back Vent." By 2002, these vents were lined with sinter and erupted high enough that droplets of water could be seen erupting from behind Lower Mortar's formation.

As in previous years, the Fan and Mortar complex continued to suffer from erosion, especially in the areas around Main Vent, East Vent, and Upper and Lower Mortar.

Related features

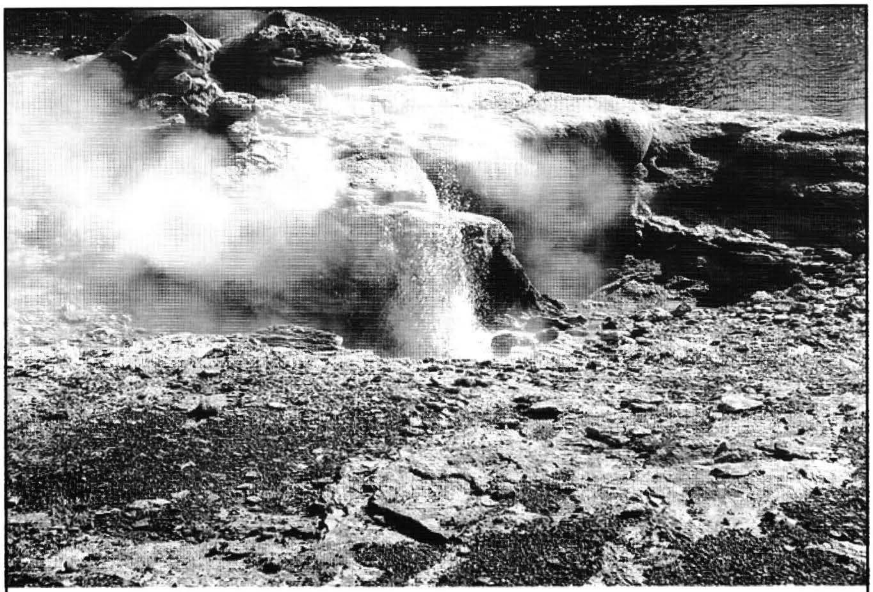
No major changes were observed in the nearby features related to Fan and Mortar in 2002. Spiteful Geyser remained dormant and sometimes dropped slightly after a major eruption of Fan and Mortar. Norris Pool had no known eruptions in 2002 but continued to show its connection to Fan and Mortar by rising several inches and boiling vigorously during their major eruptions. Backwater Spring continued to be nothing more than a tepid depression.

Some have theorized that there may be a connection between the Fan and Mortar complex and Link Geyser, located to the south across the Firehole River. During most of its known history, Link has had only minor eruptions consisting of heavy boiling 3 to 5 feet high. However, on rare occasions Link has had major eruptions that start

Table 1
List of Major Eruptions
Fan and Mortar Geysers
April 20 to November 3, 2002

Date	Time	Interval
April 20	1220	~6d17h50m
April 25	1607	5d3h47m
May 5	1345	9d21h38m
May 12	0305E	~6d13h20m
May 14	1520	~2d12h15m
May 20	0953	5d18h33m
May 25	0353E	~4d18h00m
May 28	1258	~3d9h05m
June 1	1216	3d23h18m
June 5	0656	3d18h40m
June 10	2217E	~5d15h21m
June 15	~0400	~4d6h
June 19	1704	~4d13h
June 25	2253	6d5h49m
June 30	1607	4d17h14m
July 4	1411	3d22h04m
July 9	1358	4d23h47m
July 13	1104	3d21h06m
July 16	2320	3d12h16m
July 20	1259	3d13h39m
July 23	1615	3d3h16m
July 27	1403	3d21h48m
August 1	1737	5d3h34m
August 5	1139	3d18h02m
August 9	1835	4d6h56m
August 14	1518	4d20h43m
August 17	0918	2d18h00m
August 21	1247	4d3h29m
August 26	1438	5d1h51m
August 31	2121	5d6h43m
September 7	1510	6d17h49m
September 10	1334	2d22h24m
September 16	0916	5d19h42m
September 21	0116	4d16h00m
September 26	0432	5d3h16m
September 28-29	overnight	~3¾d
October 5	1114	~5½d
October 10	overnight	~4 2/3d
October 16	0751	~6¼d
October 19	1334	3d5h43m
October 22	evening	~3¼d
October 25	b. 2100-0000	~3d
October 28-29	b. 1900-0300	~3d
November 1	b. 0100-0500	~3d

with virtually no warning, last 50 to 100 seconds, and reach heights of anywhere from 30 to 100 feet. During the summer of 2002, Link had 11 major eruptions between April and September, by far its best activity since 1983.[2] Intervals varied greatly, from about 20 hours to 35 days. While speculation about Link's connection to Fan and Mortar continued, no evidence of an obvious connection was found.



Bottom Vent in solo eruption, May 2002. (Photo by Tara Cross)

Definitions of terms used in this article

Minor cycles are typically timed from the start of River Vent's minor eruption to the start of the next River Vent. In 2002, Gold Vent followed the start of River, usually within 5 minutes, but could delay as much as 15 minutes. Angle usually followed 0 to 15 minutes after Gold, but could sometimes erupt continuously even in the time that River Vent was off. If Frying Pan was active during a cycle, it normally followed Angle, though in 2002 Frying Pan sometimes preceded Angle. After 10 to 40 minutes, all the vents shut off and a period of quiet followed. Cycle lengths in 2002 ranged from as short as 5 minutes to as long as 100 minutes.

A *pause* occurs when the minor vents of Fan shut off before Angle comes on. If only River comes on and then shuts off, this is called a River pause. If River, High and Gold come on and then all three shut off it is called a Gold pause. If Angle comes on, it is not a pause but a complete cycle.

When two pauses occur consecutively without a full minor cycle being completed, this is referred to as a *double pause*. When three pauses occur consecutively without a full minor cycle being completed, this is a *triple pause*.

Sometimes River Vent sputters on weakly and then shuts off within 3 minutes. This activity is referred to a *cough*. Occasionally High, Gold, or even Angle can have a few small spits during a cough. Coughs are not true pauses or true cycles, though in 2002 they were sometimes the first indication of rising water levels in Main Vent.

In 2002, it became more difficult to distinguish between Bottom Vent splashing and *Bottom Vent eruptions*. Typically, observers recorded Bottom Vent eruptions when the splashing was continuous and the water level reached overflow. Bottom Vent eruptions usually occurred during pauses or times of high water levels in Main Vent between cycles. More commonly, Bottom Vent would have periodic splashing at these times. Bottom Vent eruptions ranged in duration from 10 seconds to over 13 minutes.

A *Lower Mortar minor* occurs when periodic splashing in Lower Mortar builds into a sustained eruption and the water level in the vent rises to overflow. In 2001 and 2002, Lower Mortar minors were most typical when water levels are high in the "main system." Lower Mortar minors frequently started while a Bottom Vent eruption was already in progress.

Cycles that included pauses, Main Vent splashing, Bottom Vent eruptions, or Lower Mortar minors were colloquially referred to as *event cycles* in 2001 and 2002.

Until 2001, eruptions typically started from *classic lock*, behavior characterized by strong, con-

[2] Discussion of Link Geyser's historical and 2002 activity is described in another paper within this volume of *The Transactions*.

tinuous jetting in High, Gold, and typically Angle. In 2002, at least 14 eruptions were triggered from this activity. However, High Vent was sometimes the only vent that had continuous jetting during this pre-eruptive behavior.

In 2002, 18 observed eruptions began with a series of Upper Mortar surges that built in strength until a sustained surge to 5 to 15 feet triggered the eruption. These eruptions were *Upper Mortar initiated.* Upper Mortar surging typically began 10 to 20 minutes after the start of River Vent and gradually became stronger until one voluminous surge led to the start of a major eruption.

Changes in behavior in 2002

Strong cycle events: During most of 2002, the best indication of a strong cycle was splashing in Main Vent. From June 25 to November 3, no observed eruption took place without preliminary Main Vent splashing. Main Vent splashing could start anywhere from 45 to 100 minutes before the start of a major eruption, either during a pause, after a cough, or during the quiet period between eruptions. Sometimes Main Vent splashing began with a large splash and other times it began weakly and built to stronger splashes. Eruptions could result either way, but the best sign was consistent or even constant splashing over a period of 10 to 25 minutes.

In 2001, all eruptions were preceded by at least one Bottom Vent eruption, the maximum number during an eruption cycle being five. In 2002, strong cycles included anywhere from zero to eleven Bottom Vent eruptions; eruption cycles had anywhere from zero to nine. Lower Mortar minors typically occurred during pauses as in 2001. They could occur 20 to 80 minutes before major eruptions. Durations of Lower Mortar minors ranged from 20 seconds to 2m50s.

Variations on pauses: In 2001, only one known eruption was not preceded by a pause or cough. In 2002, pauses occurred in 21 of 25 observed eruption cycles. There were seven single River pauses with durations of 8 to 22 minutes, two single Gold pauses with durations of 63 and 66 minutes, eleven double pause cycles with pause lengths ranging from 1 to 30 minutes,[3] and one triple pause. However, any cycle that included Main Vent splashing and other evidences of high water levels in the "main system" could lead to an eruption.

Double pauses were a common occurrence in the 1990s. In 2001, they occurred on only 3 known occasions. In 2002, double pauses were seen frequently, and could occur in any strong cycle, not just eruption cycles. There were five known triple pauses observed in 2002 and there may have been others that were not observed. However, only one of the observed triple pause cycles led to a major eruption.

Eruption cycles: Eruption cycles could frequently be distinguished from other event cycles by water levels in the minor vents after the start of Frying Pan. If the water levels in the minor vents did not drop within 9 to 10 minutes after Frying Pan, Fan and Mortar were almost certain to erupt.[4] This was not, however, a requirement. A small number of eruptions took place during cycles with low water levels in the minor vents.

In the 1980s, a late Gold Vent start was considered a good sign for a possible eruption [Day, 1989]. In 2001, it was unusual for Gold Vent to delay more than 5 minutes after the start of River. In 2002, this happened more frequently, especially when there had been Main Vent splashing in the cycle. On several occasions, a late Gold Vent start led to a major eruption, but it was by no means a guarantee.

Classic lock: In 2002, classic lock was not so classic. In contrast to the behaviors typically seen in the 1980s and 1990s, classic lock was characterized by very strong activity from High Vent. On several occasions High Vent was the only vent that participated in classic lock, though Gold and Angle typically joined in at some point before the erup-

[3] In five known cycles with double pauses, the second pause was very short with a duration of 1 to 3 minutes. These were definitely pauses but they were not long enough to lead to any other events.

[4] This held true, with only one known exception, for the entire season from April to October.

Fan's "High Vent" in lock, July 23, 2002. During the 1990s and earlier, a "classic lock" involved continuous jetting from High *plus* Gold and Angle Vents. In 2002, as shown here, it was only High Vent that jetted continuously while Gold and Angle tended to exhibit and 'on again–off again' behavior. (Photo by Stacey Glasser)

Start types: In 2001, 17 out of 21 of observed eruptions were initiated by Upper Mortar surging. Three eruptions began during Lower Mortar minors, and a single eruption started from a classic lock. In 2002, that ratio changed dramatically. Upper Mortar surging initiated 18 eruptions and 14 eruptions started during a classic lock. No eruptions were seen starting during a Lower Mortar minor in 2002.

Classic lock changed in 2002, and so did eruptions starting from classic lock. In the 1980s and 1990s it was unusual to see any activity from Upper Mortar before or during a classic lock except for occasional small water droplets. In 2002, classic lock was usually accompanied by Upper Mortar surging. Sometimes this surging was weaker than normal pre-eruptive surging, but occasionally there was no difference between the Upper Mortar surging seen during a classic lock and that seen during an Upper Mortar initiated eruption.

On several occasions it was observed that the minor vents were in a classic lock and then returned to normal splashing before the eruption began with Upper Mortar surging. Because of this new behavior, it became increasingly difficult to distinguish between Upper Mortar starts and classic lock starts. This article based the distinction on whether the minor vents were in classic lock when East Vent, Main Vent, or Lower Mortar signaled the start of the major eruption. If the minor vents were not in classic lock when the eruption started and the eruption was triggered by a large Upper Mortar surge instead, it was considered an Upper Mortar initiated start.

tion started. Sometimes Gold and Angle would rise and fall while High Vent was in a classic lock. Whether the other vents participated or not, High Vent would frequently be the strongest of the three vents, erupting to 15 to 20 feet at times.

In 2002, a classic lock started 1 to 7 minutes before the commencement of a major eruption. On five occasions, the minor vents went into a classic lock and then dropped back to normal splashing. This usually lasted 1 to 2 minutes and took place 4 to 7 minutes before the start of the eruption.[5] As with a normal classic lock, this behavior was seen only during eruption cycles. Sometimes the vents waxed and waned in a "see-saw" effect with Upper Mortar surging. However, the vents were not seen to go into any form of classic lock without an eruption following. If the vents did not stay in classic lock, the eruption would be triggered a few minutes later by Upper Mortar (and considered an Upper Mortar start).

There was a greater variance in the time from the start of River to the start of an eruption in 2002. In 2001, the range of 15 known cases was 21 to 32 minutes (all Upper Mortar starts). In 2002, the range for Upper Mortar starts was a similar 23 to

[5] In one exceptional instance, on June 19, High Vent was in "lock" by itself for 90 seconds a full 11 minutes before the major eruption was triggered by Upper Mortar.

Table 2

Fan and Mortar Eruption Cycle Chart

April 20 – October 19, 2002*

Date	Time	Pause? (time on-off)	Bottom?	Lower Mortar minor?	Start Type**	River to start	Observer
4/20	1220	none	none	none	lock	42m	T. Cross
4/25	1607	River (7-8)	none	none	lock	36m	D. Goldberg
5/5	1345	?	none	none	lock	>29m	S. Strasser
5/14	1520	?	none	none	lock	?	Sally Johnson
5/20	0953	?	?	?	UM	?	visitor report
6/1	1216	Gold (8-34), River (8-3)	yes (d=13m27s)	yes (d=30s)	lock	26m	T. Cross
6/5	0656	?	?	?	lock	?	M. Goldberg
6/19	1704	none	none	none	UM	35m	D. Goldberg
6/25	2253	none	yes – 5	none	lock	21m	A. Bunning
6/30	1607	Gold (9-66)	yes – 9	yes (d=2m50s)	UM	24m	T. Cross
7/4	1411	River (11-16), River (8-17)	yes – 3	yes (d=20s, 25s)	lock	23m	T. Cross
7/9	1358	Gold (13-20), River (6-36)	yes – 4	yes (d=2m12s)	lock	17m	A. Bunning
7/13	1104	none	yes – 1	yes (d=1m45s)	UM	31m	T. Cross
7/16	2320	Gold (10-63)	yes – 6	yes (d=32s)	UM	26m	A. Bunning
7/20	1259	River (7-23), River (8-9)	yes – 3	yes (d=45s)	lock	25m	T. Cross
7/23	1615	River (11-15)	yes – 2	yes (d=22s, 20s)	lock	27m	A. Bunning
7/27	1403	River (8-17)	yes – 3	none	UM	27m	T. Cross
8/1	1737	River (10-8), River (11-1)	none	none	UM	28m	A. Bunning
8/5	1139	River (7-8), River (7-30)	yes – 4	yes (d=35s, 24s, 1m55s, 45s)	UM	27m	T. Cross
8/9	1835	River (8-13), River (8-2)	yes – 3	none	lock/UM	20m	S. Strasser
8/14	1518	River (10-7), River (8-2)	yes (d=3m15s)	yes (d=25s)	UM	26m	L. Stephens
8/17	0918	?	yes - 1	yes - 2	UM	?	J. Buttars
8/21	1247	River (11-10)	yes (d=2m28s)	yes (d=30s)	UM	27m	M.B. Schwarz
8/26	1438	River (7-8)	yes (d=25s)	yes (d=20s)	UM	28m	T. Cross
8/31	2121	River (10-22)	yes - 3	yes (d=1m25s, 1m27s, 27s)	lock	22m	T. Cross
9/7	1510	G (9-17), R (8-6), R (9-16)	yes - 3	yes (d=1m30s)	lock	20m	T. Cross
9/10	1334	?	?	yes - at least one	UM	23m	T. Cross
9/16	0916	River (10-17), River (11-2)	yes (d=45s)	yes (d=33s)	UM	26m	L. Stephens
9/21	0116	?	possibly	possibly	UM	?	D. Leeking
9/26	0432	Gold, River	yes – 2	yes (d~1m45s)	UM	?	D. Leeking
10/5	1114	River (9-9)	yes (d=10s)	yes (d=30s)	UM	26m	T. Cross
10/19	1334	River, River	yes (d~2m30s)	yes (d~1m)	lock	27m	K. Barger

* Chart includes only eruptions where information about the eruption cycle was available. Thank you to David Goldberg, Michael Goldberg, Sally Johnson, Andrew Bunning, Mary Beth Schwarz, Suzanne Strasser, Joe Buttars, Lynn Stephens, David Leeking, and Kitt Barger for providing information.

** UM – Upper Mortar; "lock" – classic lock.

Fan Geyser's Main and East Vents at the moment the eruption of July 23, 2002 began. (Photo by Stacey Glasser)

35 minutes, but the range for classic lock starts was 17 to 42 minutes. However, classic lock starts typically came 20 to 27 minutes after River (see Table 2).

Intervals: In 2001 some major differences between intervals in the 2 to 5 day range and intervals longer than 5 days were observed. The former were termed "short mode" intervals and the latter "long mode." This distinction was not as apparent in 2002. Rather, observers noted four distinct phases of activity between April 20 and November 3. These will be described below.

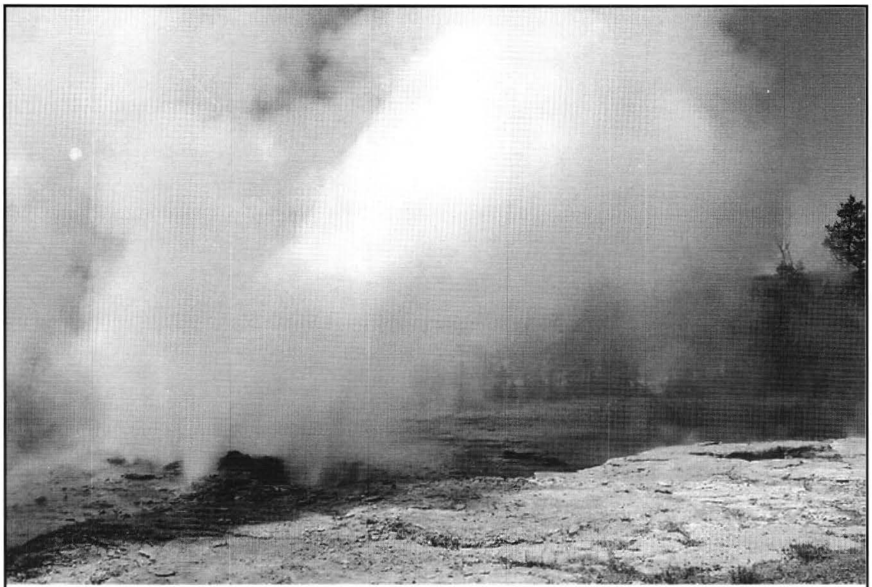
Patterns in Fan and Mortar's activity

April 20–June 25 (13 eruptions)

From sometime in early April until June 25, Fan and Mortar had very inconsistent intervals ranging from 2.5 days to 10 days. Fan and Mortar have had an annual "spring slowdown" in most years going back to the 1980s, so it was not surprising that typical intervals during April, May, and June were usually in the 5 to 7 day range. However, in late May and early June Fan and Mortar seemed to come out of "spring mode" briefly: 3 consecutive intervals ranged between 3 and 4 days.

Compared with activity seen in 2001, there were several notable differences in behavior during this time period. Minor cycles tended to be longer than they had been in 2001, with many in the 60 to 90 minute range. Main Vent could often be seen steaming in the off period while River Vent was not erupting. In 2001, this kind of activity would have been considered an encouraging sign, but in the spring of 2002 it was common to see this for hours with no eruption. Though cycles were longer, the complex was seldom quiet for longer than 20 to 25 minutes. Many disorganized "garbage cycles" occurred during this time, with shorter cycle lengths and continuous activity by Angle Vent. However, Frying Pan usually turned off between cycles.

Event cycles, including pauses, Main Vent splashing, Bottom Vent eruptions, and, rarely, Lower Mortar minors, were seen during spring mode. However, these were less plentiful than they would become later in the summer and rarely led to eruptions. Bottom Vent eruptions were uncommon before mid–May, when they rather abruptly began to happen frequently. Unlike Bottom Vent eruptions seen in 2001, the activity in May and June of 2002 was characterized by long–duration eruptions, lasting from 2 minutes to over 13 minutes. In April and early May, the only Lower Mortar minors seen or inferred occurred while Fan and Mortar were in "recovery mode" after major eruptions. By late May, a few Lower Mortar minors were seen, but they did not become common until after Fan and Mortar came out of spring mode at the end of June.



Fan Geyser in eruption on September 10, 2002. (Photo by Tara Cross)

Of the eight eruptions witnessed, there were only four occasions where Fan and Mortar were observed for any length of time before the start, so very little is known about pre–eruptive behavior between April 20 and June 25. In 3 of 4 observed cases, however, eruptions came with very little warning. Rather than having eruption attempts following strong event cycles as seen in 2001, Fan and Mortar erupted without any Bottom Vent eruptions or Lower Mortar minors in the spring of 2002. It appeared that Fan and Mortar could erupt on any cycle of respectable length. The key for observers was to watch carefully when Frying Pan started. During normal cycles, water levels in the minor vents would drop within a minute or two after the start of Frying Pan. However, in the three cycles that were observed, the water levels stayed up after Frying Pan, and the minor vents continued to build in strength until High Vent or all three of the minor vents went into classic lock.[6]

During this time period eight eruptions were seen from the start; of these, six eruptions started from classic lock, and two were initiated by Upper Mortar surging. This was a change from 2001, when only one eruption started from classic lock.

[6] The fourth eruption occurred on June 1 and was different from the other three in that there was a double pause cycle including a long–duration Bottom Vent eruption and a Lower Mortar minor leading up to the eruption.

June 25–August 14 (13 eruptions)

From June 25 until August 14 Fan and Mortar were extremely consistent, with intervals ranging from just over 3 days to just over 5 days. Because of this consistency and because all but two eruptions during that span were in daylight hours, every single eruption was seen by a knowledgeable observer. Therefore a great deal is known about pre-eruptive behavior during this phase of activity.

Minor activity was very consistent during this time. All eruptions were preceded by at least one "event" and splashing in Main Vent. Event cycles were frequent, occurring every 4 to 24 hours. Between event cycles, it was not uncommon to see clusters of weaker cycles with short cycle lengths and constant activity from Angle Vent. However, this did not mean that it would be a long time before a major eruption could occur. Minor activity could revert from weak cycles to a strong cycle with no warning. Observers carefully watched Main Vent. If Main Vent began to have visible splashes, a strong cycle with "events" usually followed.

Though minor activity was consistent during this time, pre–eruptive events were varied. The number of Bottom Vent eruptions ranged from zero to nine. There could be from zero to four Lower Mortar minors. Double pause cycles were most common, but two eruptions took place with no pause. There were also two eruptions that came from extremely long Gold pauses. These pauses were 63 and 66 minutes and were more than twice as long as any other pre-eruptive pause seen in 2002.

There was no predominant start type between June 25 and August 14; six eruptions started from classic lock and six with Upper Mortar surging. However, one eruption defied classification. Observers were left in a quandary after the major eruption on August 9. Fan's minor vents had achieved classic lock several times, going up and down with a series of Upper Mortar surging. Immediately before the eruption, there was an eruptive surge from Upper Mortar and the minor vents dropped out of lock just before East Vent began erupting. Most experienced observers present classified this eruption as an Upper Mortar start, but an argument could also be made that it started from a classic lock.

August 14–October 16 (13 eruptions)

From August 14 until October 16, Fan and Mortar reverted back to more erratic intervals that ranged from 2d18h to 6d18h. In contrast to the activity from June 25–August 14, only two intervals fell between 3 and 5 days. During this time, starts from Upper Mortar surging became more prevalent, observed 8 times out of 10 eruptions.

While minor activity leading to eruptions became more variable, eruption cycles were still distinguished by pauses, Main Vent splashing, Bottom Vent eruptions, and Lower Mortar minors. In fact, no eruption during this period was known to have occurred without at least one pause, at least one Bottom Vent eruption, and at least one Lower Mortar minor. Main Vent splashing continued to be the most important indication of energy in the Main system.

While double pauses were most common in early August, there was more variety between August 17 and October 16, with single River pauses being the most common. During this phase Fan and Mortar had its first observed eruption from a triple pause cycle since the mid–1990s. The eruption took place on September 7 and the eruption cycle was the first event cycle seen or inferred in 36 hours. Also notable was the fact that this eruption closed the longest interval since May: 6d17h49m.

Mortar Geyser, September 10, 2002. (Photo by Tara Cross)

October 16–November 3 (5 eruptions)

From October 16 to November 3, Fan and Mortar returned to consistently short intervals. In fact, all 5 intervals fell within an 18–hour window. Unfortunately for observers, four out of five eruptions occurred overnight, and nothing is known about the minor activity preceding the eruptions that were missed. In the single case where the eruption was observed, Fan and Mortar's activity remained consistent with that seen for most of the summer, with "events" preceding the eruption. The eruption started from classic lock accompanied by Upper Mortar surging. Event cycles remained frequent during this time but generally only one or two such cycles occurred before an eruption took place due to short intervals.

Recovery cycles

In 2001 and again in 2002, it was observed that after each major eruption of Fan and Mortar, the complex would go through what was called "recovery mode." For the first 6 to 8 hours after an eruption, the entire complex was quiet with no activity by the minor vents. After this, River Vent would begin to cycle weakly. These cycles progressed into stronger cycles 8 to 10 hours after eruptions. Recovery cycles could include pauses, Main Vent splashing, Bottom Vent eruptions, and Lower Mortar minors. In many ways, "recovery mode" resembled the activity seen during strong cycles later on in the interval. However, water levels were not as high in Fan's vents, and Fan and Mortar were never known to erupt from a recovery cycle.

Intervals

Intervals from April 20 to November 3, 2002 ranged from ~2d12h15m to 9d21h38m. The latter interval was the longest of the annual "spring slowdown." By far the greatest number of intervals fell in the 3 to 5 day range. Though Fan and Mortar were most consistent in July and August, 75% of intervals fell in a 48–hour window, giving Fan and Mortar its most consistent year of activity since 1997.

Conclusion

While some of the behaviors observed in 2002 were different from previous years, Fan and Mortar continued to follow many of the patterns established in 2001 and before. The frequency and regularity of eruptions in 2002 offered the best opportunity for observations in a decade. Because of the remarkably consistent patterns of behavior between late June and mid September, 23 consecutive eruptions were observed from the start by knowledgeable observers. This allowed the author and others to carefully monitor the geysers' behavior and learn more about its major and minor activity.

Acknowledgements

The primary intent of this article is to update the activity of Fan and Mortar Geysers through the 2002 summer season. For background information beyond this treatment see the various *GOSA Transactions* articles by Cross [2002], Day [1989], Schwarz [1989], Strasser [1989] and Strasser [1993].

I could not have compiled the information in this article without the help of the many geyser gazers I spent time with at Fan and Mortar. Many thanks to all the contributors listed in Table 2, especially Lynn Stephens and Andrew Bunning. Special thanks to Stacey Glasser for the use of her photos and Jens Day for the electronic data logger information. I am also indebted to the editorial readers whose suggestions and insight were invaluable.

References

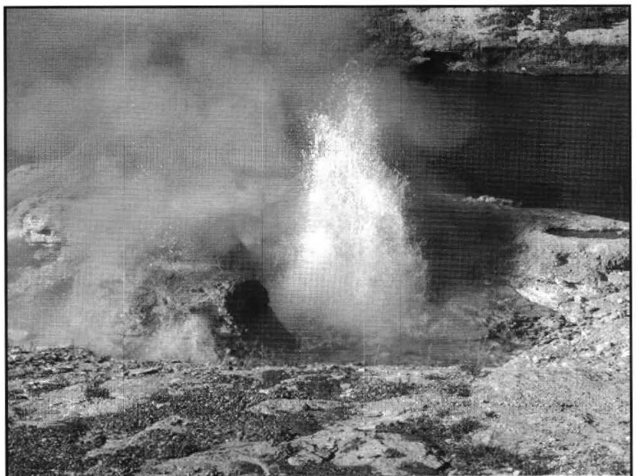
Cross, Tara, 2002, "Fan and Mortar Geysers in the Summer of 2001 — May 24 to November 4," *The GOSA Transactions*, Volume VII.

Day, Jens, 1989, "Fan and Mortar Geysers in 1988," *The GOSA Transactions* Volume I.

Schwarz, David, 1993, "Fan and Mortar Geysers in the Summers of 1991 and 1992," *The GOSA Transactions*, Volume IV.

Strasser, Paul, 1989, "Fan and Mortar Geysers," *The GOSA Transactions*, Volume I.

Strasser, Paul, 1993, "Why Mortar if Fan," *The GOSA Transactions*, Volume IV.



An additional visual record — A **Lower Mortar** minor eruption accompanied by **Bottom Vent** (lower left) prior to the eruption of September 1, 2003. (Photo by Scott Bryan)

On the Changing Eruptive Activity of Artemisia Geyser — An historical perspective

by T. Scott Bryan

Abstract

A cursory analysis of all available eruption interval data for Artemisia Geyser, dating from the earliest years of known park history into 2003, reveals that the relatively frequent and regular eruptions seen during the 1980s were probably unusual. Artemisia may now be in a gradual process of reverting to highly infrequent and erratic but potentially more powerful behavior in the future.

Introduction

During July 2001, there was discussion among geyser gazers as to whether or not the performances by Artemisia Geyser (Cascade Group, Upper Geyser Basin, Yellowstone National Park) have grown more erratic through the years. While some people thought otherwise, the fact is that the geyser has grown significantly less frequent *and* more erratic since the 1980s. Indeed, Artemisia has probably never historically bettered its performances of the 1980s decade.

However, too, the relatively regular activity of the early 1980s was probably unusual. This is quite clearly shown by an analysis of written records: descriptions of Artemisia's activity produced in the early years of the park [mostly extracted from Whittlesey, 1988; and Marler, 1973], annual reports prepared by the park's research geologists [George Marler, 1959–1971 inclusive; and Roderick Hutchinson, 1973–1986 various] and myself [Bryan, 1980–1997], information published in *The Geyser Gazer Sput* [various sources and editors, 1988–2003], and electronic data published online via the Internet [mostly from Taylor, 2002–2003].

What follows is an expanded version of a short item on this topic that appeared in the October 2001 issue of *The Sput*, updated to include more material from the early years of Yellowstone history plus years 2002 and 2003.

Activity Before 1930

Artemisia Geyser has attracted attention since the earliest days of Yellowstone's history. It boasts a large and deep, beautifully blue pool, and its eruptions are of a violently turbulent nature with a huge–volume discharge of water. Unfortunately, because its relatively remote location places it largely out of sight from most of the Upper Geyser Basin, specific eruptive data was seldom obtained prior to 1980. However, the following examples are revealing of Artemisia's true nature.

- While it was probably the "Cauliflower Spring" of A. C. Peale in 1878, the geyser first received a form of its present name as "Artemisia Spring" from Walter Weed in 1883. Both of these names, using "Spring" as part of the name, imply a lack of eruptive activity in the first decade–plus of park history. There is only a remote possibility that Artemisia was the original "Restless Geyser."
- The first eruptions of certain record were noted by Arnold Hague in 1886, when Artemisia was said to be "playing very frequently." Two years later, however, Thomas Moody told Hague that Artemisia was "very irregular, infrequent and weak." Curious is the additional statement that it was then "scarcely reaching fifty feet in height." More on this later in this paper.

Whittlesey's *Wonderland Nomenclature...* [1988] ends with the above, but Marler's *Inventory...* [1973] continues with additional historical notes.

- In 1890, Riley had Artemisia's eruptions as "infrequent" but also described them as "...very fine, an immense column of water rising some 75 to 100 feet." In the same year, A. B. Guptill described Artemisia as "extremely irregular" with too few intervals seen to judge the intervals as better than "authentic rumor."

• Olin Wheeler, in his geyser table published in 1896, gives the height as 100 feet.

• Charles Phillips, in 1927, wrote: "Its interval is unknown and it is evidently irregular but the writer's observations would lead him to put it between one and three days." Phillips also noted that "the jets occasionally reach fifty feet or more."

• Just two years later, in 1929, E. T. Allen and A. L. Day [1935] made an observation quite in contrast with those made before. Whereas the eruptions that they had previously observed were "probably never higher than 10 or 12 feet," they then saw an eruption that threw water to a height of "...35 feet." The duration of this eruption was also different, in that it lasted 25 minutes; the previous had usually had durations of "a few minutes only."

In summary, we have evidence that Artemisia's performances were usually (if not always) erratic in their frequency during the first sixty years of park history, but also that the eruptions sometimes attained heights that would be considered astounding today.

Activity from 1930 through 1957

Certainly there were many years between 1930 and 1957, but my personal collection contains but one reference that includes eruptive data for Artemisia. That reference is suspect in its accuracy. Nevertheless, C. Max Bauer [1937] cites: "Interval, irregular — from one to two days." I am certain that additional eruption data exists for these years but have been unable to locate it.

Activity from 1958 through 1969

In the 1958 edition of *Haynes' Guide*, George Marler [*in* Haynes, 1958] lists Artemisia's interval as "24 to 30 hours."

I am in possession of Marler's annual reports for each year of 1959 through 1971 (Marler's last annual report). It is apparent that the 1959 earthquake had a minimal effect on the geyser, only a slight and temporary increase in frequency being noticeable during 1960 and 1961. For the remaining years of this span, virtually no specific data is given for Artemisia. When information is given, the intervals are commonly cited as either "about 1 per day" or "20 to 30 hours."

The one small, but important, exception to this is the annual report for 1967. There, intervals as short as 5½ hours are noted. Although no durations are given, this is evidence for what we now refer to as minor eruptions. Also, an increase in frequency might have been seen in 1968, when Marler's table in the 1969 edition of *Hamilton's Guide* [*in* Lystrup, 1969] gives the interval as "16 to 30 hours." In addition, I possess a copy of a one–page typescript table titled "Eruptive Activity of Important Geysers, 1968" that lists the interval for Artemisia as: "At least 2 times daily." The author of this table is not given, but it was probably Marler.

Any minor eruptions aside, it seems quite clear that throughout the 1960s Artemisia largely held to the same frequency as before. In spite of the 1968 lists, in his report for 1969, Marler said: "Year after year it erupts on essentially the same pattern."

Activity from 1970 through 1979

Something significant happened to Artemisia between the 1969 and 1970 summer seasons. In 1970, a concerted effort by observers determined 121 closed intervals. They averaged 11h 46m, amounting to a doubled frequency of eruption.

This, of course, leads to the obvious question as to whether the "one per day" pattern had actually been double intervals. Marler himself posed this question, but clearly it is a question with no answer. However, another concerted study, conducted in 1977 primarily by geyser gazer Jamie Espy, again found an average close to 11½ hours. That same report [Hutchinson, annual report for 1977] also made special note of one duration of just 8m 40s, and also of a "brief three–foot surge" seen by Naturalist Frank Balthis on Christmas Day, 1977. Both of these reports imply minor eruptions.

Although this data is sparse, it indicates that Artemisia began more frequent activity circa 1970 and then maintained a relatively constant level of activity throughout that decade.

Activity from 1980 into early 2002

The great majority of today's geyser gazers began this hobby since 1980, and they have therefore witnessed a highly changeable Artemisia Geyser. It is the ongoing decline in regularity that triggered this entire discussion.

From a combination of my own annual reports (produced while I was employed as a seasonal naturalist and then as a volunteer), miscellaneous reports generated by Research Geologist Rick Hutchinson, data from various sources cited in *The Geyser Gazer Sput* newsletter and recent electronic monitoring data provided by Ralph Taylor, the most consistent record of Artemisia's activity is in hand. I present this data with this report, as a table (column right) and as a graphical chart (Figure 1).

Two conclusions can be readily made. First, similar to the change recorded in 1969–1970, something dramatic clearly took place between 1977 (average interval about 11½ hours) and 1980 (average interval 6h 19m). This is a 77% increase in frequency.

From 1980 until about 1992, the general trend was toward longer average intervals and a greater range between the shortest and the longest observed intervals during a given season. Since 1992, the long–run average interval has been quite constant, but the range has continued to expand. Although Artemisia has not yet reverted to its pre–1970 level of activity, it may be headed in that direction.

ARTEMISIA GEYSER 1980–2003
eruptive data in decimal hours *

Year	Mean	Short	Long
1980	6.32	5.35	7.27
1981	7.22	6.23	8.27
1982	8.88	5.72	11.97
1983	8.77	6.53	10.12
1984	9.77	7.57	11.32
1985	10.27	8.40	12.45
1986	9.95	6.87	13.38
1987	8.45	6.82	10.92
1988	9½	8.1	12
1989	10½	8	13
1990	10½	9	13
1991	11.87	8	15
1992	15	10	19½
1993	15	12	16
1994	15.57	14	19.57
1995	15.17	10.35	20.45
1996	16.20	12.67	19.37
1997	14.48	12.02	19.80
1998	15.18	9.57	22.95
1999	13.52	7.22	17.12
2000	14.23	9.87	21.02
2001	15.63	9.08	23.60
2002	12.55	6.20	29.00
2003 **	13.42	7.03	23.67

Notes:
* Data given with two decimal places is exact; other data points are approximate
** Data for 2003 is January 1 through July 5

The Changes of 2002

Although the long–run average interval of Artemisia has hardly changed since 1992, during shorter spans of time there have been some occasionally dramatic changes in its behavior. This sort of thing was best seen during 2002 when, thanks to the electronic recorder maintained by NPS Ther-

Figure 1

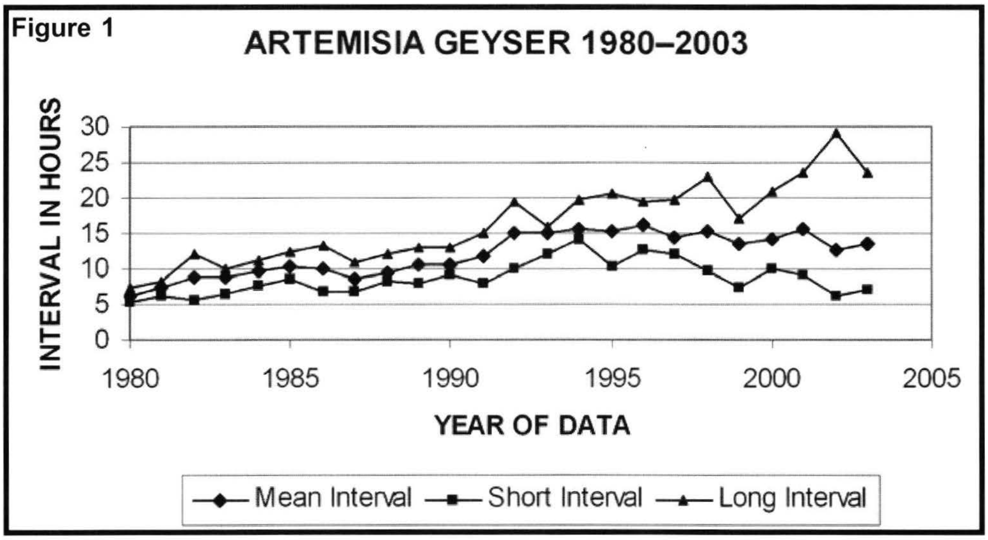
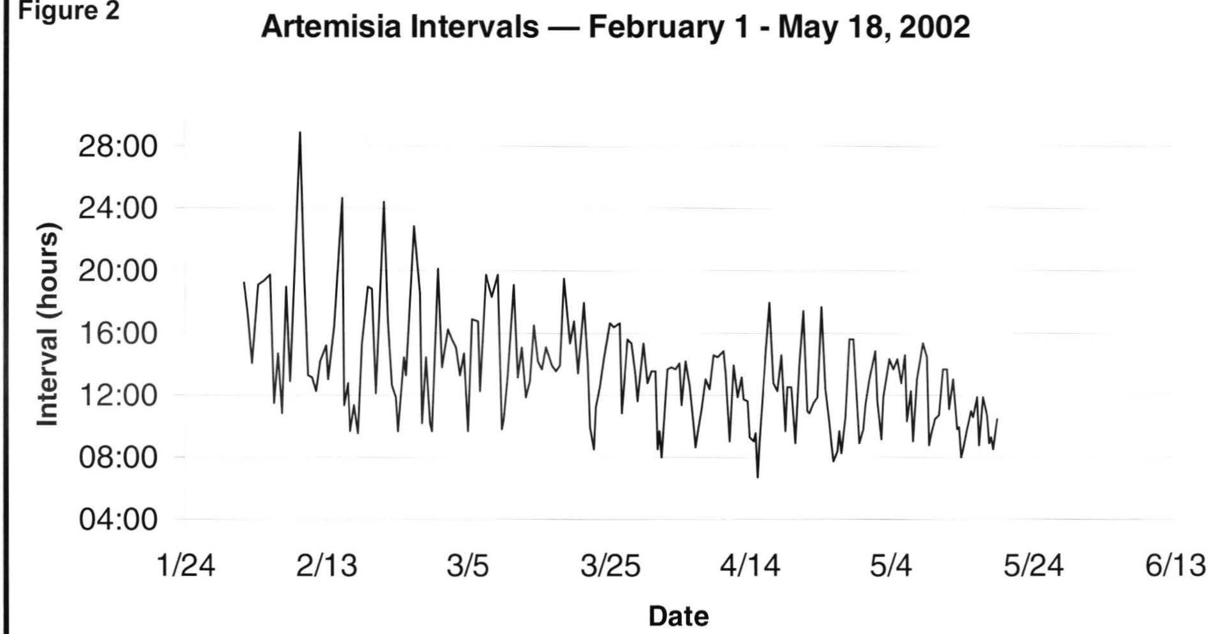


Figure 2



mal Volunteer Ralph Taylor, an extraordinarily complete record of Artemisia's activity is available.

The initial change took place on about March 1, 2002, when the intervals began a gradual decrease in average. More significantly, the short–to–long range among the intervals was almost immediately reduced. The time span of these changes is shown in Figure 2 (above).

Since early March, 2002, no interval has exceeded 24 hours and, in fact, for several months there were none more than 17 hours long. In company with this, a number of intervals were only slightly longer than 6 hours — the shortest since 1982.

These changes were temporary, however. Figure 3 is a chart of the full data from October 2000 into July 2003. The decrease in 2002 is obvious, as is the fact that Artemisia has now (July 2003) essentially reverted to the pattern seen before 2002.

About Eruption Heights and Minor Eruptions

Although it is true that some early guidebook writers simply repeated the data published by others, the fact that observers as astute as A. C. Peale, Arnold Hague and Walter Weed consistently gave Artemisia Geyser's height as great as 100 feet is notable. I am intrigued by Moody's note of Artemisia being "...weak" and "scarcely reaching fifty feet," seemingly reflecting earlier, stronger performances. Perhaps as telling is Charles Phillips' "fifty feet or more" from 1927. Not until 1929 do we find heights given within today's accepted range.

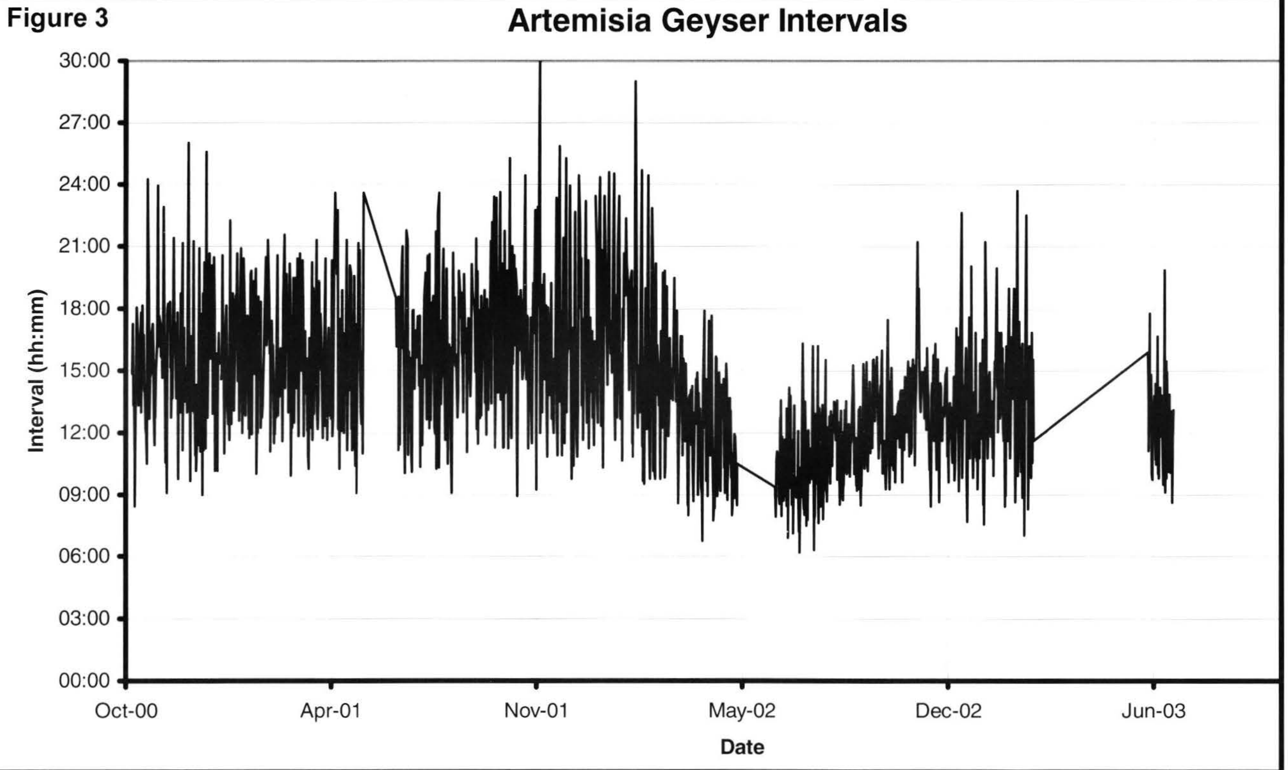
Were these early reports exaggerated? Probably not — too many people over the course of half a century reported the same magnitude of height. When combined with intervals as long as three days that were so erratic as to not even count as "rumor," Artemisia could well have had eruptions more powerful than any modern observer has witnessed.

Also of interest are short intervals and short durations. Quite consistent in early reports are durations shorter than those of today, including Allen and Day's "a few minutes only." There are also occasional notes of intervals as short as 5½ hours. From the mid 1980s into the 2000s, such intervals invariably followed eruptions with durations as short as 5 minutes. We call these "minor eruptions," but much of the historical record indicates them to be the normal mode. The longer durations (greater than 20 minutes) we are used to might be the exceptional ones.

Closing Speculation

Given the historic record dating back as far as the 1870s, it seems likely that Artemisia will continue to grow more erratic rather than more

Figure 3



regular in the future. But just think: someday you might have to wait several days to see an eruption, but then the eruption jets will tower even above the old roadway. Cool! In any case, Artemisia Geyser no longer belongs to the realm of highly–predictable geysers known to the gazers of twenty years ago, and this is how it is likely to remain.

Acknowledgement

Special thanks to Ralph Taylor, who reviewed the content of this paper and supplied the complete electronic data for years 2000 to July 2003. Figure 3 is copied directly from his Excel spreadsheet file.

References

Allen, E. T. and Day, A. L., 1935, *Hot Springs of the Yellowstone National Park*: Carnegie Institute of Washington, Washington, D.C.

Bauer, C. M., 1937, *The Story of Yellowstone Geysers*, Haynes, Inc., Yellowstone Park, Wyoming.

Bryan, T. S., 1980–1997, unpublished annual reports submitted to the Naturalist Division, Yellowstone National Park.

Haynes, J. E., 1958, *Haynes Guide — Handbook of Yellowstone National Park*: Haynes Studios, Inc., Bozeman, Montana.

Hutchinson, R. A., 1973–1986, unpublished annual reports produced for the Research Division, Yellowstone National Park.

Lystrup, H. T., 1969, *Hamilton's Guide — Yellowstone National Park*: Hamilton Stores, Inc., West Yellowstone, Montana.

Marler, G. D., 1973, *Inventory of Thermal Features of the Firehole River Geyser Basins and other selected areas of Yellowstone National Park*: National Technical Information Service, PB–221289, Washington, D.C.

Marler, G. D., 1959–1971, unpublished annual reports produced for the Naturalist Division, Yellowstone National Park.

Taylor, R. C., Jr., 2002–2003, "Recent Geyser Activity," Internet distributed tabulations.

Whittlesey, L. H., 1988, *Wonderland Nomenclature: A History of the Place Names of Yellowstone National Park*: Montana Historical Society, Helena, Montana; revised version, The Geyser Observation and Study Association, Palmdale, California.

various editors and contributors, 1988–2003, "The Geyser Gazer Sput," the bimonthly newsletter of The Geyser Observation and Study Association.

Geyser Activity in the Myriad Group

Upper Geyser Basin, Yellowstone National Park

December 1998 through March 2001

by Mike Keller

Abstract

Twenty–nine geysers and three perpetual spouters out of the nearly 50 springs historically known to have erupted within the Myriad Group were active during the three winter seasons of December 1998 through March 2001. This paper summarizes the observations of that activity and, additionally, provides general information based on the studies of prior and more recent seasons.

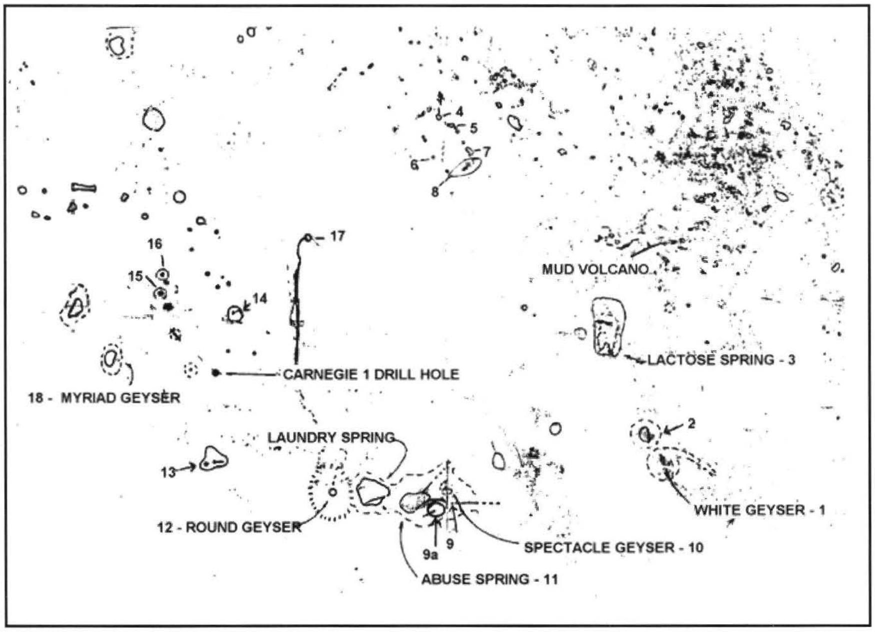
Introduction

Despite being located within the Upper Geyser Basin, the features of the Myriad Group are probably the most ignored of any in this area. No trail enters the group, so most observations must be made from the roads that pass nearby. In the winter months, when the main flow of visitor traffic does not pass near this area, the National Park Service has allowed me to study the features in this area. Access to this area requires their pre-approval.

During this time period I found a total of 29 active geysers and 3 perpetual spouters. Not all of these geysers were active at the same time, and a couple of them only erupted once or twice. Most of the geysers that I observed were small, playing to a height of less than 5 feet. None of the historically large geysers (Abuse, Round, or Myriad) were active and there were only a few small eruptions of Spectacle Geyser.In an effort to more adequately describe the activity that was observed during this period, I have created three "sub–group" names for general reference. These are not "official" names. However, because very little historical literature has been written about the Myriad Group, I found it convenient to create these designations for reference.

The Spectacle Geyser Sub–Group

I assigned all the features in the main portion along the eastern side of the Myriad Group away from the trees into this area (see Map A). This includes all the features starting from the Yellowstone Park Service Station (the "lower station"), following the service road past the Xanterra "Laurel" dormitory behind the Old Faithful Inn, to the grove of trees behind Spectacle Geyser. All the features in the open central part of the Myriad Group fall into this area. While the biggest geysers in the Myriad Group can be found here, the largest activity seen from this area (by Spectacle Geyser)



MAP A. The Spectacle Geyser Sub–Group of the Myriad Group. Reproduced from Germeraad and Watson [1959], resized to scale of 1 inch = 100 feet.

only reached about 30 to 40 feet high. A number of smaller geysers can also be found throughout the area. During this period of observation I found 13 active geysers.

The **"2. UNNS"** that causes occasional dormancies in adjacent White Geyser occupies the crater at the left foreground; outbuildings of the Old Faithful Inn are in the left background. (Photo by Mike Keller, March 2000)

1. White Geyser. White was inactive from December of 1998 through mid March of 1999. During this time an unnamed spring located 12 feet to the northwest was in steady overflow. When I returned to the park in mid April of 1999 White had reactivated. Apart from a two week span in August of 2000 when the same nearby spring was overflowing, there has not been a prolonged period of dormancy in White. Intervals between eruptions in White have been from 3 to 22 minutes with durations of 33 to 62 seconds. Bursts have reached from 3 to 15 feet in height.

White Geyser. (Photo by Scott Bryan, August 1983)

2. UNNS. This feature is located 12 feet to the northwest of White. For all of the winter season of 1998–1999, it was in steady overflow, which resulted in the dormancy of White. This is consistent with previous observations (Keller 1992, 1994, 1997). In April of 1999, when White was first observed to be active, the water level in this pool had lowered about two feet below its rim. Over the next three years the water level in this spring has been from one to four feet below overflow. The only exception was in early August of 2000, when this feature once again returned to overflow and caused another two week dormancy in White Geyser.

3. Lactose Spring. Apart from short periods of activity in 1999, Lactose was dormant. The best activity that year occurred over a seven week span from June through August. No exact intervals or durations were obtained, but I saw two eruptions that lasted over 12 minutes. Based upon observations in and around its basin, I would speculate that the intervals between eruptions were several days long. The best bursts observed were about ten feet above the ground. From late August until the end of October of 1999 there was only one other eruption. It occurred between October 01 and October 04. Since that eruption there has been no further activity.

Fissure of UNNG's below Lactose. In the shallow basin located 28 feet to the northwest of Lactose is a crescent shaped fissure containing over ten vents. At least eight of these have been known to erupt since 1987 (Keller 1988, 1989, 1991, 1992, 1994, 1997, 1998). During this period of observation, I saw five of them active, here designated as numbers 4 to 8.

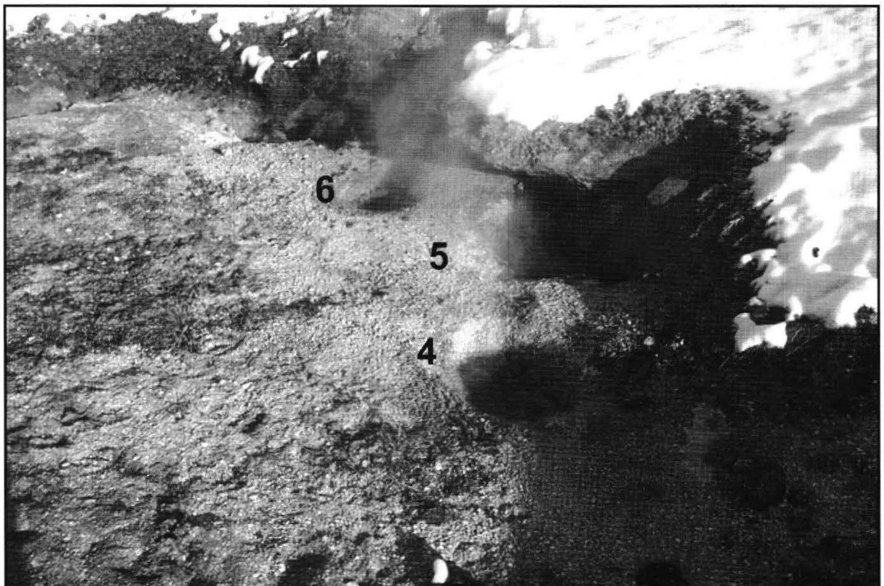
4. UNNG. This geyser was inactive in December of 1998. In early January of 1999 there was a shift of energy along the fissure and this feature reactivated. Most years this is the largest and most active vent. When active, its basin is a deep magenta color. The intervals were only a minute or two apart, and the play could reach up to about two feet. This geyser has remained active since January of 1999.

5. UNNG. Like #4, this geyser was inactive in December 1998 but reactivated in January 1999. When active it can have very brief (less than three seconds) but definite pauses in its near perpetual activity. The play reaches a little over a foot in height.

6. UNNG. This vent is the circular vent located in the open area a few feet to the north of #5. It is the only geyser I have seen to be active and dormant regardless of the activity of its nearby companions and is the only geyser not on the fracture in the immediate area that I have seen active. From December of 1998 through September of 1999 it was active, but then from October 1999 through the remainder of this observation period it was dormant. Intervals varied from 1 to 15 minutes, durations were a few seconds, and the play reached about 18 inches.

7. UNNG. This small geyser was active in December of 1998, but stopped in January of 1999 when the energy moved back to vents #4, #5, and #6. The intervals were about five minutes apart, and the play was about ten inches high.

8. UNNG. This vent was the largest I have ever seen erupt along this fissure. When first observed in December of 1998 the intervals were from nine to fourteen minutes apart, and the play was from three to four feet high. The eruption was mainly forced steam with fine droplets of water. After the energy shift, this feature continued to erupt for about a week before finally going dormant. It has not been active since January 1999.



Three of the five vents along **"Fissure of UNNG's below Lactose"** that were active during this study. Superimposed numbers correspond to the descriptions in the text. (Photo by Mike Keller)

9. "Squirtgun" Geyser. This small perpetual spouter was never observed to be inactive apart from a short period of time after an eruption of Spectacle Geyser. It is located in the man made runoff channel from Abuse immediately south of Spectacle. For a majority of the time, the play was perpetual

Spectacle Geyser. (Photo by Scott Bryan, July 1974)

and reached from 2 to 3 feet in height. When Spectacle was in eruption, this feature would sometimes start jetting up to about 6 feet. When Spectacle would go into steam phase, the activity of "Squirtgun" would stop. This pause would last up to about 20 minutes before activity resumed.

9a- UNNG's near "Squirtgun." The small area of hot ground to the southwest of "Squirtgun" began to heat up in mid June of 1999. In an area roughly 15 feet in diameter located immediately south of "Squirtgun," a number of small spouters have formed. The largest of these is located in the man made runoff channel from Abuse. Its play reached up to 2 feet in height.

10. Spectacle Geyser. In December of 1998 and early January of 1999 Spectacle was dormant. The last known prior eruption was in October of 1998. Between January 23 and January 27, 1999, Spectacle had its first eruption of the winter season. This eruption was not observed, but there was extensive wash on the eastern side of the basin. A second eruption was seen on February 05 @0844 ie. This eruption was seen by a number of people standing outside the Snowlodge. The eruption lasted just under three minutes and was estimated to be from 30 to 40 feet in height. A third eruption occurred between February 17 and 19. There was at least one eruption of Spectacle between March 16 and April 05. Two more eruptions of Spectacle occurred in the spring of 1999. The first was between May 11 and May 16, and the other was on June 10. Following the eruption on June 10, there was no further activity until a single eruption was seen on October 14, 1999. At 0844, while I was driving along the service road, I saw Spectacle in late steam phase. Wash around the crater indicated an eruption size of around 20 feet. Spectacle has been dormant since 1999.

Round Geyser. (Photo by Scott Bryan, July 1974)

11. Abuse Spring. No eruptive activity was observed in Abuse. The water level in early December of 1998 was about four inches below overflow. By late December it had risen enough to overflow, and there were definite palpitations on the surface of the pool. However, in late January 1999 the color rapidly changed from deep blue to a soft green color, indicating a decrease in temperature. For most of February, Abuse was an emerald green color. By May, Abuse had reheated and was once again its former sapphire blue color. The water level and color of Abuse has not changed since May of 1999.

12. Round Geyser. No eruptions of Round occurred during this observation period. In January and early February of 1999 there was a greater degree of boiling from Round, sometimes reaching up to around three feet high. For the rest of the season, these surges, although frequent, rarely were larger than about 18 inches tall. There has been no significant change in Round since May of 1999.

13. UNNG. This geyser lies 31 feet to the west of Round Geyser. Its basin is oval shaped, measuring 12 feet in length by 5 feet in width. The pool is about 4 feet deep at its deepest point on the western side, and has three vents within its crater. The only vent I have ever seen erupt is the one on the easternmost side. This geyser has been active every year since at least 1987. Intervals over the years have varied. During this observation period they were from 28 to 70 minutes in length, 40 minutes being the average. At the start of the eruption the pool will quickly rise about six inches, taking it to a point about 3 inches below overflow. With this there will be heavy palpitations over the entire pool. Most bursts only reach a few inches but occasional splashes have been seen to reach up to two feet high. The eruption lasts about a minute, following which the water level in the crater will drop from 10 to 14 inches.

14. UNNG. Not active. The last time this feature was observed active was in March of 1989.

15. UNNG. Frequent small subterranean eruptions were seen from this geyser in March and August of 2000. It is possible that it was active at other times as well. The eruptions were a few minutes apart

Table I. Summary of geyser activity for the Spectacle Sub–Group

Name	Interval	Duration	Height (feet)	Comments
Abuse Spring (11)				Dormant
Lactose Spring (3)	days	>12 minutes	15	
Myriad Geyser (18)				Dormant
Round Geyser (12)				Dormant
Spectacle Geyser (10)	days	2 to 5 min	15 to 40	Dormant since 10/99
"Squirtgun" Geyser (9)	perpetual	perpetual	2 to 6	Perpetual Spouter
UNNG (4)	1 to 2 min	seconds	1	
UNNG (5)	near steady	near steady	1	
UNNG (6)	1 to 15 min	seconds	1 to 2	Dormant since 10/99
UNNG (7)	5 min	seconds	1	Dormant since 1/99
UNNG (8)	9 to 14 min	20 sec	3 to 4	Dormant since 1/99
UNNG (13)	28 to 70 min	1 min	2	Active since 1987
UNNG (14)				Dormant
UNNG (15)	1 to 4 min	seconds	inches	
UNNG (16)	perpetual	perpetual	inches	
UNNG (17)				Dormant
UNNS by White (2)				Overflow results in dormancy in White Geyser
White Geyser (1)	3 to 22 min	30 to 60 sec	3 to 15	

and would consist of a series of superheated sizzles and strong palpitations within its basin.

16. UNNG. This small geyser was also active when #15 was active. Unlike its neighbor, the activity from this feature was perpetual during its active episodes. It reached a few inches above the surface.

17. UNNG. Rocco Paperiello saw this small geyser playing following a major eruption of Round Geyser in 1989. From December 1998 through March, 2001 this feature's temperature never reached above 156ºF.

18. Myriad Geyser. No intermittent eruptive activity was observed in Myriad. Perpetual surges from its vent reached about a foot in height. The temperature in its basin remained at 203ºF.

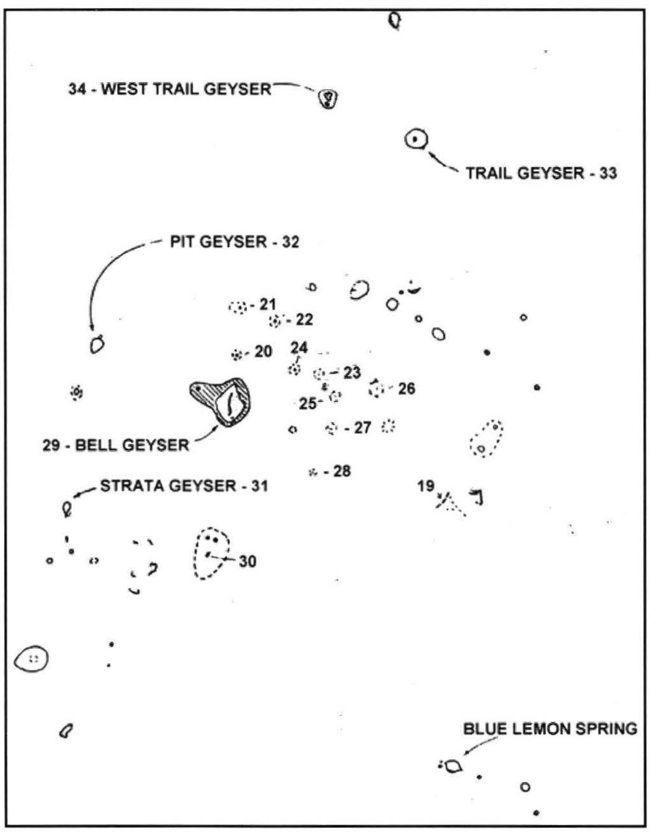
The Bell Geyser Sub–Group

I assigned all the western features within the trees between Myriad Geyser and the one-way road leaving Old Faithful to this portion of the Myriad Group (see Map B). In January of 1999 several features in this group reactivated. While the activity has gradually declined since then, a few of the geysers still remain active. A total of eight different features were known to be geysers during this observation period.

19. "Suture" Spring (also informally known as "Rift" Spring). This odd feature was active from December of 1998 through May of 2000. It was also active in 1988, 1989, 1991, 1992, and 1994. When it is dormant, the vent is almost impossible to find since it is nothing more than a series of four small cracks within the gravel. "Eruptions" consist of upwelling water and strong overflow from these cracks. They can last up to 3 hours. No closed intervals were obtained but I would speculate "Rift" was erupting at least twice a day. A sure sign that "Rift" is active is the presence of cyanobacteria around its vent. The gravel will be orange and brown when it is active, and white when it is dormant.

20. UNNG. No eruptive activity observed. Its temperature was never measured higher than 154ºF. I have not seen this feature active since the winter of 1988–1989.

21. UNNG. Of all the small geysers around Bell, this has been the largest I have seen erupt. It is closely associated with Bell Geyser, erupting in concert with the major eruptions of Bell. When Bell was dormant in December 1998, this geyser's vent was lined with cyanobacteria. But in January 04, 1999, I found extensive (over 60 feet in length) runoff channels carved into the nearby snow and gravel leading away from this vent. When Bell Geyser had a major eruption at 1250 on that day, this geyser erupted at the same time to a height of about 8 feet. Over the next two weeks I saw several eruptions of this geyser that reached from 4 to 15 feet in height. Most eruptions lasted about 25 seconds. As the winter progressed the strength of eruptions from this geyser lessened so that by late



MAP B. The Bell Geyser Sub–Group of the Myriad Group. Reproduced from Germeraad and Watson [1959], resized to scale of 1 inch = 100 feet.

February of 1999 the biggest bursts only reached a few feet. The last known eruption from this vent was on March 08, 1999. This vent continues to overflow heavily during major eruptions of Bell.


The vents of **"Ghoul Geyser."** (Photo by Mike Keller)

22. "Ghoul" Geyser. I have unofficially called this vent "Ghoul Geyser" because of the shape of its vent. From January 04 to 17 of 2000 this geyser was active. Eruptions would take place in association with #20 and Bell Geyser's major eruptions. The largest play reached about a foot. Apart from this one week of activity, this geyser was dormant.

23. UNNG. This geyser's vent is a small beaded cone. No eruptive action was observed. The water level stayed a few inches from the surface. I have not seen this geyser erupt since activity I observed in the summer of 1993.

24. UNNG. No eruptive activity observed. Of the small, unnamed geysers around Bell, this has the largest vent. The water level was always within an inch or two of overflow. This geyser has not been active since the winter of 1988–1989.

25. UNNG. This geyser's vent is a small, decaying cone. No eruptive activity was observed. The water level was several inches below overflow. This geyser has been inactive since the winter of 1988–1989.

26. UNNG. This geyser was not active prior to February 15, 2001. On that day, and for the remainder of the winter season, it would have small subterranean eruptions every few minutes. This was the first activity observed from this feature since the winter of 1988–1989.

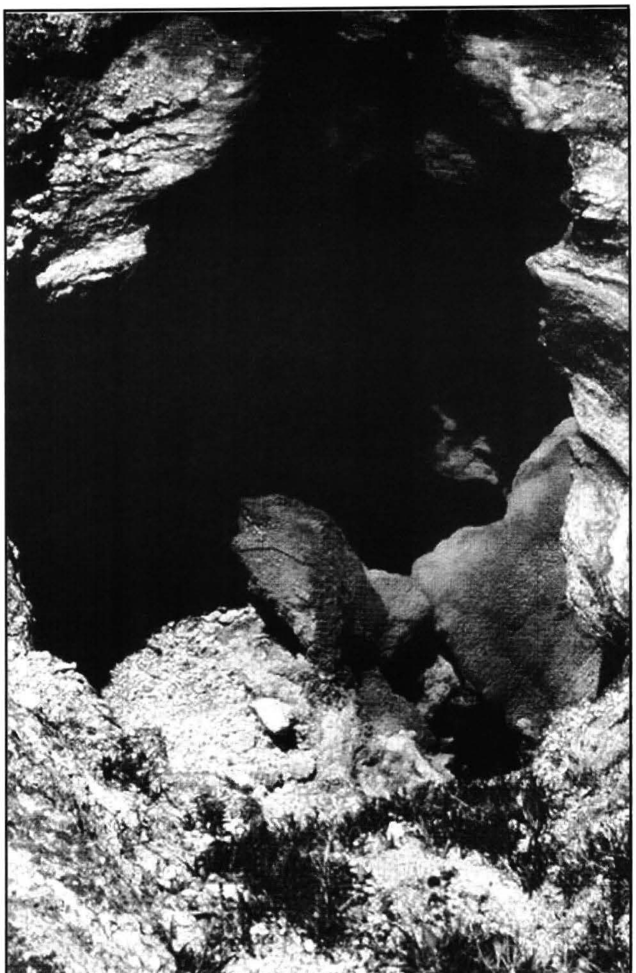
27. UNNG. This small subterranean geyser was inactive from 1991 until October 1999. Frequent small eruptions were seen between then and March 2000. By April of 2000 it had once again lapsed into dormancy. The water level of this feature has remained about a foot below overflow.

28. UNNG. No eruptive activity observed. While this feature has a beaded sinter cone and eroded evidence of a sizeable runoff channel, no eruptions have ever been seen from it.

29. Bell Geyser. Bell was inactive before January 04, 1999. On that date it was very evident that Bell was active. There were a number of freshly cut runoff channels in the surrounding gravel and the main vent, which had been lined with brown and green bacteria, had heated up and was a soft blue color. Bell has two vents in its basin that it can erupt from. The main vent is located deep within the heart of the pool. The other vent is at the top of the bell, on the shallow side of the feature. All eruptive activity from January of 1999 to March of 2001 came from the main vent; no eruptions have been seen from the smaller vent since 1994. Bell has two types of eruptions. A minor eruption consisted of heavy palpitations over the main vent, accompanied by audible thumps from steam bubbles collapsing at depth and a large amount of "fizzing bubbles" (bubbles that appeared to be more gas than steam — they would fizz like a soda pop). These eruptions would last about 20 seconds. Major eruptions consisted of heavier palpitations, stronger thumping, and occasional bursts as the steam bubbles reached the surface. These bursts would be from one to four feet in height. A major eruption would last up to 2 minutes. From January to March of 1999 the intervals between minor eruptions were 14 to 24 minutes. Major eruption intervals were 44 to 238 minutes. In September of 1999, minor intervals were 8 to 40 minutes apart and major intervals were 52 to 188 minutes apart. In January and February of 2000 the minor intervals were 6 to 44 minutes apart and the major intervals were 29 to 331 minutes apart. During the summer of 2000, the water level in Bell dropped about 14 inches and the deep part of its basin was a soft blue color. By December of 2000, it had refilled and was once again a dark brown and green along the walls. Activity during January and February of 2001 was similar to that of 2000.

30. UNNG. This geyser had its first known eruptive episode on February 13 of 1999. It is located within a larger spring (roughly 20 feet by 30 feet) with two vents. Most years this spring is full and all the vents within it are underwater. Prior to 1999 I had never known any vent in this large spring to be a geyser. On February 13, 1999, I found the crater to be empty and a previously unknown vent within the basin having frequent small eruptions. The intervals between eruptions were erratic. The geyser would stop erupting for 20 to 60 seconds and then would erupt for 30 seconds to five minutes. The eruptions reached about 4 feet high. When I returned to this area on February 19, this geyser was dormant and the larger spring was once again full. Over the next few weeks this geyser was active every few days. Every time I found it active, the larger spring that covered it with water was empty. Activity from this vent continued into June of 1999, but it has not been seen since.

(unnumbered) Blue Lemon Spring. In the trees south of Bell Geyser lies Blue Lemon Spring. This feature is lemon–shaped, measuring about 8 feet in length by 4 feet in width, and blue in color. No eruptive activity has ever been observed from this feature.



The crater of **Strata Geyser**, showing some of the rhythmic geyserite layers that gave the geyser its name. (Photo by Scott Bryan, August 1974)

31. Strata Geyser. Strata was never observed to be dormant during the entire period of observation. All eruptions were subterranean, but would reach from one to two feet above its pool. Intervals were frequent, normally 8 to 21 minutes apart, and durations were from 30 to 50 seconds in length.

32. Pit Geyser. No eruptive activity was observed. The water level would cyclically rise and fall a few inches within the basin, but never reached overflow.

33. Trail Geyser. No eruptive activity was observed from Trail. The water sat at a level about

Table II. Summary of geyser activity for the Bell Geyser Sub–Group

Name	Interval	Duration	Height (feet)	Comments
Bell Geyser (29) minor	6 to 44 min	seconds		inches
Bell Geyser (29) major	29 to 331 min	2 min	1 to 4	
"Ghoul" Geyser (22)	29 to 331 min	20 to 30 sec	1	Dormant since 1/99
Pit Geyser (32)				Dormant
"Rift" Spring (19)	days	hours	overflow	
Strata Geyser (31)	8 to 22 min	30 to 50 sec	1 to 2	
Trail Geyser (33)				Dormant
UNNG (20)				Dormant since 3/89
UNNG (21)	29 to 331 min	20 to 30 sec	1 to 15	Dormant since 3/99
UNNG (23)				Dormant since 8/93
UNNG (24)				Dormant since 3/89
UNNG (25)				Dormant since 3/89
UNNG (26)	2 to 6 min	seconds	1	
UNNG (27)	1 to 4 min	seconds	1	Dormant since 4/00
UNNG (28)				Dormant
UNNG (30)	3 to 7 min	30 sec to 5 min	4	Cyclic feature, dormant since 7/99
West Trail Geyser (34)	perpetual	perpetual	1 to 3	Perpetual Spouter

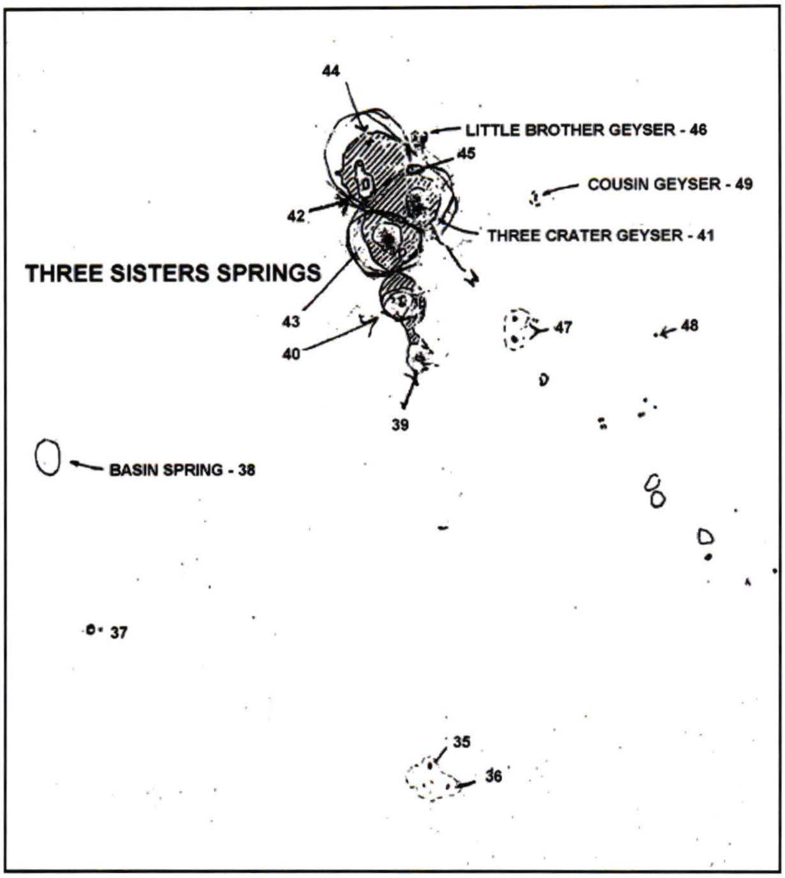
six inches below overflow, and gentle boiling was always observed.

34. West Trail Geyser. Every time West Trail was observed, its basin was full and its activity was that of a small spouter, reaching about a foot in height. In early May of 2000 the water level dropped about three feet and all eruptive activity quit. By late fall, the water had risen to a level about eight inches from overflow, but the spouting activity never resumed until October, 2000. With the renewed spouting activity, the water level remained about 8" below overflow.

The Three Sisters Sub–Group

The remaining features of the Myriad Group, on the northern side nearest the access road towards the lower gas station and store have been assigned to this area (see Map C). The main feature in this area is Three Sisters Spring. Unlike the other areas in the Myriad Group, the major rejuvenation of features around Three Sisters Spring took place in May and June of 1999 with the reactivation of Little Brother and "Mugwump" Geysers. During this period of observation 11 of the features in the area were geysers.

35. UNNG. Prior to December of 1998 I am not aware of any eruptive activity from this geyser. It and #36 are located in a circular depression in the trees about 180 feet to the south–southwest of South Three Sister. The first eruption seen from this feature was on December 26, 1998. The geyser was well into its eruption when I first observed it, sending a mixed column of steam and water to a height of about 6 feet. A second eruption occurred on December 28, and was followed by another between January 01 and 04, 1999. I was fortunate enough to finally see an eruption from the start on January 07. With little warning, the water would suddenly become very agitated within its vent. After a moment of splashing the geyser would send up a mixed column of spray and steam to a height of about 8 feet. While the eruption would last over 20 minutes, the greatest amount of water displacement took place within the first 30 seconds of action. After this, the majority of the eruption would be steam mixed with a very fine spray. While this geyser was in eruption, all of the nearby vents would drain and #36 would go into a weak steam phase. Following an eruption, it would require several hours for the water levels in the entire area to recover. There were two more eruptions of this geyser in January (13th and 22nd). Since the eruption



MAP C. The Three Sisters Sub–Group of the Myriad Group. Reproduced from Germeraad and Watson [1959], resized to scale of 1 inch = 100 feet.

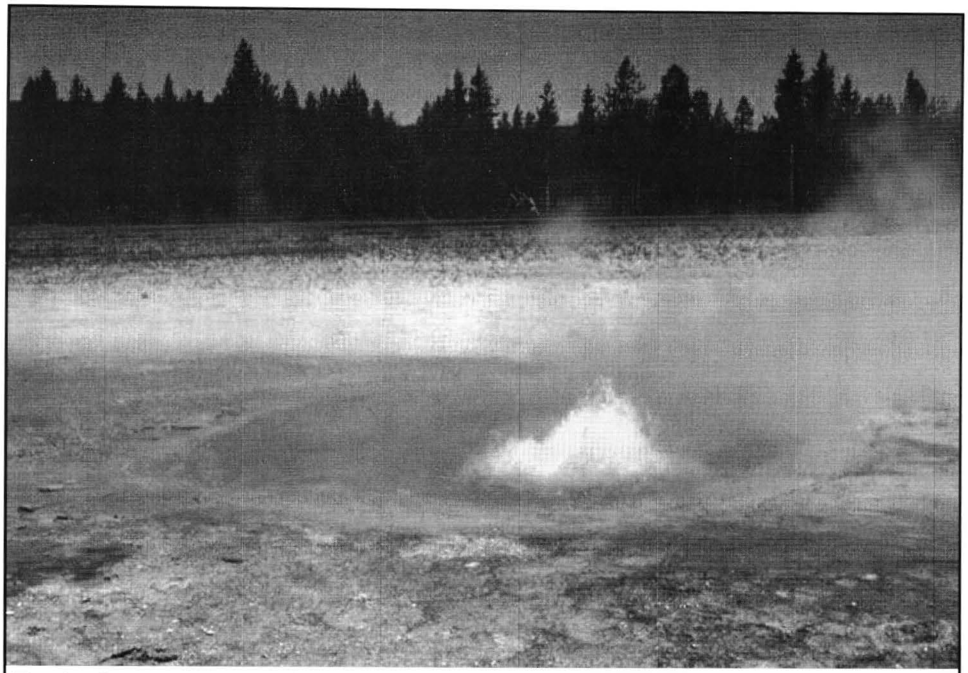
of January 22, 1999, this geyser has been dormant.

36. UNNG. This geyser's vent lies within the same basin as #35. In past years it has been seen to erupt a small fan–shaped spray up to 3 feet high at short intervals. It was very weakly active in the winter of 1998–1999, but had stopped all eruptive activity by June of 1999. During eruptions of #35, this geyser would drain and go into a weak steam phase. No eruptive activity has been seen since June of 1999.

37. UNNG. This small geyser is about 40 feet to the south of Basin Spring. It is located in the grass at the edge of the gravel area which fans out below South Three Sister Spring. In past years this feature has been a geyser, perpetual spouter, or intermittent spring. From December, 1998 through January, 2001 it was in overflow, cool (148°F), and lined with green cyanobacteria. In early January of 2001, however, it was found to be a few inches below overflow and had warmed up enough to kill the cyanobacteria within its vent. While it remained hot (180°F), during the rest of the winter season no eruptive activity was observed.

38. Basin Spring. Basin was dormant in December of 1998 but had reactivated by May of 1999. At first the eruptions were frequent, normally being 15 to 25 minutes apart. The eruptions would last from three to six minutes and reached up to four feet. Over the

Basin Spring, erupting from a low pool level during the present study. (Photo by Mike Keller, March 2000)



Basin Spring during a full–pool eruption nearly twenty years ago. (Photo by Scott Bryan, August 1984)

summer of 1999, the intervals slowly lengthened so that by late September they were over 40 minutes long. In January 2000 the intervals were about 3 hours long. By that May they had shortened back to about 30 minutes, but once again they began to lengthen over the summer. In July 2000 the intervals varied from one to five hours and by October they were several days in length. Basin Spring was dormant by December of 2001 and has remained so since then.

39. South Three Sister. No eruptive activity observed. This feature has not been active since July of 1997.

40. Middle Three Sister. No eruptive activity observed. Wash around the basin was caused by the radiating surface waves during eruptions of Three Crater Geyser.

41. Three Crater Geyser. This geyser has been active during every year since at least 1987. From December, 199, through March, 1999 the intervals were 8 to 22 minutes. Eruptions would last about 2 minutes and reached up to about six feet. With the reactivation of Little Brother in May of 1999, the intervals for Three Crater increased and varied from 14 to 50 minutes with 30 being the average. When Little Brother ceased its activity that June, Three Crater's intervals returned to the shorter 8 to 22 minute range.

42. The "Mugwump." No eruptive activity was seen from this geyser until June 04, 2000. When Little Brother was active in 1999, the water level over this vent would rise and fall at roughly 20 minute intervals. In late May of 2000 the temperature of this vent heated up enough to kill all the cyanobacteria around it, and Mugwump was active by early June. The intervals between eruptions were 14 to 22 minutes long. There would be one or two series of bursts that could reach up to 15 feet high. By the end of June it had lapsed back into dormancy and by the fall of 2000 the vent was once again lined with orange cyanobacteria.

43. UNNG. This geyser's vent is located within the basin of North Three Sister, being the one closest to the Middle Three Sister. No eruptions were ever seen from it, but sometime between March and May 2000 it had at least one major eruption. New runoff channels were formed in the surrounding gravel to the west and the silt within its basin had been moved. Prior to this, there had been no historic reference to this vent erupting.

44. UNNG. This geyser's vent is also located within the basin of North Three Sister. It is located between #42 and #46 along the northern rim of the crater. It has been active every year since at least 1987. The eruptions only reach a few inches but are frequent enough to be seen a few times every hour.

45. UNNG. This geyser was jokingly called "Bastard" Geyser by Rocco Paperiello and Marie Wolf in 1999. It is located between #41 and #46. This geyser was not active prior to April of 1999. During May and June of that year its intervals were very erratic, but it would normally erupt once or twice an hour. In 2000 this geyser became very frequent with intervals of 8 to 15 minutes. The eruptions would last about four minutes and reach about three feet tall. If this geyser erupted at the same time when Three Crater was due, it would delay Three Crater's next eruption by about six minutes. In 2001 the activity from this geyser was once again erratic, with intervals varying from 11 to 75 minutes in length.

46. Little Brother Geyser. During the winter months of 1998–1999 there was no activity from Little Brother, apart from occasional periods where its basin would empty. In April 1999 this had stopped and Little Brother would occasionally "swell up" and produce brief periods of overflow. This was probably the beginning of what later turned out to be Little Brother's first period of activity since 1983. In late April and early May of 1999 small one foot eruptions were observed. As May progressed, these gradually and steadily increased in size, duration, and volume. By the end of May Little Brother was frequently reaching from 10 to 20 feet in height. As the frequency and height of the eruptions in Little Brother grew, the water level in all the vents of the Three Sisters slowly dropped. At its lowest point, none of the vents in North Three Sister were connected at the surface. In mid June of 1999, Little Brother became dormant, and by that October its vent was again lined with thick orange cyanobacteria. No eruptions have been seen from Little Brother since June 1999.

Little Brother Geyser, viewed from across the large pool of North Three Sister. (Photo by Scott Bryan, July 1983)

47. "Surging Spring." The name for this feature comes from the Hall Manuscript of 1926, and thus has standing even though it duplicates a name also used at West Thumb. The spring is 80 feet to the southeast of "Cousin" Geyser and consists of two vents. Starting in December of 1998, this spring began having small eruptions. The intervals were about 4 to 6 hours long and most bursts reached about 2 feet in height. Following an eruption, the water would drop to a level about 3 feet below overflow. It would take about 4 hours for this level to eventually reach ground level. An eruption would start just after the water level of both vents became connected at the surface. Eruptions would last from 6 to 8 minutes. Although it was still active in May 1999, this geyser went dormant by that July and it has remained dormant since then.

48. UNNG. This small geyser was active in December of 1998 through February of 1999. It was dormant by the end of that month and has not been active since. Intervals were erratic, ranging from 3 to 42 minutes. The eruptions were very small, sometimes only consisting of palpitations and weak overflow. Other times, it could boil up to about a foot. Durations were from 20 to 35 seconds in length.

49. "Cousin" Geyser. Prior to January of 2001, the temperature of "Cousin" was never measured above 85°F. During this time, the water level was always about 6 inches below overflow and the vent was lined with thick mats of cyanobacteria. In early January of 2001, the water level rose about four inches and the temperature increased to 184°F. By February 2001, "Cousin" would sometimes fill to the brink of overflow and then recede. The temperature continued to rise during February as well. On February 15 it was measured at 190°F, and on February 26 it was 194°F. Despite the increase in temperature, no eruptions took place.

Map Reference

Germeraad, W. and Watson, B., 1959, "Myriad Group, Upper Geyser Basin," mapped on November 6, 1959, scale 1 inch = 50 feet; Yellowstone National Park, item number NP–YEL 8749.

Editor's Note: With the encouragement of the author, a number of historic photos of Myriad Group features taken by Scott Bryan were added to this paper for illustrative purposes. These off–trail pictures were taken while on duty in Park Service uniform or while serving in a volunteer capacity.

Table III. Summary of geyser activity for the Three Sisters Sub–Group

Name	Interval	Duration	Height (feet)	Comments
Basin Spring (38)	15 min to days	3 to 6 min	1 to 4	Intervals varied greatly during observation
"Cousin" Geyser (49)				Dormant
Little Brother Geyser (46)	7 to 26 min	10 to 40 sec	1 to 20	Dormant since 6/99
Middle Three Sister (40)				Dormant
"Mugwump" Geyser (42)	14 to 22 min	5 to 20 sec	3 to 15	Dormant since 6/99
South Three Sister (39)				Dormant since 7/97
"Surging Spring" (47)	4 to 6 hrs	6 to 8 min	2	Dormant since 7/99
Three Crater Geyser (41)	8 to 50 min	2 min	2 to 6	Intervals varied with activity of UNNG #45
UNNG (35)	days	30 min	8	Dormant since 1/99
UNNG (36)	2 to 15 min	seconds	3	Dormant since 6/99
UNNG (37)				Dormant
UNNG (43)				Had at least one eruption between 03/00 and 05/00
UNNG (44)	5 to 20 min	30 to 45 sec	inches	
UNNG (45)	8 to 75 min	2 to 4 min	3	
UNNG (48)	3 to 42 min	20 to 35 sec	1	Dormant since 2/99

The Discovery and Activity of "Phoenix Geyser," 1995-2002

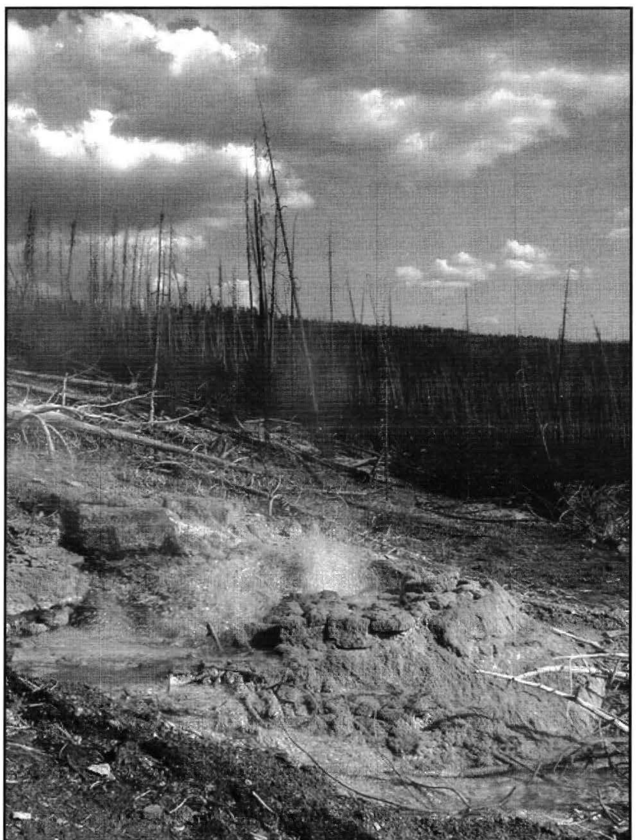
by Jeff Cross, Carlton Cross, and Tara Cross

Abstract

The discovery and recent activity of Phoenix Geyser, in the Gibbon Hill Group of the Gibbon Geyser Basin, is presented in this short account.

Background

Phoenix Geyser erupts from a small pool and an adjoining fissure breaking out on a small cone of sinter lying 82 feet north of Gibbon Hill Geyser's formation. Phoenix Geyser rejuvenated in 1995, after a decades–long dormancy. That year we found the old, weathered sinter formation surrounded by heavy wash. At the north end of a fissure cutting the mound, water had excavated a small alcove and the runoff had washed a substantial channel down the steep hillside. The activity was obviously recent, since that season's grass lay dead in the washed areas.



"**Phoenix Geyser**," in eruption on July 13, 2003. (Photo by Carlton Cross)

When we first arrived at the geyser it was below overflow and there were no obvious signs of a recent eruption. Four hours later the geyser was having weak intermittent overflows, but it had not erupted.

We returned in 1996 and found that Phoenix was rapidly evolving. The wash basins were clear of debris and were rapidly acquiring a heavy sinter deposit. One observed eruption lasted for 23 minutes, preceded by 90 minutes of overflow. At this time Rocco Paperiello, who had accompanied us, suggested the name "Phoenix Geyser" in reference to the way in which the geyser had sprung to life on a hillside badly burned in the 1988 forest fires.

Phoenix Geyser is rapidly establishing itself as the most important feature in the Gibbon Hill Group, barring a rejuvenation of Gibbon Hill Geyser (which would be an unlikely event, since its crater was thoroughly buried and choked by a mudslide following the 1988 forest fires). The runoff channel of Phoenix, which in 1995 was just a small gully in the gravel, is washed clean and is sintered nearly to the base of the slope. The crater and sinter mound have been covered with a heavy sinter deposit which, interestingly, is white where submerged during the eruption and a tan color where exposed to the air. The rate of sinter deposition seems closer to 1 cm per 10 years than to the more frequently cited 2.5 cm per century rate. It may be that initial rates of sinter deposition are in excess of rates for established formations. However, too, the water of Gibbon Hill Geyser used to thoroughly coat fallen pine needles and cones with fresh geyserite within a few weeks.

Phoenix is clearly an older feature that has reactivated. Probably it is Allen and Day's [1935] "second geyser" at the Gibbon Hill Group. Fifty years after Allen and Day, Paperiello and Wolf [1986] mentioned "a small hump of sinter" with "an hour-glass-shaped opening... now choked with grass and soil" near Gibbon Hill Geyser. They added: "Out of three or four humps amid a broken and over-grown sinter sheet on the hillside, this one looks closest to having been active 50 years ago." Close examination of the hillside right below the formation reveals an old, terraced sinter deposit, beaded in places. The type of beading present is typical of the sinter that forms in the runoff channels and splash basins of other erupting hot springs in Yellowstone.

Table 1 — Phoenix Geyser, Summary of Electronic Data

Year of Data	Number of Intervals	Average Interval	Short Interval	Long Interval
1998	71	123 m	100 m	141 m
1999	140	115 m	96 m	136 m
2000	56	233 m	214 m	243 m
2001	48	296 m	263 m	323 m
2002	203	318 m	264 m	396 m

Observational Data

In 1997, an interval of 149 minutes and three durations of 5 to 10 minutes were observed. The eruption paused once during each of two 5– to 7–minute durations, and paused three times during one 10–minute duration. Overflow preceded one eruption by 21 minutes.

Data for 1998 through 2002 was obtained by placing an automatic data logger under NPS permit (see Table 1). The temperature record clearly shows eruption starts, but the ends of the eruptions are less distinct, making it difficult to estimate the durations.

In 1998, for 71 consecutive intervals, Phoenix Geyser was erupting every 100 to 141 minutes, with an average interval of 123 minutes and a standard deviation 6.7% of the average. Overflow preceded the eruptions by 15 to 30 minutes, and each eruption consisted of either two or three separate surges of activity spaced 3 to 5 minutes apart. Two observed durations were 6 to 7 minutes.

In 1999, for 140 intervals, eruptions occurred every 96 to 136 minutes. Intervals averaged 115 min with a standard deviation 5.8% of the average.

In 2000, two observed eruptions were preceded by 26 minutes of overflow, both eruptions lasting for a full 33 minutes. For 56 intervals, the eruptions came 214 to 243 minutes, with an average of 233 minutes (3h 53m) and a standard deviation of 2.3%.

In 2001, the average interval climbed to 296 minutes (just under 5 hours), with a standard deviation of 4.9% for 48 intervals. The intervals' range was 263 to 323 minutes. One observed eruption lasted for 58 minutes and was preceded by 38 minutes of overflow.

In 2002, the average interval had increased to 318 minutes (5h 18m), with extremes of 264 and 396 minutes and a standard deviation 7.2% of the mean for 203 intervals. Another set of 64 intervals recorded earlier in 2002 showed nearly identical data. One duration of 62 minutes was observed.

The above data show that the interval and duration for Phoenix Geyser have varied significantly over a six-year period, but that the intervals at any given time are reasonably regular. It also demonstrates that the durations have increased along with the interval.

Most of the water erupted by Phoenix surges to 3 feet high, but some fine spray sometimes reaches heights of 6 to 8 feet.

References

Allen, E. T., and Day, A. L., 1935, *Hot Springs of the Yellowstone National Park*: Carnegie Institution of Washington.

Paperiello, R., and Wolf, M., 1986, *Report on Lesser Known Thermal Units of Yellowstone National Park, 1981-1985*: photocopy, available from The Geyser Observation and Study Association.

Note: The original electronic data was recorded in seconds. Here those values have been simply divided by 60 and then expressed to the whole minute.

Geyser Activity at Shoshone Geyser Basin
1988–2002, with update notes into July 2003

by Jeff Cross, Tara Cross, and Carlton Cross

Abstract

Geyser activity from over seventy thermal features at Shoshone Geyser Basin between 1988 and early summer 2003 is described. The most notable activity occurred in the North Group from 1998 into 2003, where several new geysers began erupting and numerous other geysers either rejuvenated or increased their activity. Two of these geysers erupted to at least 20 feet. In other parts of the geyser basin, Taurus Spring underwent major eruptions in 1997 and in 2003, for only the second and third times in recorded history. A new mode of activity for Minute Man Geyser developed over several years, beginning in the middle 1990's. Data logger studies carried out under an NPS research permit revealed that during 1998 and 1999, Frill Spring was erupting in series every 4 to 5 days.

INTRODUCTION

Thermal features at Shoshone Geyser Basin are separated into fourteen groups (Map A). The main activity occurs in the Little Giant, Minute Man, and Orion Groups on the east side of Shoshone Creek, and in the North, South, and Western Groups on the west side of Shoshone Creek. Less active are the Yellow Crater Group in the Basin's northwest corner, the Shore and Lake Groups along the edge of Shoshone Lake, and the Camp and Island Groups, which lie along Shoshone Creek downstream from the Orion and South Groups. South of the main geyser basin is the "Horse Camp Group," which lies in a meadow on the west side of Shoshone Creek, and the aptly–named "Swamp Lake Group," which is in the marsh at the west end of Shoshone Lake. The Sulphur Hills Group is just east of the Little Giant Group and west of the Shore Group; it contains no known geysers.

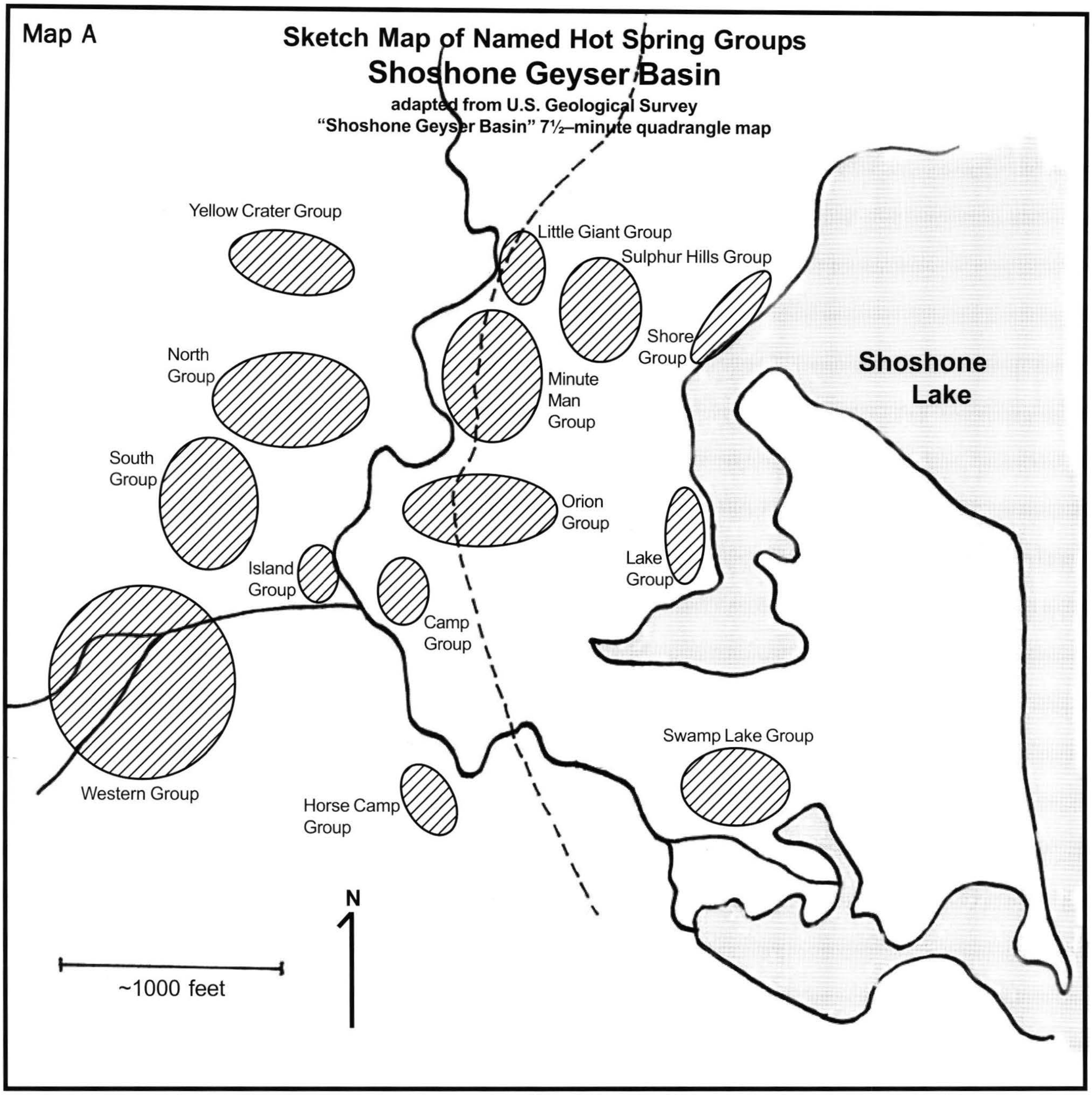
The largest geyser to have erupted at Shoshone Geyser Basin during the course of this study was Taurus Spring, which erupted to 50 feet for a very brief period in early July 1997, possibly as the result of a small earthquake that occurred beneath the Pitchstone Plateau on 28 June 1997. Another occurrence of major eruptions of Taurus took place following the 1959 Hebgen Lake earthquake. Major activity also took place just prior to July 12, 2003, but that action was not witnessed. Union Geyser, which can erupt to 110 feet, and Minute Man's Pool, which can erupt to over 50 feet, have both been dormant since the late 1970's [Bryan, 1995]. Little Giant Geyser, which is capable of 50–foot eruptions, has apparently erupted twice in recent years, once in 1988 and again in 1991 [Bryan, 1995; Paperiello, 1992], but neither eruption was seen. The largest consistently active geyser at Shoshone is Minute Man Geyser, which can erupt to 30 feet. Frill Spring and Knobby Geyser are also capable of 30–foot eruptions, but the visitor will find that most geysers at Shoshone erupt to less than 10 feet high.

Important Note: Paperiello [1989, 1992] has mapped much of the geyser basin in detail. Numbers in the text correspond to numbered vents on Paperiello's maps, which are reproduced in this paper as Maps B, C, D, E and F.

LITTLE GIANT GROUP (see Map B)

"Trail Geyser" #2a

Also known as "Trailside Geyser" [Bryan, 1995], this geyser's recorded intervals from 1992 through 2002 ranged from 6 to 10 minutes with averages between 6½ and 7½ minutes. Observed durations ranged from 17 to 51 seconds, with average durations between 32 and 40 seconds. Maximum heights were 3 feet. As noted previously [Cross, 1998], Trail can have minor eruptions lasting only a few seconds. If this happens, the major eruption usually follows within less than a minute, although one delay of over 2 minutes was noted.



Unnamed geysers #2b-e

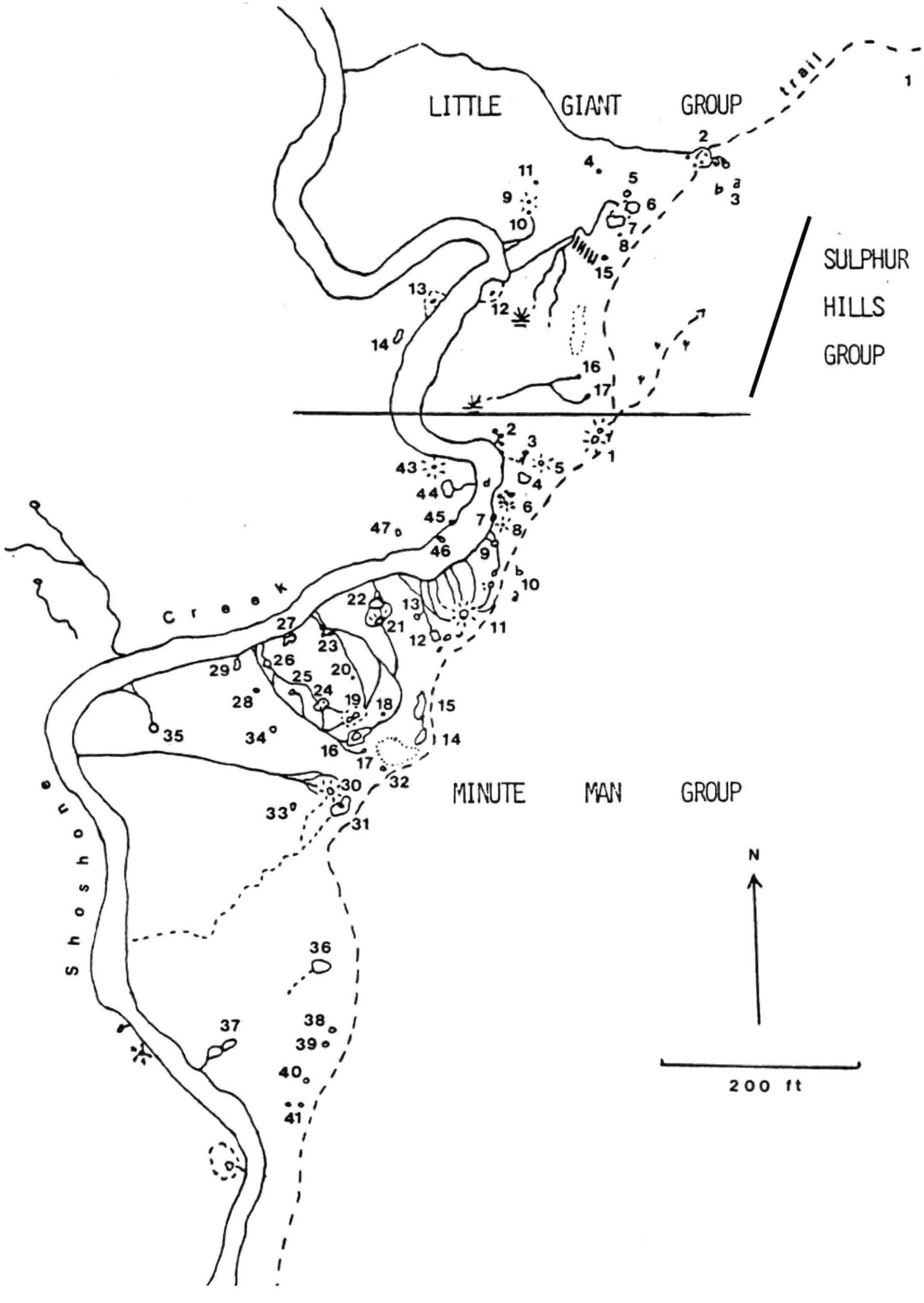
Two of the vents on the apron below Trailside have each been seen in eruption once, the maximum height being only a few inches.

"Double Geyser" #10

Double consists of a pair of vents within a shallow, dark red crater. Eruptions begin after an extended period of overflow, building gradually to a height of 8 to 12 feet. The end of the eruption is indistinct, the total duration being about 5 to 7 minutes. From 1989 through 1999, observed intervals were 54 to 74 minutes, with only one 81–minute interval, seen in 1997 during a powerful storm, falling outside this range. Average intervals ranged from 54½ to 69 minutes. However, beginning in 2000 and continuing through 2002, longer intervals have been observed, ranging from 71 to 103 minutes with averages of 77 to 88½ minutes. At times intervals were extremely regular, as shown by a data set of 23 intervals obtained in July 1998 that had a standard deviation only 1.9% of the 66–minute average. Eruptions from Double and Little Giant seemed qualitatively weaker in 2002 than at any time previously.

From 1998 through 2002, most of the data was

Map B — Little Giant and Minute Man Groups, Shoshone Geyser Basin



collected over a period of one to several days with an automatic temperature logger under NPS permit. For data collected manually, the start time was defined as the first continuous discharge of water into the south runoff channel.

It is interesting to note that Double completely dominates the complex of vents surrounding it. Little Giant, a small unnamed geyser (see #11 below), and another spring immediately southeast of Double all respond to Double's eruptions with lowered water levels and increased eruptive activity.

Little Giant Geyser #9

Aside from a large but unrecorded eruption that scoured its runoff channels in the fall of 1991 [Paperiello, 1992] and another large eruption reported in 1988 [Bryan, 1995], Little Giant had only minor activity. The small, splashing minor eruption begins just after Double starts and dies down to an indistinct end. In 2002, Little Giant was less active than at any time during the past fifteen summers. The small, formerly vigorous spouters between it and Double were inactive.

Unnamed geyser #11

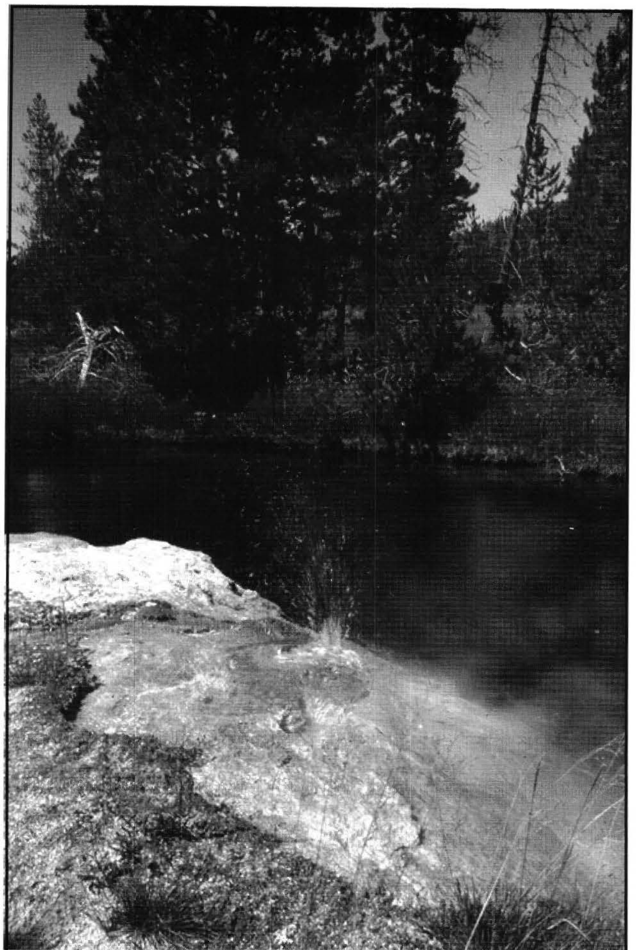
Mapped by Paperiello as #11, this geyser was regularly observed from 1991 through 1996. It was also noted active in August of 2000. Whenever seen, the inches–high spraying eruptions began shortly after Double's, the interval between eruptions being punctuated with weak sputtering.

"Meander Geyser" #12

Meander Geyser was observed in eruption during every year between 1993 and 2002, and also in 1991. Intervals and durations seem to be hours long with eruptions reaching around 3 feet.

"Trio Geyser" (unnumbered)

This new geyser, first seen in 1998, erupts from three small, closely–spaced vents on the upstream side of Meander's platform. Also observed in 1999, 2000 and 2002, eruptions have preceded all witnessed starts of Meander. The delay between the start of Trio and the start of Meander has been 27 to 30 minutes, the total duration of Trio being 33 to 38 minutes. Maximum heights are around 4 feet.



Trio Geyser in July 1999. (Photo by Jeff Cross)

Locomotive Geyser #14

Locomotive has been conspicuously dormant from 1990 through 2002. Grass is presently growing on the platform.

SULPHUR HILLS GROUP (not mapped)

Lying immediately east of the Little Giant Group and west of the Shore Group is the acidic Sulphur Hills Group. The main focus of activity is at the west end, just over a low ridge east of Trail Geyser. The trail from the lake to the geyser basin used to pass through this group but was partially obliterated by a hot spring that developed in 1994. The trail has been rerouted around the north end of the ridge separating the lake from the main geyser basin.

MINUTE MAN GROUP (see Map B)

"Skylight Geyser" #10a

Although this geyser is easily visible from the trail, its small size makes it easy to overlook. It has been active every year from 1998 through 2002, with intervals ranging from 69 to 94 seconds and durations of 39 to 56 seconds. The maximum height is 1 foot. Some eruptions barely break the surface. Geyser activity was also noted during 1992–1996. Overflow issues from a secondary spring closer to the creek.

Soap Kettle #11

The large eruptions that occurred throughout the 1990's occurred less often in 2002. Intervals from 1998 through 2002 remained in the 6 to 27 minute range, with durations of 25 to 225 seconds. Typically the intervals and durations varied substantially during an hour. Longer eruptions tended to be more powerful. Sometimes there was a trend of lengthening intervals and durations over several cycles, corresponding to progressively larger eruptions. After a long interval, intervals and durations abruptly shortened, only to gradually lengthen again.

Little Bulger #12

Little Bulger's east vent remained active at all times; no activity from the main vent was seen. The tendency for Little Bulger's east vent to pause more frequently, with a corresponding drop in the pool level, following larger eruptions of Soap Kettle was noted in 1999, 2001 and 2002. Several of the rocks emplaced by vandals in 1994 still obscure the main vent.

Minute Man Geyser #30

That Minute Man Geyser erupts in series is generally known. That it often has up to three brief eruption series, consisting of one to several eruptions, prior to the full series is less well known. These were observed in 1994 [Paperiello and Murray, 1994], 1995 and 1996 by Rocco Paperiello [Paperiello *in* Cross, 1998], and by us in 1997 [Cross, 1998], 1999 and 2000. In each case, there was only one preliminary series. But in 2001, one full series was preceded by two preliminary series, and in 2002 all full series seen from the start followed three preliminary series. Intervals between preliminary series were 30 to 60 minutes, with a 55 to 105 minute interval preceding the full series. The occurrence of multiple preliminary series seems to be a recent phenomenon.

Minute Man has two types of eruptions. Individual eruptions *not* accompanied by Minute Man's Pool (see below) typically reach 10 to 20 feet high and last for about 10 seconds. But when accompanied by the Pool, Minute Man's eruptions last up to 50 seconds, often reach 30 feet high, and are accompanied by a soft roaring sound. Individual eruptions of either type are typically separated by one to several minutes.

Series start–to–start intervals from 1998 through 2002 ranged from 5 to 9½ hours. The longest known interval occurred in 2002 and may be related to the numerous preliminary series observed that year. Series durations during the same time have been 3 to 4 hours.

Little Bulger Geyser, as it was in August 1974 before the development of its east "parasite" vent. (Photo by Scott Bryan)

Minute Man's Pool #31

Although large eruptions of Minute Man's Pool have not been observed since the middle 1970's [Bryan, 1995], the Pool has been consistently active as a geyser. Eruptions occur exclusively toward the end of Minute Man's series. Individual eruptions of the Pool always begin after individual eruptions of Minute Man have begun, and end after Minute Man ends.

Two of the sixteen series with recorded end times seen from 1998 through 2002 involved eruptions of the Pool. Maximum heights have been 8 feet.

Minute Man's Pool during one of the major eruptions of May 1977. (Photo by Scott Bryan)

Unnamed vent west of Minute Man (unnumbered)

This vent has enlarged considerably since 1992, when it appeared as a small hole in Minute Man's western runoff channel. A second vent appeared in 1993. Further enlargement occurred between the summers of 1997 and 1998 when a small pool formed, obliterating the original vents. Although small sputtering eruptions were seen prior to 1997, none have been seen since then.

Gourd Spring and Shield Geyser (#16 and 19)

Gourd Spring and Shield Geyser became exceptionally active during the summer of 1997. Prior to this, intervals of 1 to 2 hours and durations of up to 1 hour were noted in 1995 and 1996. After the nearly continuous activity of 1997, Gourd and Shield gradually returned to the more usual 1 to 2 hour intervals and 1 to 1½ hour durations by 2000.

Rosette Spring #15

Intermittently rising and falling water levels in Rosette have been occasionally noted [Bryan, 1995; Cross, 1998]. However, at some time between mid–July and late–August, 2001, Rosette had one or more significant overflows that washed out a runoff channel leading toward Shoshone Creek.

Unnamed geyser #21

During the early 1990's, intervals of 9 to 12 minutes and durations of 1 to 2 minutes were noted. Although generally only an intermittent spring, overflows were occasionally accompanied by violent boiling and rare eruptions. Because this vent lies in the middle of one of Shield Geyser's runoff channels, it is effectively squelched whenever Shield erupts. The generally greater activity of Shield from 1996 through 2002 has prevented this feature from having its best activity. Recent intervals have been as short as 15 minutes but are often quite a bit longer.

Unnamed geyser #22

This very pretty intermittent spring was overflowing every 2 minutes during 2002. Eruptions have been noted in every year since 1986 [Bryan, 1995; Paperiello 1989], and a second vent was also active in 1999 [Murray, 2003].

Five Crater Hot Spring #23

After suffering a dormancy due to the heavy activity of Shield Geyser during 1997 and 1998, Five Crater was active as a geyser in 1999, and has remained active since then. Intervals ranged from 295 to 380 seconds, with durations of 110 to 180 seconds. One data set of ten eruptions obtained in 2002 had intervals of 345 to 380 seconds with an average of 362 seconds and a standard deviation of only 3.1% of the average, demonstrating that Five Crater can be quite regular. At the same time, the durations were 110 to 140 seconds with an average of 124 seconds (ten durations). The maximum height of the eruptions is 3 feet. Because it lies in the middle of Shield Geyser's runoff channel, Five Crater acts as a pulsing intermittent spring when drowned by Shield's overflow. Five Crater was also seen erupting as a geyser from 1991 through 1994 [Cross, 1992, 1998].

ORION GROUP (see Map C)

It is unfortunate that the Orion Group has suffered a severe and long–standing dormancy. Most seriously affected are Union Geyser (#27) and the thermal features directly east of it — White Hot Spring (#35) and "Sea Green Pool" (#30) — which have remained at very low levels for the nearly the entirety of this study. The water levels seem to be related to the local ground water table, being higher earlier in the season, highest during wet years and lowest during dry years. Year 2003 marks the 27th consecutive summer of Union Geyser's dormancy.

Taurus Spring #6

Following Taurus's spectacular 50–foot high eruptions in July 1997 [Murray *in* Cross, 1998], Taurus remained inactive until just prior to July 12, 2003, when one or more unseen eruptions occurred, as inferred from heavy wash. Unlike the 1959 and 1997 eruptions, the 2003 activity apparently was not associated with any earthquake. (See photo on page 178.)

Unnamed geyser #21

For just over a decade, this was the only geyser we ever saw erupting in the Orion Group. Geyser activity was noted in 1989 and 1990, and from 1992 through 1998. It was likely active in 1991, too, although no eruptions were seen directly. Intervals were always between 1 and 4 minutes, usually in the 1 to 2 minute range, with durations of 15 to 69 seconds, again usually near the shorter end of the range. It was dormant in 1999. Ironically this dormancy happened because a nearby spring (#22) had increased its overflow, flooding the geyser's small crater with cold water. The dormancy continued through 2001. By 2002 the runoff had dried out again and #21 was erupting continuously to 1 to 2 feet.

Unnamed geyser #36

In 2002 this vent was active as a perpetual spouter, erupting to 1 foot. At other times it has been active as an intermittent spring.

Unnamed geyser #25

Located on the bank of Shoshone Creek, this geyser was observed erupting a few feet high in 1997 [Paperiello *in* Cross, 1998]. A similar thermal feature lies just upstream.

CAMP GROUP (see Map D)

Geyser Cone #24

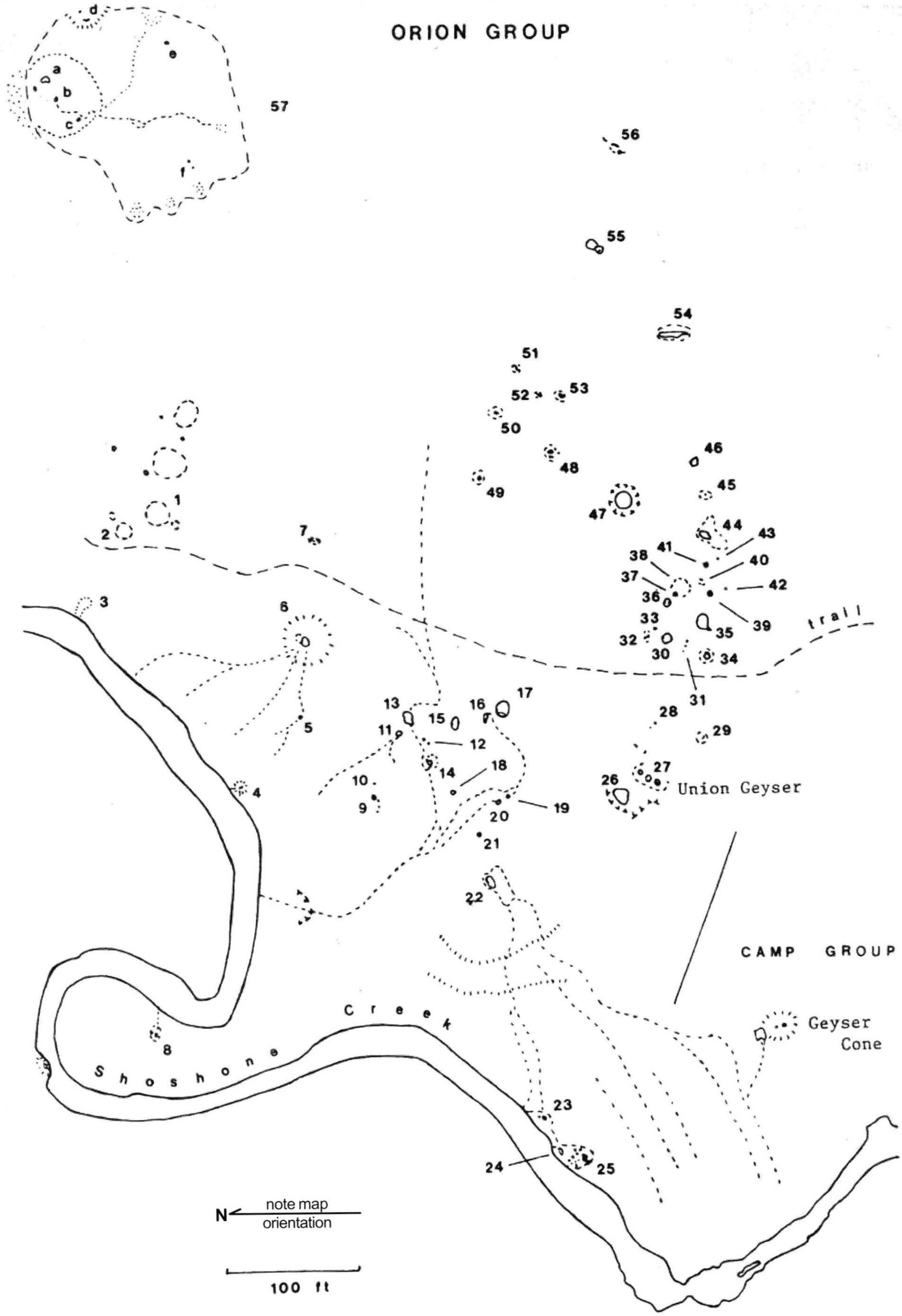
Geyser Cone has been dormant since the summer of 1996. At some time between the summers of 1995 and 1996, it underwent a large eruption that scattered sinter pebbles over the mound and washed sand off the formation, depositing it up to 45 feet away. Whatever happened to Geyser Cone had a catastrophic effect, since only quiet gurgling has been seen from it since then. Grass has been growing in the crater since 2001.

Although Geyser Cone was active before 1993 [Bryan, 1995; Paperiello, 1989], we did not see it erupt until then and were unaware that it was a geyser. During 1993, 1994 and 1995, we saw it erupt in series every 26 to 48 minutes, with eruptions occurring every few minutes during the series. The eruptions sprayed water to 3 feet.

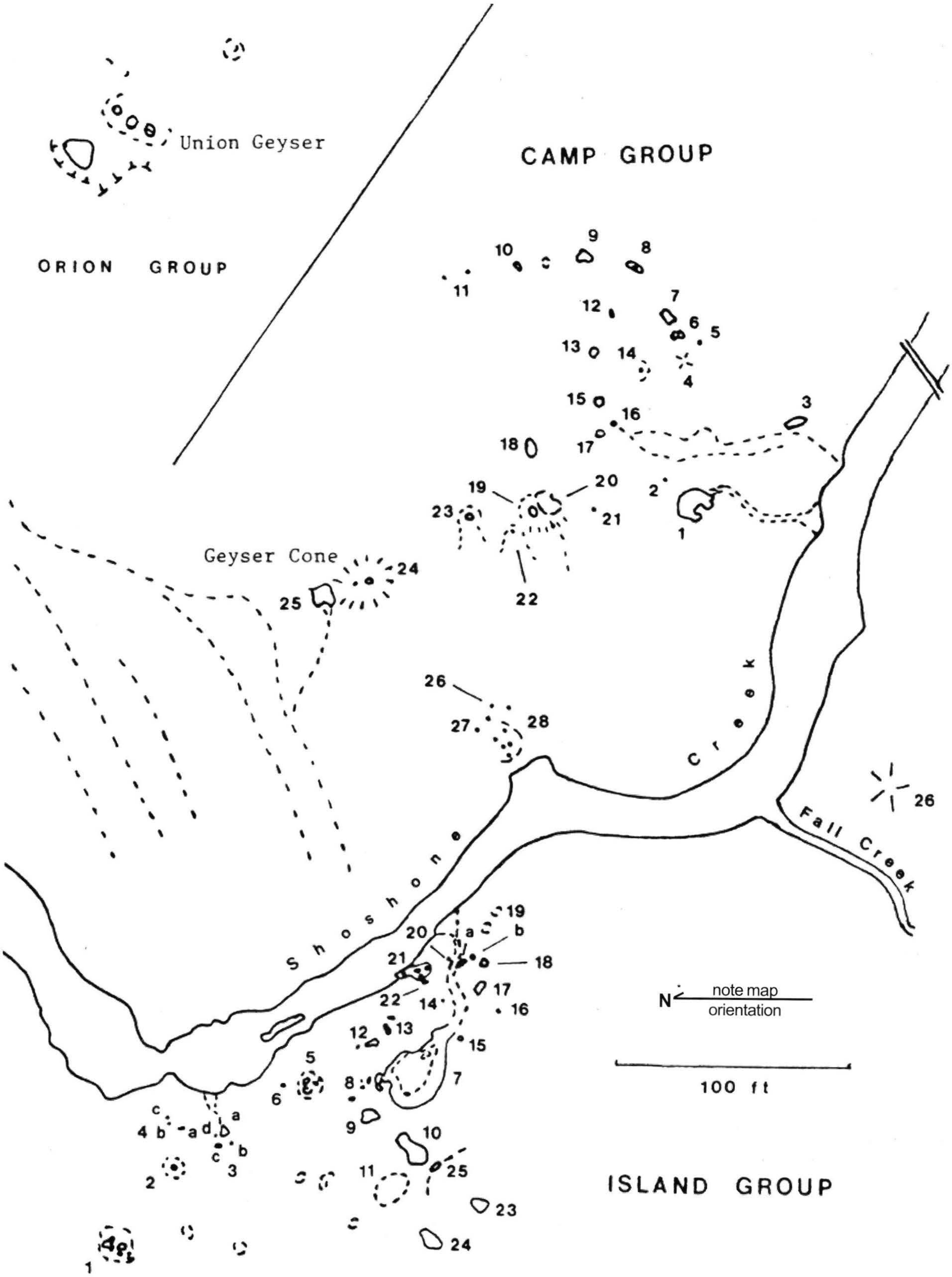
Unnamed geyser #16

Heavy wash around this vent indicated that it had erupted some time during the first half of 2002. It was probably dormant for the remainder of the year. It was also active in 1996 [Paperiello *in* Cross, 1998].

Map C — Orion Group, Shoshone Geyser Basin



Map D — Camp and Island Groups, Shoshone Geyser Basin



Unnamed geyser #7

One tiny eruption a few inches high was seen in July 1999.

Unnamed geyser (unnumbered?)

One of the muddy vents in the vicinity of Paperiello #s8–11 was active as a small geyser in July 1999.

YELLOW CRATER GROUP (not mapped)

Unnamed geyser

This pool was active as a geyser in 2000. No eruptions were seen, but wash surrounded the pool and grass was killed and pushed over as far as 10 feet away from the pool's large end. The pool, which is triangular and roughly 30 feet by 15, is 75 paces (about 187 feet) west–northwest of Blowout Pool, a hot and tremendously deep pool southwest of an old and barely visible trail that used to cross Shoshone Creek west of Minute Man Geyser. This spring is on the north side of this same trail. Just south of it is a collection of perpetual spouters. (It is possible that the historic name, Boiling Pond, refers to this feature, which recently has been informally called "Wedge Spring."

Unnamed geyser

This is the northernmost thermal feature on the west side of Shoshone Creek. It sits atop a sinter mound at the southwest edge of a large meadow. Several of the numerous vents in the pool have been periodic at various times, one of them showing geyser action in 1996 and 1997, and 2003 [Murray, 2003]. Maximum heights have been 1 to 2 feet, although heavy wash suggests that larger eruptions may sometimes occur.

NORTH GROUP (see Map E)

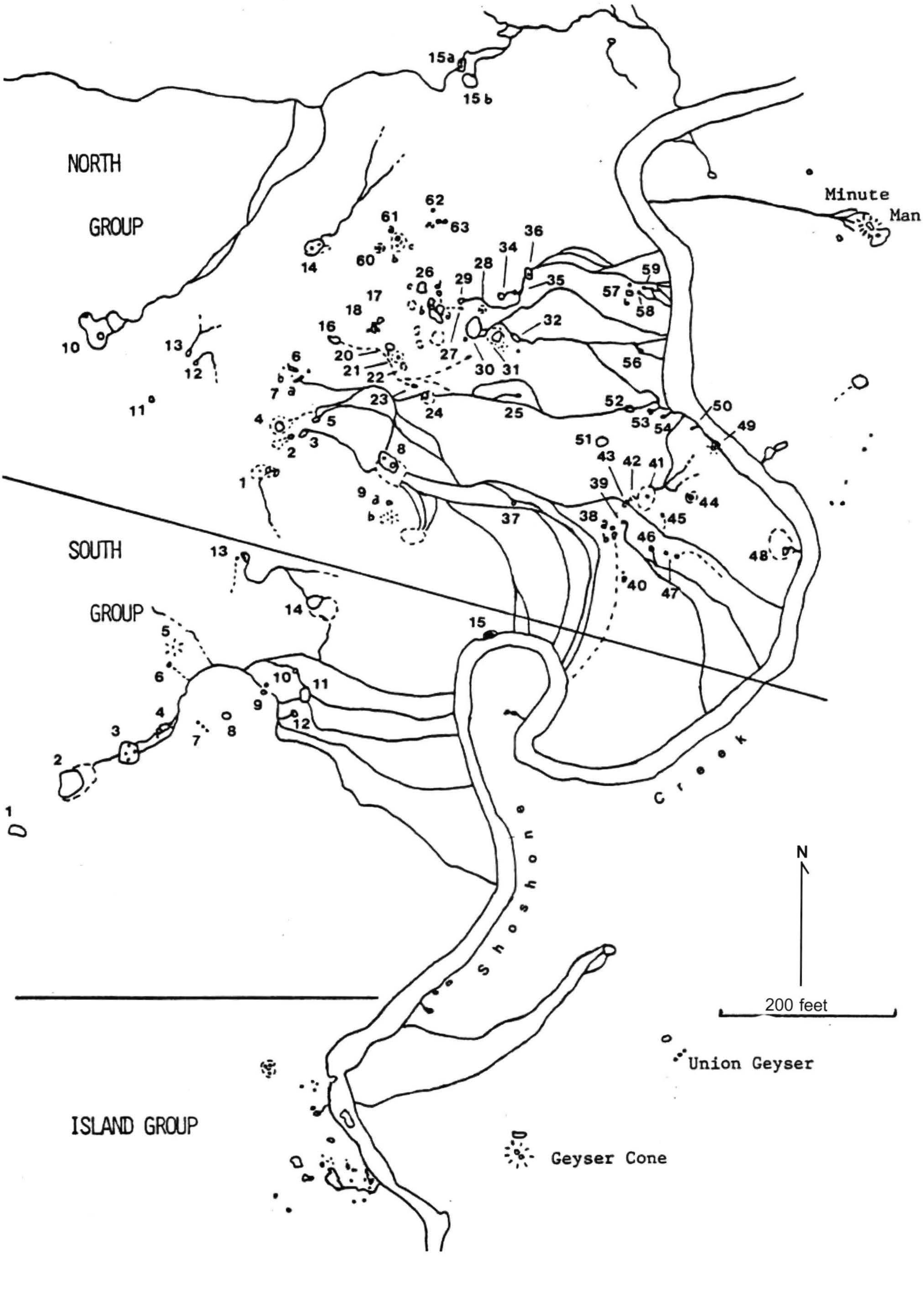
The North Group contains at least 26 geysers. Many of them were influenced or created by a remarkable increase in hydrothermal activity that appeared in the North Group in 1998 and continued through 2002. Two geysers, informally named "The Hydra," which began erupting in 2002, and "Slosh Geyser," which was active in 1999 and was first seen in eruption in 2001, had no known history of eruptions. Numerous other geysers, such as Velvet Spring, Fissure Spring and its companion "Snail Geyser," rejuvenated after years–long dormancies. An exchange of function shifted energy from Yellow Sponge Spring to Small Geyser, which began overflowing for the first time in many years. Finally, Bead Geyser reactivated after a dormancy of unknown but possibly century–long duration and was seen erupting in early June 2003 [Young, 2003] and again later in the month, indicating that the North Group is still dynamic and merits future attention.

Lion Geyser #41

Lion was active during most years from 1988 through 2003, with dormancy in 1996 and also possibly in 1990. It was seen erupting in October 1991 [Paperiello, 1992], but was not seen by us earlier in the year. Lion's most impressive activity took place in 1992 and 2003, when eruptions

Lion Geyser in July 2003, when it was undergoing extraordinarily large–size eruptions. (Photo by Jeff Cross)

Map E —North and South Groups, Shoshone Geyser Basin



Another July 2003 eruption of **Lion Geyser**. (Photo by Jeff Cross)

reached 20 feet vertically and 40 feet horizontally, occurring on intervals of 2 to 4 hours and lasting for up to 11 minutes. During other years eruptions were about half that size with shorter intervals of close to one hour and durations of around 5 minutes. Fifty–three closed intervals recorded to–the–second from 1998 through 2002 ranged from 52 to 67½ minutes, with averages of 54½ to 58 minutes. Standard deviations of 1.8 to 5.4% of the mean demonstrate that Lion's intervals were quite regular. Durations ranged from 249 to 363 seconds, with standard deviations of 1.9 to 5.0% of the average, demonstrating that Lion's durations were also regular.

Interestingly, Lion sometimes became irregular during and immediately after rainstorms. The most striking example of this occurred on 03 August 2002. Intervals beginning at 8:06 that morning ranged from 58 to 62 minutes. During the late afternoon it rained. The two intervals immediately following the rainstorm were 66 and 100 minutes. Lion followed the 100–minute interval with two normal intervals of 58 and 56 minutes [Goldberg, 2002]. The same phenomenon was also seen in 2001, when an 80–minute interval occurred during a rainstorm, followed by intervals of 53 and 57 minutes.

Unnamed vents #44 and 45

Downhill from Lion are several vents, some of which lower their water level when Lion erupts. The most prominent is a small reddish vent southeast of Lion. Although it is has often been surrounded by a small sand berm and has a lightly incised runoff channel, we have never seen it erupt.

"Old Lion Geyser" #43

This vent southwest of Lion blew out in 1991 and was active as a geyser, with one observed eruption occurring in October [Paperiello, 1992]. The vent remained open through 1992 and 1993, but it has since disappeared under a thick layer of silt. Another hole (#42) between Lion and Old Lion also opened in 1991 and was silted over by 1994, but it blew out again in 1998 and remained open in 2003.

Iron Conch Geyser #46

Iron Conch was consistently active from 1989 through 2002. Intervals between 1995 and 2002 ranged from 221 to 560 seconds, with averages of 269 to 383 seconds and standard deviations of 4.5 to 22% of the average. Intervals were timed between the initiations of overflow in consecutive cycles; this is the only distinct event that occurs during the cycle. Eruptions splash water to 3 feet.

Bronze Geyser #38b

Bronze Spring has been dormant since the mid–1980's [Paperiello *in* Cross, 1998].

"Slosh Geyser" #25

Slosh Geyser is the largest of several geysers that made their appearance in the North Group between 1998 and 2003. It was certainly active in 1999 when heavy wash was noted about the crater,

"**Slosh Geyser**" in July 2001. (Photo by Jeff Cross)

but no eruptions were seen. Slosh was inactive in 2000, but in 2001 it was active again. Heavy wash surrounded the crater and frequent minor eruptions, reaching a few feet high, were noted. The bursts of the minor eruptions pushed the water back and forth in the small crater, creating a pronounced sloshing, hence the name.

A major eruption occurred on 14 July 2001. It began during a strong minor eruption and gradually built strength as it emptied the crater, peaking at 20 feet before going into a forceful steam phase, which was still in progress 29 minutes after the eruption's start. The eruption column entered the crater through a small vent about 30 inches below the surface, struck the far wall, and deflected upward. The runoff was cloudy and Shoshone Creek was noticeably opacified by the discharge. Numerous small pieces of rock and sinter were thrown out of the crater during the eruption.

An interval of 15 hours was inferred in July, 2001. However, in August a data logger placed under NPS permit recorded two eruptions, spaced two days apart. No eruptions occurred for four days prior to the first eruption, and none occurred for five days after the second eruption, suggesting that the intervals at that time were both long and irregular. Only one other eruption of Slosh was reported during 2001 [Moats, 2001].

Observations in 2001 indicated that Slosh's minor eruptions were squelched by cool runoff flowing downhill from Knobby Geyser. The major eruption began during an exceptionally long Knobby interval. Slosh has enlarged its vent since the 2001, blasting out large chunks of sinter. Evidence of this was seen in 2002, indicating some unseen major eruptions that season. One major eruption was observed by Clark Murray in July 2003 [Murray, 2003], and others were inferred by heavy wash in the runoff channel.

Frill Spring #31

Frill Spring's activity has long remained elusive. A few people were lucky enough to witness eruptions during the mid–1990's, but the frequency at which such events occurred was uncertain. With the use of data loggers, it was determined that during 1998 and 1999 eruptive series occurred every 4 to 5½ days, each series lasting 7½ to 10 hours. Within a series, eruptions came every 8 to 25 minutes, with the shorter intervals at the beginning of the series. Durations could not be determined from the data logger records, but durations during a series seen by us in 1997 [Cross, 1998] were less than 30 seconds long. The maximum height was around 10 to 15 feet.

From 2000 through July 2003, Frill has been dormant. The cause of this dormancy is uncertain, although it may be related to an influx of runoff from Small Geyser ponding in Frill's splash basin, which contains a few small vents that could drain into Frill itself. Frill was active in 1994 and 1996 [Paperiello *in* Cross, 1998]. It was also active in 1997, seen by us once and by Clark Murray [*in* Cross, 1998] on separate occasions. The series we observed in 1997 lasted only 167 minutes, which is abnormally short relative to the data logger records and personal observations of others.

The pool just uphill from Frill is known to be related to Frill. It has been observed to stop overflowing while Frill is in series, and we have seen it stop overflowing when Frill has a strong overflow.

Pearl Spring #32

Eruptions were noted in 1996 while nearby Frill Spring was having an eruption series [Paperiello *in* Cross, 1998].

Unnamed geyser (unnumbered)

This small vent south of Pearl Spring was active as a small, 6–inch high geyser in 1994 and 1996, erupting every 25 minutes for 20 seconds [Paperiello *in* Cross, 1998].

Grotto Spring #34

Grotto Spring was apparently active as an intermittent spring or small geyser in 1998. Although none of the activity was seen, it was inferred from light wash, dead plants, and intermittently silty water. Downhill from Grotto Spring is a sinkhole (#36?) that opened up between the 1997 and 1998 summer seasons.

Mangled Crater Spring #26

Mangled Crater Spring is a highly regular geyser. Of the 27 closed intervals obtained from 1999 through 2002, none strayed from the 90 to 97 minute range. Durations were 9 to 12 minutes. Eruptions gained power in 1997, bursting as high as 6 feet and discharging enough extra water to carve a new runoff channel leading downslope from the main vent. The stronger eruptions continued for several years, but had diminished to pre–1997 activity by 2002.

It is important to note that only by watching the eruption of the north vent can one accurately record duration and interval data for Mangled Crater. There is extensive preplay from the main vent that is easy to mistake for a full eruption. When the north crater begins boiling, the main vent often increases its power quite suddenly, but this increase is not always obvious from a distance. The end of the eruption is distinct.

Unnamed geyser #63

Activity from this geyser began in 1996. New runoff channels remained freshly washed until 2002, when they began to weather, implying dormancy. The unseen activity probably reached a few feet high. The erupting vent opens under a sinter ledge.

Unnamed geyser #61b

A small geyser vent in this complex just upslope from #63 has been active from 1998 through 2002. No intervals or durations have been determined. The eruption is usually only a few inches high.

Knobby Geyser #24

During most years, Knobby Geyser is the most prominent and vigorous geyser in the North Group. Its best activity during the last five years was in 1999, when eruptions occasionally reached 25 feet. Knobby's eruptions often naturally sort themselves into three types: majors, intermediates, and minors. Majors typically reach 10 to 25 feet high and last 1 to 5 minutes. Intermediates typically reach around 5 to 10 feet high and last less than 2 minutes. Minors typically are brief and reach less than 5 feet high. Intervals tend to be bimodal at around 10 to 12 minutes or less than 5 minutes, but the modes have shown considerable flexibility and the 10 to 12 minute mode may split to include intervals of 8 minutes or of 17 to 18 minutes without significantly altering the classical form of the series.

Series typically begin with intermediate eruptions occurring every 10 to 12 minutes. One of these intermediate eruptions turns into a major that lasts for several minutes. The major is followed by numerous minor eruptions occurring on intervals of seconds to a few minutes, and a period of quiet then ensues until the next series starts. This type of activity was seen in 1991, and 1995–1999, but it seems to have evolved into a more free–form structure during 2000–2002. Unimodal series of relatively weak eruptions were seen in 1992–1994. Activity prior to 1998 is discussed in Cross [1998].

In July 1998, major eruptions did not occur. However, the intervals followed the usual pattern, with 10 to 14 minute intervals at the beginning of the series and sub–5 minute intervals at the end. Oddly, the intermediate eruptions, at only a few feet high, were now *smaller* than the minors, which reached up to 12 feet high. The major–minor classification was made on the basis of interval, not eruption size. That the larger eruptions occurred toward the end of the series was due to the crater emptying with each successive eruption. The early, full–crater eruptions seemed to be weakened by the excess water that was present at the beginning of a series.

In August 1999, Knobby had its best activity since the early 1990's. Major eruptions frequently reached 25 feet. Classical series patterns were followed, but quiet periods between series were shorter than usual. Oddly, 1999 also included the only recent known dormancy of Knobby, which occurred in July while a hole a short distance upslope was acting as a drain for a runoff stream.

In 2000, intervals were again bimodal, with 464 to 773 seconds and 177 to 305 seconds forming the two modes. Durations were similarly bimodal, with 106 to 168 and 7 to 42 seconds forming the two modes. The classical series behavior was not present. Instead, short major eruptions were commingled with intermediate and minor eruptions seemingly at random. Long intervals tended to follow longer eruptions, and sometimes a repeating long–short pattern of intervals and durations developed.

In 2001, classical series beginning with intermediates and ending with minors were observed. However, following a major eruption, Knobby often went back to intermediate eruptions followed by another major. Occasionally a major eruption would interrupt a series of minors. In any case, Knobby was in–series most of the time.

In 2002, Knobby was again in–series most of the time. Classical series behavior was not seen, although the intervals and durations were sometimes strongly modal. Taken as a whole, the summer's activity was trimodal, with short mode intervals that varied from 150 to 350 seconds, a second mode that was typically 450 to 550 seconds, and a long mode that was around 900 seconds. Durations were also bimodal at times, with a short mode of less than 40 seconds and a long mode of around 100 seconds. Also seen, for the first time, were series of descending intervals. Durations during these episodes did not follow the same trend, but long eruptions were never associated with short intervals.

Unnamed geyser #23

This geyser's crater, presently 7 feet by 4 feet, formed between the summers of 2001 and 2002.

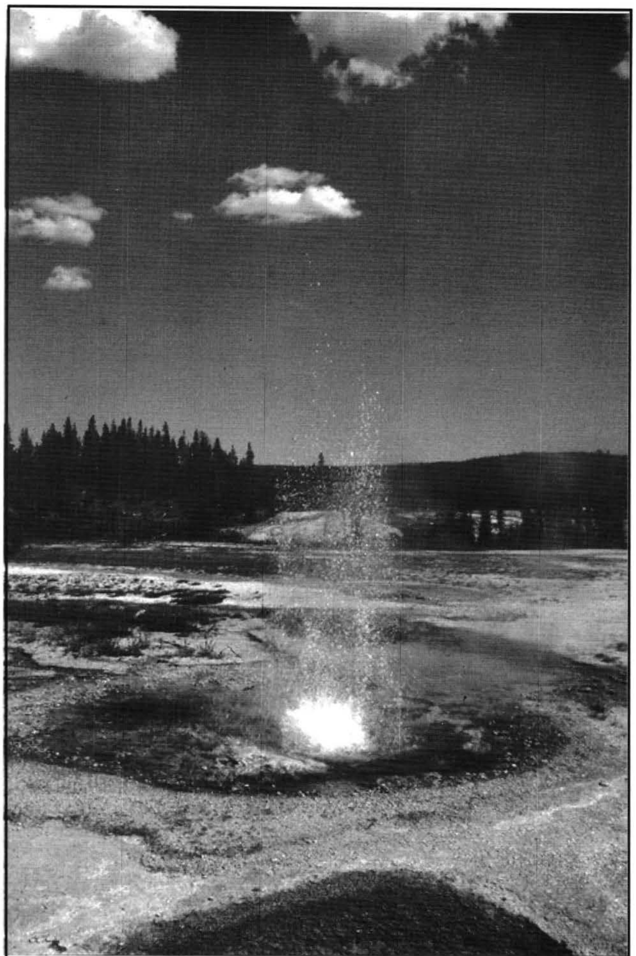
The recent history of this vent, which occupies a sunken area just upslope from Knobby Geyser, has been one of continual change. It was open in 1991, covered in 1992, open from 1993 to 1995 and again covered from 1996 to 1998. It opened again in 1999, when it was acting as a sink for a runoff stream. That Knobby was dormant at that time was likely not coincidental, since the water seemed to circulate down through this vent and flow out through Knobby, squelching its eruptions.

In 2000 numerous small vents were present at the site. In 2001 the area had sunk even more, revealing broken sinter sheets. Sometime between September 2001 and June 2002 the area completely caved in, forming a crater full of tilted plates and blocks of sinter. A small geyser could be seen playing under the rubble. The observed 1 to 2 foot eruptions were related to the cycles of Knobby Geyser. Larger eruptions were not seen, but their occurrence was clearly inferred from heavy wash around the crater. Although most of the crater–forming activity took place prior to July 2002, the crater continued to grow throughout the summer.

Bead Geyser #21

After a decades– and possibly century–long dormancy, Bead Geyser was seen in eruption in June 2003. Two eruptions seen in early June occurred about an hour apart and reached 15 to 20 feet high [Young, 2003]. Two weeks later, four eruptions were seen on intervals of 108, 98 and 95 minutes, reaching heights of 10 to 20 feet and lasting for 100 to 120 seconds. Eruptions began after several minutes of increasingly vigorous bubbling.

For many years, Bead Geyser and nearby Terracette Spring have had an interesting relationship: the water rises and falls in both, and is always high in one when it is low in the other. This continued in 2003, when eruptions of Bead would occur 7 to 8 minutes after the last high water level



Bead Geyser in July 2003. A small part of "Terracette Spring's" crater is in the foreground. (Photo by Jeff Cross)

peak of Terracette.

During bead's long dormancy, the area surrounding its crater became weatehred and overgrown with moss. In 2003, all of the moss and sinter gravel that had accumulated around the crater was washed away, revealing an old crater decorated with delicate beaded deposits.

"Terracette Spring" #20

This beautiful round spring is inlaid with tiny sinter "terracettes," was erupting as a geyser in August 2000. The eruptions came in pairs every 8 to 11 minutes, with the two eruptions spaced just over a minute apart. The eruptions lasted for 1 to 1½ minutes and threw water a foot or two into the air, accompanied by loud thumping sounds. Occasionally Terracette skipped an eruption pair, and at these times nearby Bead Geyser rose to within a few inches of overflow. The runoff followed an old channel to the south and carved a new channel to the north.

In 2001, Terracette was still active, but the intervals had lengthened to 19 minutes and only infrequently did a cycle include any bursting. By 2002, the cycles had lengthened to 22 to 27 minutes. Prior to 2000 Terracette had often been surrounded by a light sand berm, suggesting that it might have had rare eruptions. Ever since we first watched it in 1992 Terracette has been an intermittent spring, and Bead Geyser's water level has always reciprocated with it. Some small eruptions were noted in the early 1980's [Paperiello *in* Cross, 1998].

Following an eruption of Bead Geyser, the water in Terracette drops 4 to 6 inches.

"Troll Spouter" #18

This spouter erupts from a crater spanned by a thin bridge of sinter. The small eruption has sometimes been periodic and reaches up to 2 feet high. The name was suggested by Clark Murray.

Small Geyser #16

Small Geyser is much more active than it used to be. Prior to 1997 it never overflowed, despite the existence of a prominent runoff channel. In 1997, some wash in the runoff channel and around the crater was noted. In 1998, Small was overflowing weakly. By 1999 it was overflowing heavily, and this continued through 2002. Although the overflow was heavy, it never completely filled the old runoff channel. It is likely that Small Geyser now discharges water that used to issue from the Yellow Sponge complex a short distance to the south. Small's short cycles of several minutes each lack any definite structure. The eruptions are usually less than 4 feet high.

Yellow Sponge Spring #6

Prior to 2000, Yellow Sponge Spring was vigorously active. The nearly–continuous eruption waxed and waned, reaching up to 10 feet above pool level. In 2000, Yellow Sponge apparently suffered an exchange of function to nearby Small Geyser and its activity is now severely enfeebled.

"Yellow Sponge Crack" #7a

Along with Yellow Sponge, which is situated only a few feet away, this long fissure is nearly dormant. Prior to 2000 it overflowed heavily and spouted to a foot or two, pausing briefly several times an hour.

"Yellow Sponge Cone" #7b

In 1998 and 1999 this small geyser erupted from a tiny cone at the eastern edge of the Yellow Sponge complex. Eruptions came at irregular intervals of up to 8 minutes. Durations were less than a minute, and the maximum height, seen in 1998, was 3 feet. By 2000 it had stopped erupting.

"**Snail Geyser**" during 1999, when it underwent eruptions larger than at any other known time. (Photo by Jeff Cross)

Fissure Spring and "Snail Geyser" #2 and #4

Fissure Spring and nearby Snail Geyser erupt together. Snail is the larger of the two, and strangely its biggest bursts seem to occur as the water level is falling below overflow. It usually continues to splash for a long time after Fissure Spring has stopped.

Fissure and Snail reactivated in 1998 and were active through 2002. Intervals have varied significantly, from a short of 88 minutes in 1999 to a long of 251 minutes in 2001. In 2002 two intervals of 4 and 7½ hours were seen, but sometimes an entire day would pass without any eruptions. Durations have always been 6 to 10 minutes. The best activity occurred in 1999, when intervals were 88 to 113 minutes with an average of 94 minutes. Eruptions of Snail reached up to 6 feet high, about twice the height usually seen. The 1999 eruptions killed grass and expanded the washed area around the crater.

These geysers were also active in 1991 through 1994 on intervals similar to those seen from 1998 through 2001. Fissure and Snail are clearly related to a nearby unnamed spring (#3) located a short distance to the northeast — their eruptions always lower its water level. When Fissure and Snail are inactive, this nearby spring is commonly at or near overflow while several small vents along the spring's margins sputter a few inches high.

Unnamed geyser #1

Beginning in 1998 and continuing through 2002, this small geyser was frequently active. Apparently it is cyclic; sometimes eruptions were not seen for extended periods but were quite frequent at other times. When erupting, its intervals typically ranged from 1 to 3½ minutes, with durations of 20 to 160 seconds. Both durations and intervals tended to be irregular.

Three vents form the geyser complex. The eruptions come from the low cone at the peak of the formation. West of the cone is a pool with an irregularly–shaped vent. To the south is a small vent that overflows when the cone is not in an eruptive phase. Geyser activity in the cone causes both the other vents to ebb. Overflow from the cone was rare prior to 1998 (although intermittent activity was noted in both 1992 and 1994). By 2000, runoff channels from the new activity were established. When active, its 1– to 3–foot high eruptions came at intervals of 1 to 3½ minutes. In 2002, the geyser was still active, but less frequently than before; in July 2003 the action was again frequent and vigorous.

Velvet Spring #8

Velvet Spring was active in 1988, 1994, briefly in July 1996 [Murrya, 2003], and 1998 through 2001. Average intervals ranged from roughly 11½ to 13 minutes, with standard deviations typically being less than 10% of the average (often around 2 to 4%). Average durations ranged from about 2 to 2¼ minutes, the variation in duration being greater than that in the interval, typically 5 to 11% of the average.

As noted previously [Cross, 1998], Velvet has occasional false starts. False starts occur about when an eruption is expected, and are followed by a normal eruption after a pause of 4 to 5 minutes; the total interval is around 17 minutes instead of the usual 12½. In 2001, two false starts were correlated with discharge from eruptions in the Fissure Spring complex flowing into Velvet's west vent.

Velvet Spring as it appeared in July 1976. (Photo by Scott Bryan)

In 1998, 1999 and 2001, Velvet would sometimes go several hours without any eruptions. Any eruptions that occurred during these periods were weak and occurred on short, irregular intervals. When major activity resumed the initial eruption was often exceptionally forceful. The cause of these brief dormancies is unclear, although in 2001 one such episode correlated with a heavy rainstorm.

When active the crater partially empties between eruptions. When inactive, Velvet is full and intermittently overflowing, occasionally boiling up a foot or two.

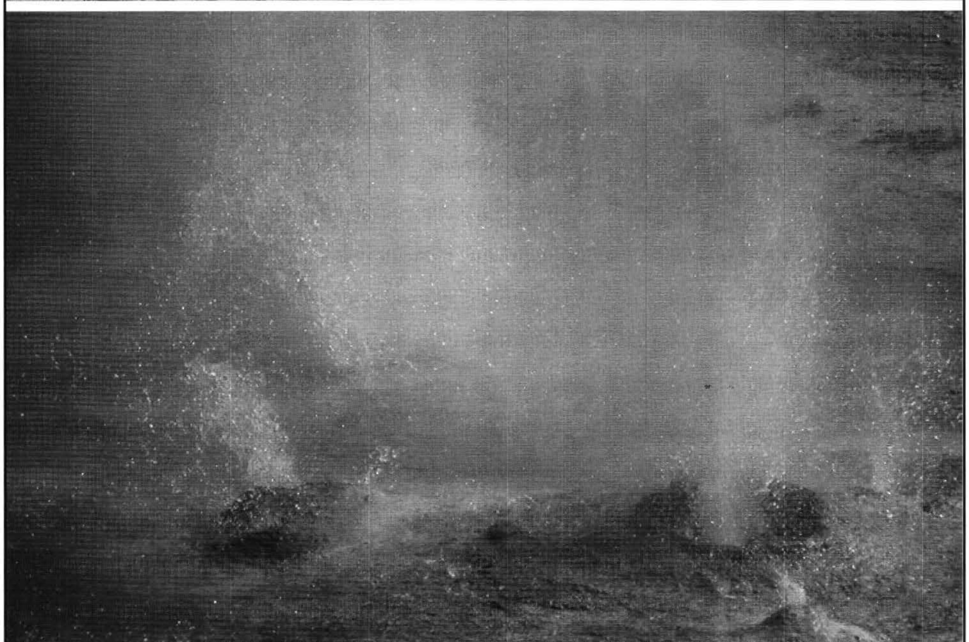
A view looking south–southwest toward "**The Hydra**" in July 2002. (Photo by Jeff Cross)

"The Hydra" #9

One of the most important developments in the North Group is the unprecedented geyser activity in this small cluster of vents south of Velvet Spring. The complex consists of a small sinter formation having the general profile of a volcanic cinder cone (#9b). Scattered around the flanks of the cone are twelve smaller vents. Immediately to the north is a small pool (#9a).

In 2002, we were surprised to discover that the entire complex was experiencing forceful eruptions. The eruptions occurred in series every 1 to 4 days, as shown by data logger placed uner NPS permit and direct observation. Intervals between series were irregular, although seven of the thirteen known intervals were between 40 and 46 hours. Intervals between individual eruptions were typically 1½ to 2 hours. The observed series on 11 and 13 July 2002 each included a single minor eruption between the first and second major eruptions of the series. Minor eruptions were detected by the data logger placed in 2003; they were not detected in 2002 but no doubt still took place.

The eruptions were impressive. The highest jets came from the central cone, which shot an atomized pencil–thin stream to 8 to 12 feet, while the pool



Two additional views of "**The Hydra**." (top) A view toward the east, on July 21, 2002. (bottom) A July 13, 2002, close–up looking toward the northeast. (Both photos by Carlton Cross)

Prior to 2002, the central cone had been active as a small perpetual spouter. This was the case in the late 1980's and, after a dormancy, was noted again in 1998, 2000 and 2001. It is obvious that the activity is unprecedented. Several of the side vents on the cone have been reamed out; sand has been washed out from under thin but established sheets of sinter surrounding the pool; and sand that used to buttress thin sinter lamina on the cone has been washed away. Oddly, all the vents in the complex descend to only a shallow depth before turning horizontally. This, too, is inconsistent with a history of geyser eruptions.

Unnamed spouter #37

This small cyclic perpetual spouter erupts 1 to 2 feet high. It was first observed active in 1996.

played a rooster–tail to 5 to 15 feet. The smaller vents surrounding the cone sputtered a few feet high. The initial eruption on 13 July began with a sudden upwelling of water in the cone vents; heavy discharge from the pool flooded over the rim in all directions. Subsequent eruptions in the series began with a forceful steam phase. Following a series, the water boiled in the central cone and slowly rose in the pool, requiring many hours to reach overflow.

Brown Sponge Spring #12

Both Brown Sponge and the small pool west of it (#13, below) have consistently acted as intermittent springs.

"Chocolate Geyser" #13

First observed with its name suggested by Rocco Paperiello in July 1994, this small pool was also seen in eruption in 1997. [Paperiello *in* Cross, 1998]. More commonly it acts as an intermittent spring.

Unnamed spring #11

This tiny and almost unnoticeable vent that plays from the hillside was seen sputtering in 2001 and 2002.

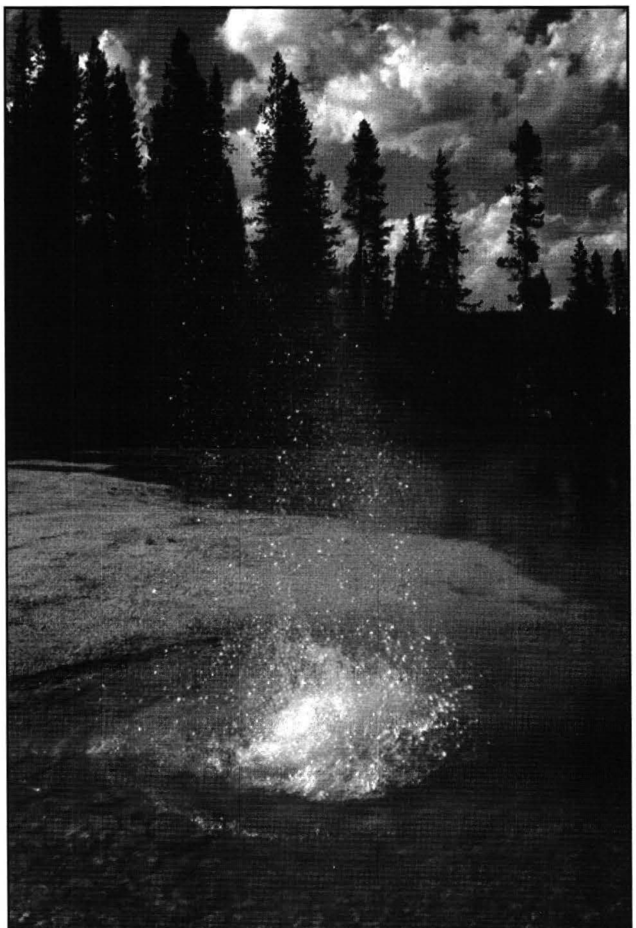
Glen Spring #10

One closed interval of 140 minutes was obtained in 1995. Glen Spring was also seen in eruption in 1994, 1996 [Paperiello *in* Cross, 1998], 1998 and 2002. The eruptions were only a foot or two high, and often seemed to come only from the back vent.

SOUTH GROUP (see Map E)

Flake Spring #11

Although not generally known as a geyser, Flake Spring was seen erupting to 4 to 5 feet once in 1994. Judging from wash around the crater, it was undoubtedly erupting during subsequent years until 1999, when it cooled considerably and became dormant. The dormancy persisted through 2002, but it was found to again be active in July 2003 Murray, 2003].



Outbreak Geyser in 1991. (Photo by Jeff Cross)

Unnamed geyser #12

Since 1999, this geyser has played from a fissure to heights of 3 to 6 feet. Although no intervals or durations have been obtained, it seems to be in eruption most of the time. Its reactivation in 1999 coincided with dormancy in nearby Flake Spring.

Unnamed geyser #9

A loud chugging eruption was observed in July 2001. It lasted in excess of 9 minutes and reached 2 feet high. This vent blew out in 1994, scattering sinter sheets and flushing sand over the surface of the surrounding sinter terrace. It is probable that this vent was active as a geyser at other times between 1994 and 2001. Because of its location in the middle of an actively depositing sinter sheet, it is likely that this vent has blown out and been sintered over repeatedly.

Unnamed geyser #10

Just uphill from Flake Spring, this small vent was active as a geyser in 1992 and 1999.

"Outbreak Geyser" #8

Data collected in 1991, 1993, 1994 and 1996 gave intervals of 25 to 39 minutes, durations of 110 to 154 seconds, and heights of up to 15 feet. Eruption intervals could be quite regular, as shown by the standard deviation of 3.5% of the mean in 1996 for 16 intervals. Eruptions were larger in the early 1990's than in the mid-1990's, when they typically did not exceed 6 feet. Even when active in 1993 and again in 1996, regression to perpetual spouting was noted by two different observers [Bryan, 1995; Paperiello *in* Cross, 1998].

After many years of frequent, regular eruptions, Outbreak Geyser has lapsed into a long dormancy that continued, with one known interruption, through 2003. When dormant as during 1997 through 2001, and also in 1992 and 1995, it splashed continuously from a low water level. In 2002 and 2003, the dormancy was more pronounced—Outbreak was completely quiet and had green microorganisms growing in the crater. A small stream flowed into the vent from a nearby sinter terrace. Several eruptions were noted in August, 2000, with heights of up to 6 feet and durations of 1 to 2 minutes. The intervals were undetermined, but were probably hours long. By 2003 the vent was silted shut.

"Diverted Geyser" #4

Geyser activity from Diverted began after the rim of nearby Three Crater Spring was broken, diverting Three Crater's runoff stream, which had previously flowed directly through the geyser's pool. This break was probably caused by a bison since we found bison hoof prints in Three Crater Spring itself. The name was suggested by Clark Murray.

Beginning in 1995 [Murray *in* Cross, 1998] and continuing from 1996 through 2001, Diverted Geyser erupted every 320 to 716 seconds for durations of 82 to 208 seconds. Average intervals were consistently 506 to 580 seconds and were reasonably regular most of the time. Average durations were 84 to 126 seconds. Heights of up to 5 feet were noted.

Apparently Diverted can lapse into brief dormancies. For example, it was not seen by us in July 2000, but was active in August. That it was not seen at all in 2002 should not indicate that it is finished for the long term.

Coral Pool #2

Coral Pool's overflow has consistently been intermittent. Rarely, small geyser eruptions have been noted [Paperiello, 1989]. In 1998 seven collected intervals between overflows were trimodal, with the short mode including 2 intervals of 5 and 6 minutes, the intermediate mode including 3 intervals of 10, 10 and 11 minutes, and the long mode including 2 intervals of 14 and 15 minutes. The duration of the overflow was also variable — long overflows preceded long intervals. Coral Pool's activity certainly warrants greater study in the future.

Unnamed Spouter #13

Consistently active, this perpetual spouter erupts to several feet from a beautiful crater. No pauses have been seen.

ISLAND GROUP (see Map D)

Unnamed vents #4a-c

These three cones were sputtering continuously in 1993 with overflow, and were active again without overflow in 1996. Usually they are dry and completely inactive.

WESTERN GROUP (see Map F)

Unnamed geysers #2 and #10

At the northeastern end of the Western Group are two pools. The lower one is hot and clear of microorganisms, while the shallow upper pool supports a bright red growth. Both of these pools have erupted to 1 to 2 feet as small geysers. Durations and intervals were not determined but were probably long. Both the pools were active as geysers in 1994 and again in 2002. The lower pool was also erupting in 1995 and 1997.

"Pectin Geyser" #14

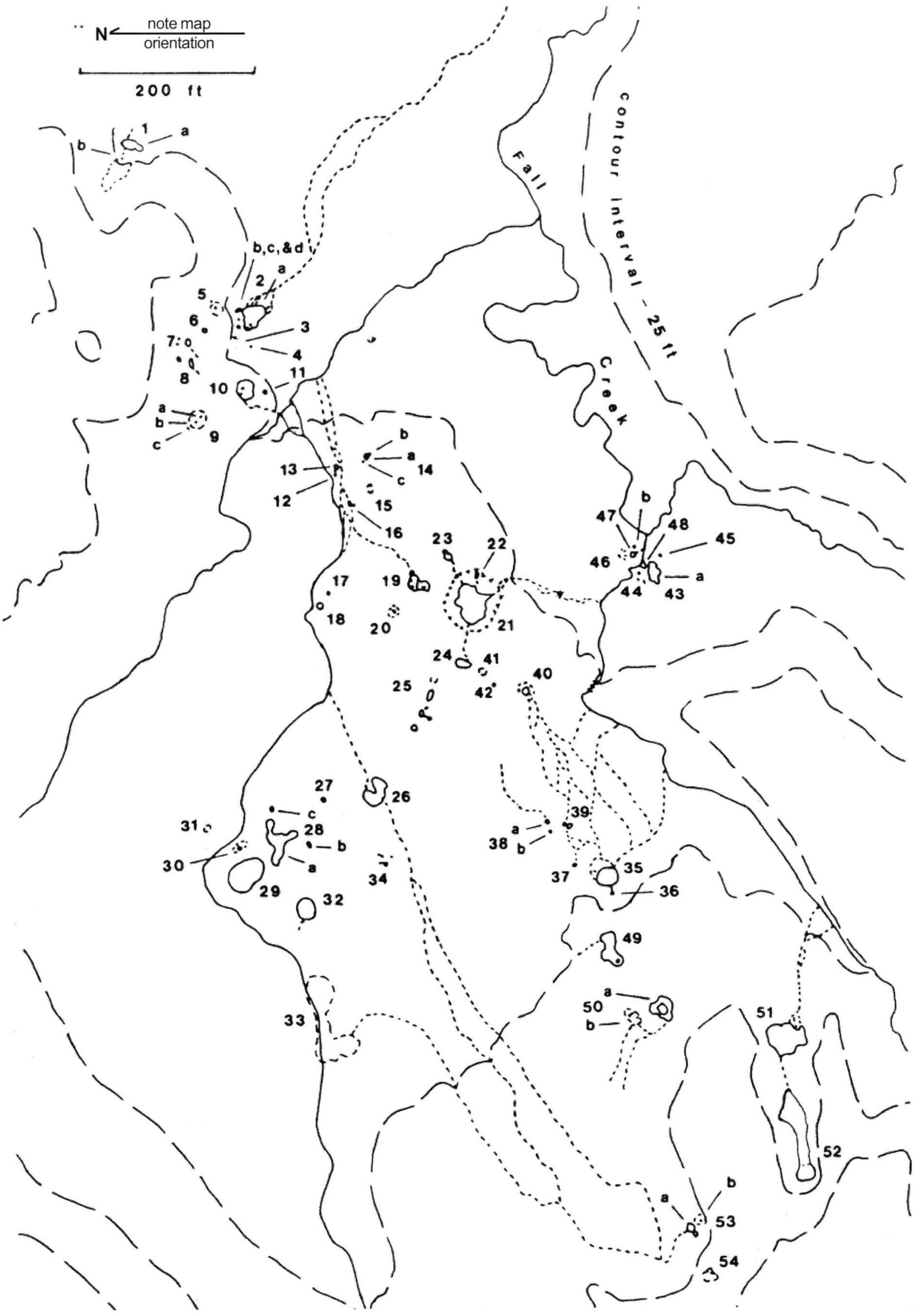
Continuous eruptions from a pool in the Pectin Geyser complex have been noted during most years. In 2000–2002, water levels were extremely low.

Unnamed geyser #12

Informally known as "Not Pectin Geyser," this interesting feature lies directly across Boiling Cauldron's runoff stream from Pectin Geyser. The name was contrived to resolve the confusion inherent in having two small geysers located near each other and next to the same runoff stream, which is the only landmark in the area. Future observers should note that Pectin is on the south side of the stream and Not Pectin is on the north.

Not Pectin reactivated in 1987 [Paperiello, 1989] and has been active every year from 1991 through 2002. Intervals in 1993 and 1994 were 11 to 12 minutes, but in 1996 they lengthened to 19 to

Map F — Western Group, Shoshone Geyser Basin



25 minutes. All 20 intervals obtained from 1998 through 2002 have been 18 to 21 minutes. In 2001 a series of 5 intervals had a standard deviation of 1.8% of the average, indicating a high degree of regularity.

Individual eruptions begin with a sudden rise in water level, proceed with bursting and overflow, and end with a drain, followed by loud rumbling at depth. The maximum height is 3 feet, and the whole display, sans rumbling, lasts just under 2 minutes. There is often a continuous drum–like rumbling from the vent between eruptions.

A small nearby pool (#13) has acted as a drain for Not Pectin's runoff in the past; it became silted over in 1996. In September 2002, it was noted to have collapsed inward. There were no signs of explosion or eruption around the crater. Not Pectin was active, but the eruption seemed anemic.

"Channel Spouters" #16

One vent in this complex was active as a microscopic geyser in 1997.

"Double Crater Spring" #26

Geyser activity was noted in September 2002. During a brief period, six intervals of 104 to 198 seconds were obtained. Although often indistinct, the eruptions involved true bursts to 1 foot. Apparently the eruptions were part of a series, since no eruptions were seen later in the day.

This spring is a bit mysterious. Tinted an odd green, it produces a very heavy runoff stream that intersects that of Boiling Cauldron near Not Pectin Geyser. Heavy wash was noted near the intersection of the two streams, but the observed geyser activity failed to account for its extent. The spring is located about 200 feet west of Boiling Cauldron but is difficult to see from that location due to an intervening stand of trees.

Moss Basin #35

Moss Basin has cooled considerably from several years ago; it is now lined with very dark red–brown microorganisms.

"Tunnel Geyser" #54

After appearing in 1988, this feature eroded its way back into the hillside so that its eruptions are now completely subterranean, hence the name. Audible splashing has been periodic since 1991 [Paperiello *in* Cross, 1998]. In 2001 and 2002, intervals of 31 to 95 seconds and durations of 24 to 79 seconds were recorded. The eruptions are invisible and often indistinct, which probably accounts for the large variations in interval and duration.

SHORE GROUP (not mapped)

The Shore Group is located on a large black–sand beach on the edge of Shoshone Lake. At the north end of this beach are the "Burning Eyes," a pair of perpetual spouters that erupt to a foot or two from a bright red–orange deposit. Immediately north of the northern vent of Burning Eyes and on the same formation is a small hole, known as "Burning Eyes Geyser." The geyser reactivated in 1996; before then its last known activity had been in 1982 [Paperiello *in* Cross, 1998]. Also noted in 1996 was a vent seventeen feet south of the southern Burning Eyes spouter, which blew out a small crater through the beach sand. This crater has since disappeared.

"Burning Eyes Geyser"

Major eruptions that spray water up to 4 feet high are typically separated by numerous sputtering minor eruptions. During some years the activity was cyclic but eruptions were not clearly defined. This occurred in 1998, 2000 and 2002. Intervals during other years varied greatly, from 14 to 29 minutes in 1996 and 1997 (4 intervals) to 5 to 8½ minutes in 1999 (4 intervals), to 94 to 119 seconds in 2001 (11 intervals). Durations also varied, from 6½ minutes down to 34 seconds. The durations at any given time showed little relationship to the intervals.

"HORSE CAMP GROUP" (not mapped)

The largest pool in this small hot spring group has been consistently active, splashing to 1 to 2 feet. Because it was observed only in passing it is uncertain whether it was truly periodic at times.

LAKE GROUP (not mapped)

Only one unnamed geyser has been seen in this small group of hot springs on the shore of Shoshone Lake, straight east of the Orion Group. Erupting from three small vents near an isolated pine tree at the southwestern edge of the group, it was active in 1997, when two intervals of 43 and 44 minutes were obtained. The three observed eruptions lasted 50 to 60 seconds and reached a grand height of several inches. Runoff channels were observed in 1995 and 1996, but the geyser was apparently dormant from 1998 through 2002. In 1998, the small half–cone that surrounded one of the three vents had broken free and moved a short distance to the south, where it began to weather rapidly. Since the cone was very small and was not part of a coherent mineral formation, it is possible that wave action, occurring while parts of the group were inundated by Shoshone Lake, was responsible for this.

"SWAMP LAKE GROUP" (not mapped)

The Swamp Lake Group has never been visited by the authors. Paperiello [1989] notes one possible geyser in this group.

References

Bryan, T. Scott, 1995. *The Geysers of Yellowstone*: University Press of Colorado.

Cross, Jeff, 1998, "Recorded Observations of Thermal Activity at Shoshone Geyser Basin, Yellowstone National Park: 1988-1997": *GOSA Transactions*, Volume VI.

Cross, Jeff, 1992, "Observations at Shoshone Geyser Basin, July 17-18, 1991": *GOSA Transactions*, Volume III.

Goldberg, David, 2003, Personal communication.

Moats, Will; *in* Monteith, David, 2001, "Summer 2001 Geyser Activity," *The Geyser Gazer Sput* newsletter, August 2001, v. 15, no. 4, p. 24.

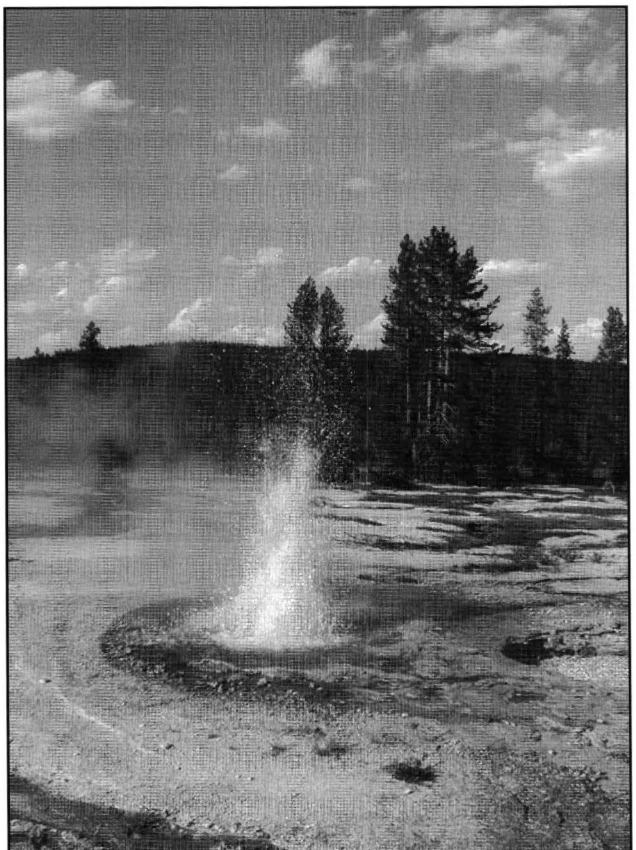
Murray, Clark, 2003, Personal communications to the authors and editor.

Paperiello, Rocco, 1989, "Hot Springs of the Northern Part of the Shoshone Geyser Basin, Yellowstone National Park": *GOSA Transactions*, Volume I.

Paperiello, Rocco, 1992, "Hot Springs of the Central Part of the Shoshone Geyser Basin, Yellowstone National Park": *GOSA Transactions*, Volume III.

Paperiello, Rocco, and Clark Murray, 1994. "Geyser activity seen on July 13 and August 17-18, 1994": unpublished report.

Young, Jake, 2003, Personal communication.



Another view of **Bead Geyser**, on July 16, 2003. (Photo by Carlton Cross)

The Activity of Glade Geyser, 1997–2002

by Jeff Cross, Tara Cross, and Carlton Cross

Abstract

Glade Geyser was active from 1997 through 2002. Intervals obtained during July, August, and early September of these years varied from just over one hour to five days.

Glade Geyser, along with the better known and more frequent Rustic Geyser, is one of two sizeable geysers at Heart Lake Geyser Basin. Because of infrequent observations, Glade's activity has generally remained enigmatic. We were therefore surprised in July of 1997 to discover that Glade was erupting at intervals of just over an hour. Three closed intervals of 65 to 68 minutes were recorded, with durations of 109 to 127 seconds and heights of up to 45 feet. A triple interval of 3 x 67 minutes was also obtained. These intervals were obviously much shorter than at any time since we had started visiting the area in 1993.

The short intervals of 1997 were again seen during the summer of 1998, when a series of 66 intervals obtained by a data logger placed under an NPS research permit gave an average of 90 minutes, with a standard deviation 7.2% of the mean and a range of 75 to 105 minutes. Three eruptions actually witnessed in July of 1998 had intervals of 78, 95 and 97 minutes, durations of 106 to 137 seconds and heights of up to 45 feet.

No eruptions were observed in 1999, but Glade was still active. The intervals were longer, the average being just under 7 hours with a standard deviation of 22% and a range of 4½ to 9½ hours (20 intervals). Durations for this and all subsequent data sets are difficult to obtain because the data logger's temperature probe readily picks up the start of the eruption as a large temperature spike, but the end of the eruption is much less distinct. Durations were approximated where possible.

In 2000, the average interval rose to 30½ hours, with a standard deviation of 12% and a range of 26½ to 37½ hours (8 intervals). In 2001, the intervals had increased drastically to average 96 hours with a range of 56 to 127 hours and a standard deviation of 25% (10 intervals). The durations were estimated at around 15 minutes. In 2002, the average interval fell to 23 hours with a range of 20 to 26 hours and a standard deviation of 8.9% for one data set of 10 intervals, and 24 hours with a range of 14 to 33 hours and a standard deviation of 13% for a second set of 44 intervals. Durations were approximated at around 20 minutes.

Glade Geyser on August 2, 1998. (Photo by Carlton Cross)

Table 1 — Glade Geyser, Summary of Data

Year of Observation	Interval Range	Average Interval	Std Deviation (% of average)	Duration	Height
1997	65 - 68 m	67 m	-----	109-127 s	45 ft
1998	75 - 105 m	90 m	7.2% (66 int)	106-137 s	45 ft
1999	4½ - 9½ h	7 h	22% (20 int)	-----	-----
2000	26½ - 37½ h	30½ h	12% (8 int)	-----	-----
2001	56 - 127 h	96 h	25% (10 int)	~15 m	-----
2002 (data set 1)	20 - 26 h	23 h	8.9% (10 int)	~20 m	-----
2002 (data set 2)	14 - 33 h	24 h	13% (44 int)	-----	-----

It is interesting to note that the longer duration eruptions in 2001 and 2002 occurred when intervals were many hours long, and that the shorter durations seen in 1997 and 1998 occurred when intervals were only a few hours long.

It should also be noted that we saw a closely–spaced pair of eruptions in August of 1996, which consisted of an initial 30–foot eruption lasting just over 2 minutes which, after 3 minutes of splashing and heavy steam, was followed by a second 20–foot eruption lasting 16 minutes, giving a duration of 21 minutes for the entire show.

In conclusion, data records for Glade Geyser over the last six summers show that it can be regular and relatively frequent over the course of several summer seasons, but that in the long term its activity is highly variable.

A black–and–white photo does not do justice to a picture of **Watermelon Geyser**. The cone is brilliantly colored with orange and green cyanobacteria and (true) algae). Watermelon, which is actually a perpetual spouter, lies at the bottom of the Grand Canyon of the Yellowstone near the base of Lower Falls. It used to be accessible via Uncle Tom's Trail, but because of frequent rockslides, that route was blocked to public access in the early 1970s. (Photo by Scott Bryan, 1971)

Mysterious Names from Early Interpretation in Yellowstone: Who Were Frank R. Oastler and Joseph G. Hawkes?

research by T. Scott Bryan

Abstract

The hope of being able to date a glass lantern slide in my personal collection lead into research about the photographer and the person who apparently hired him to take the image. Only general information about the people was gained, but the photo probably dates to 1929.

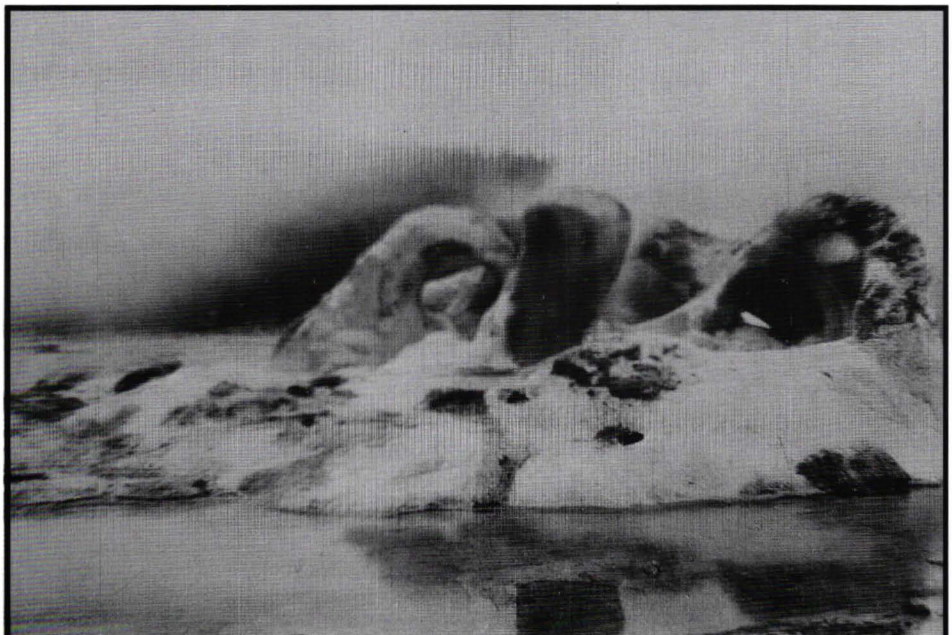
Introduction

My limited personal collection of historic Yellowstone items includes a set of exactly 50 glass lantern slides that I obtained in 1972. Most show thermal features, and the majority can be identified as products of Haynes Studios.

However, five of the slides are of somewhat mysterious origin. One, showing New Crater Geyser, was shown and discussed in *GOSA Transactions*, Volume VII (page 127). Absolutely nothing has been learned about when or by whom that picture was produced.

The other four slides in question were taken by a photographer named Joseph Hawkes. All four bear labels on the slide that read in bold, gold lettering: **MADE BY JOSEPH HAWKES NEW YORK CITY**. The captions on the slides identify the subject and triggered this research. They are:

- "Grotto Geyser, Hawkes Photo Oastler"
- "Norris (duplicate)"
- "Minerva Terrace"
- "Mound Terrace"



The picture that started it all... A grayscale reproduction of the glass lantern slide whose caption, handwritten with India ink on white adhesive tape *inside* the glass, reads: "**Grotto Geyser, Hawkes Photo Oastler—**".

The obvious questions are: Who was Joseph Hawkes; and who was "Oastler"?

Both clearly are unknown persons to current National Park Service historians. An early query was sent to Yellowstone's Lee Whittlesey. He forwarded the questions to others with the NPS. The two direct results state that Oastler's name is included in two publications about the development of interpretation in the national parks, but that "...neither tells us who he is or what his affiliation was..." [Pitcaithley, 2002], and secondly that "...last week I came across a statement on Oastler — I think it was an obituary" [Sellars, 2002].

Frank R. Oastler

I began my research by investigating Oastler, because I quite quickly found a reference to him in Haines [1977]. This reads: "In 1923, Ansell F. Hall [*sic*] was designated Chief Naturalist [of the National Park Service] and placed in charge of educational programs in all the parks, and the following year Director Mather secured the services of Dr. Frank R. Oastler of New York as consultant to prepare a general policy for such activity."

A more recent treatise by Mackintosh [2000] calls some of Haines' statement into question. While the appointment of Hall in 1923 is confirmed, there is no mention whatsoever of Oastler until his appointment by the Secretary of the Interior, Roy West, to the Committee of Study of Educational Problems in the National Parks, in 1928.

Beyond this, virtually nothing more was learned about Oastler's offical role with the National Park Service. However, some about his personal life and, with that, his connection to the national parks was found.

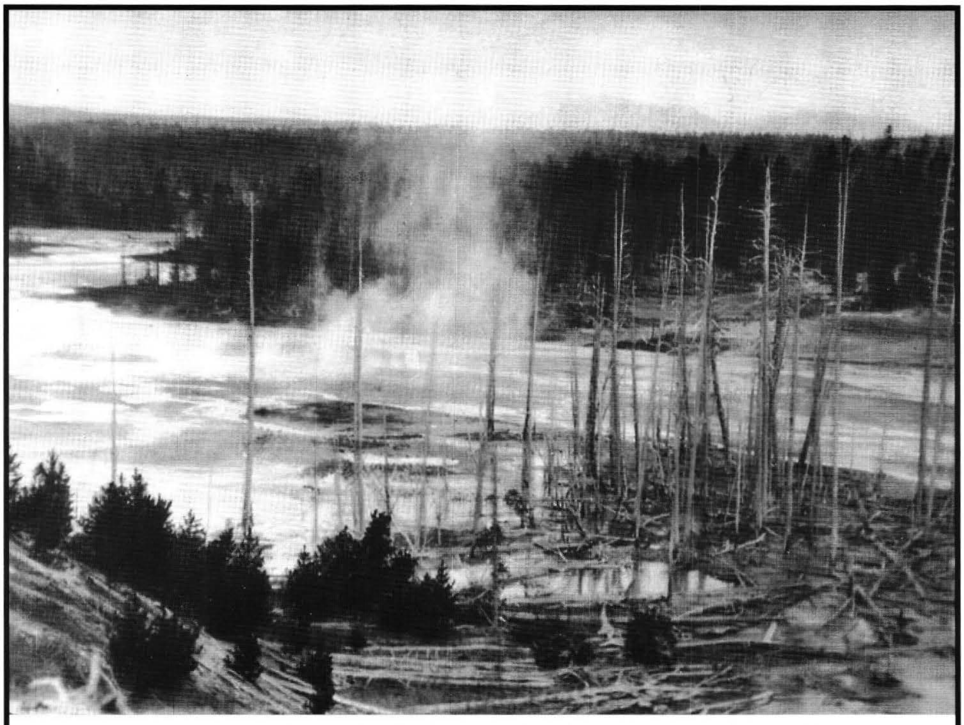
Oastler was born in New York City in 1871; he died in that city in late 1936. By profession, he was a distinguished surgeon, specializing in neurological problems and surgery in, yes, New York City. Clearly, he made an outstandingly good living.

He and his wife (who I've seen identified only as "Mrs. Oastler") initially visited Glacier National Park in 1912. At first they arrived via the Northern Pacific Railroad [*sic*; Great Northern Railroad?], but in time the journey all the way from New York City was made in their personal limousine. The Oastlers are said to have toured much of Glacier on "well–appointed horseback excursions."

After the doctor's death in 1936, Mrs. Oastler continued her visits to Glacier. Her annual "arrival in state" was said to mark the beginning of the season for the Many Glacier Hotel. It was there that she met and became a fast friend with Hopalong Cassidy in 1948. Although her date of death is unknown, her last visit to Glacier was in 1956 [above three paragraphs all Schwab, 1999]. *

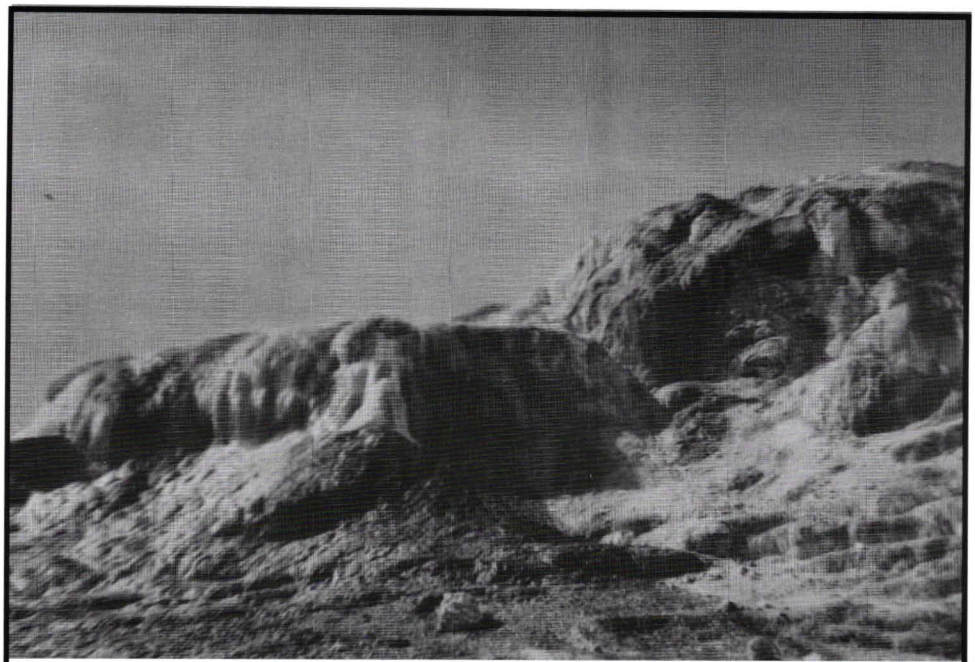
Nowhere in my research did I find a mention of Dr. Oastler ever visiting any national park other than Glacier except once to Yosemite. Neverthe-

* A genealogical search on the Internet revealed that the person who was probably this "Mrs. Oastler" was named Corra (spelled with two 'r's), born in August 1886 and died in October 1963, both events in New York City [Wang, 2002].



Hawkes' photograph of the Norris Geyser Basin, a view northwest from above Dark Cavern Geyser, is labeled simply "**Norris (duplicate)**". This and the slides of Minerva Terrace and Mound Terrace have the slide captions handwritten with India ink on varnished adhesive tape on the *outside* of the glass.

less, he must have been recognized as a supporter of the parks in general, with Glacier being his favorite. Perhaps it was a lack of public information in these early years of the parks that led to his interest in formal interpretation. Whether he ever actually visited Yellowstone is unknown, but somehow, sometime, his involvement must have included Yellowstone's geysers... and at least one photograph by photographer Joseph Hawkes.



Hawkes photo labeled "**Mound Terrace**". The relative blurriness of this picture accurately reflects the poor quality of the hand–tinted original.

Joseph G. Hawkes

At no point in my research did I ever find a reference to Hawkes in Yellowstone — I have only the four lantern slides as evidence of that. Tom DuRant, Graphic Materials Archivist at the NPS Harpers Ferry Center, wrote: "I have not run across this name in the 22 years I have worked in the Graphic Archives here in Harpers Ferry. A lot of this work was contracted for in the early days before the NPS hired the first photographer, George A. Grant, in 1929" [DuRant, 2002].

Hawkes worked in New York City. In a 1921 letter to William Goodyear (see below), the letterhead bears two New York City addresses: "1476 Broadway (Longacre Building)" and "147–157 West 42nd Street" [Peimer, 2002]. These addresses indicate that Hawkes was very successful. The Broadway address is *on* Times Square and most likely was the public place of business. The ten–number address on West 42nd was less than a block away and might have served as a photograph processing facility.

Hawkes photo labeled "**Minerva Terrace**". The relative blurriness of this picture accurately reflects the poor quality of the hand–tinted original.

Even armed with the business addresses and date, a query to the New York Historical Society resulted in the following: "Unfortunately I have not been able to find additional information concerning the life or career of Joseph Hawkes. He is not listed in newspaper indexes or our library holdings" [Robinson, 2003].

Given the evidence of business acumen, it is surprising that extensive Internet searches resulted in virtually no biographical information. The little that was learned follows.

This Joseph Hawkes was *probably* the one who was born in 1870, in Allegheny County, Pennsylvania, and he was *probably* the one who died in New York City, in 1938 [Wang, 2002; and personal investigations].

Hawkes seemed to specialize in photographic series. For example, the Archives of American Gardens (a part of the Smithsonian Institution) holds seven of his lantern slides. They all show scenes within formal gardens in New York and Massachusetts. These were produced (probably under contract) either for the Garden Club of America itself or for some of the club's individual members, in about 1930. Six of those seven slides bear Hawkes' identification in gold lettering identical to that on my slides; interestingly, the seventh has silver lettering [Connolly, 2002; Hurlock, 2002].

The Anthropological Archives of the Bureau of American Ethnology (another part of the Smithsonian Institution), also holds two Hawkes slides showing American Indian "chiefs." Neither bears a date nor further identifying information [Anonymous, undated].

Additional, possibly similar slides (as many as 14) are held by the University of Pennsylvania Museum of Archaeology and Anthropology. Unfortunately (and curiously), those slides are not described in any catalog or index, only simply listed in a database. Indeed, the Museum's archivist does not even know the physical location of the slides! To learn details about them would require extensive on–site research [Kline, 2003].

William Goodyear was the first curator of fine arts for the Brooklyn Institute. It was Goodyear, for the Institute, who hired Hawkes to travel to the Paris Exposition in 1900, and images of that world's fair reside in the Goodyear Archival Collection. Also, although none of his other slides now exist in the Brooklyn Institute (at least, not that can be identified), Hawkes probably also worked with Goodyear at the Columbian Exposition in 1893 and in Italy in 1895 [Peimer, 2002].

Finally is a brief Internet notice of a 1988 auction in which a set of 53 lantern slides by Joseph Hawkes "relating to the Custer fight" was sold from the Custer Collection of John M. Carroll. Produced about 1910, the slides were packed in three wood boxes designed for the purpose [Pacific Book Association, 1988].

Conclusion

It might be inferred that Oastler and Hawkes were professional acquaintences in New York City so that, when Oastler found the need for photos as part of the interpretive planning he was involved in, he went to Hawkes to obtain them.

The interpretive planning committee that Oastler was a member of was established in 1928 and it was terminated in 1930 [Mackintosh, 2000]. If produced under contract to Oastler/NPS, that pretty much leaves the summer of 1929 as the only likely time in which Hawkes could have obtained these photos. The alternate possibility is that Hawkes took the photos many years earlier, such as circa 1910, when he is known to have been in the Montana–Wyoming region while producing the photograph set "relating to the Custer fight." In this case, he may have simply pulled them from his own archives at the request of Oastler.

As little as it is, the above comprises the total result of several months of letter, telephone, e–mail and Web researches into the identity of Frank R. Oastler and Joseph G. Hawkes, two mysterious gentlemen who helped formulate interpretation in the national parks.

References

Anonymous, undated, Smithsonian Institution Research Information System (SIRIS): at www.siris.si.edu/

Busch, D., 2002, e–mail dated December 31, 2002: resident of New York City, forwarded through C. Millis as result of "geysers" listserv query.

Connolly, J., 2002, e–mail dated November 15, 2002: Museum Specialist, Archives of American Gardens, Smithsonian Institution.

DuRant, T., 2002, e–mail dated November 4, 2002: Graphic Materials Archivist, Harpers Ferry Center, National Park Service.

Haines, A. L., 1977, *The Yellowstone Story: A history of our first national park*: Yellowstone Library and Museum Association in cooperation with Colorado Associated University Press; v. 2, p. 208.

Hurlock, W., 2002, e–mail dated September 30, 2002: Reference Services Librarian, Archives of American Art, Smithsonian Institution.

Kline, C., 2003, personal phone call on January 7, 2003 in response to e–mail query, Museum Archivist, University of Pennsylvania Museum of Archaeology and Anthropology.

Mackintosh, B., 2000, *Interpretation in the National Park Service: A historical perspective*: ParkNet, National Park Service; retrieved from www.cr.nps.gov/history/online_books/mackintosh2/origins_interp_institutionalized.html

Pacific Book Association, 1988, PBA Galleries Sale #153, February 9–10, 1988: retrieved via search to www.pbagalleries.com

Peimer, L., 2002, e–mail dated November 4, 2002: Mellon Project Archivist, Goodyear Collection, Brooklyn Museum of Art, Brooklyn, NY.

Pitcaithley, D., 2002, e–mail to Lee Whittlesey, forwarded: Washington (D.C.) Office, National Park Service.

Robinson, E., 2003, e–mail dated January 22, 2003: Reference Library Assistant, New York Historical Society.

Schwab, D., 1999, "Hopalong Cassidy at Many Glacier": *The Inside Trail* (newsletter), Glacier Park Foundation, Summer 1999, unpaginated.

Sellars, R., 2002, e–mail to Lee Whittlesey, forwarded: Santa Fe (NM) Office, National Park Service.

Wang, K., 2002, two e–mails dated December 20, 2002 and December 24, 2002: results of searches in "Family Seearch Internet Genealogy Service" Mormon church Website.

Beryl Spring, July 1931

photo by Marian E. Dremn, from the Yellowstone Archives

"Deriving its name, perhaps both from its color and its chemical content, this spring was for a long time known as the hottest spring in the park. It is actually of a temperature less than boiling — the violent agitation on its surface being attributable to the rapid rise of hot gasses from beneath."

Mud Pots and Geysers Near Niland and the Salton Sea, Imperial County, California — An Update, and a Story of Research and Exploration

By T. Scott Bryan

Abstract

Recent maps concerned with the future of the Salton Sea indicated the existence of mud pots at several previously undocumented localities near the known Wister Field and McDonald–Schrimpf Field. This paper resulted from research and field study about these mud pots as well as the general the geothermal history of the area.

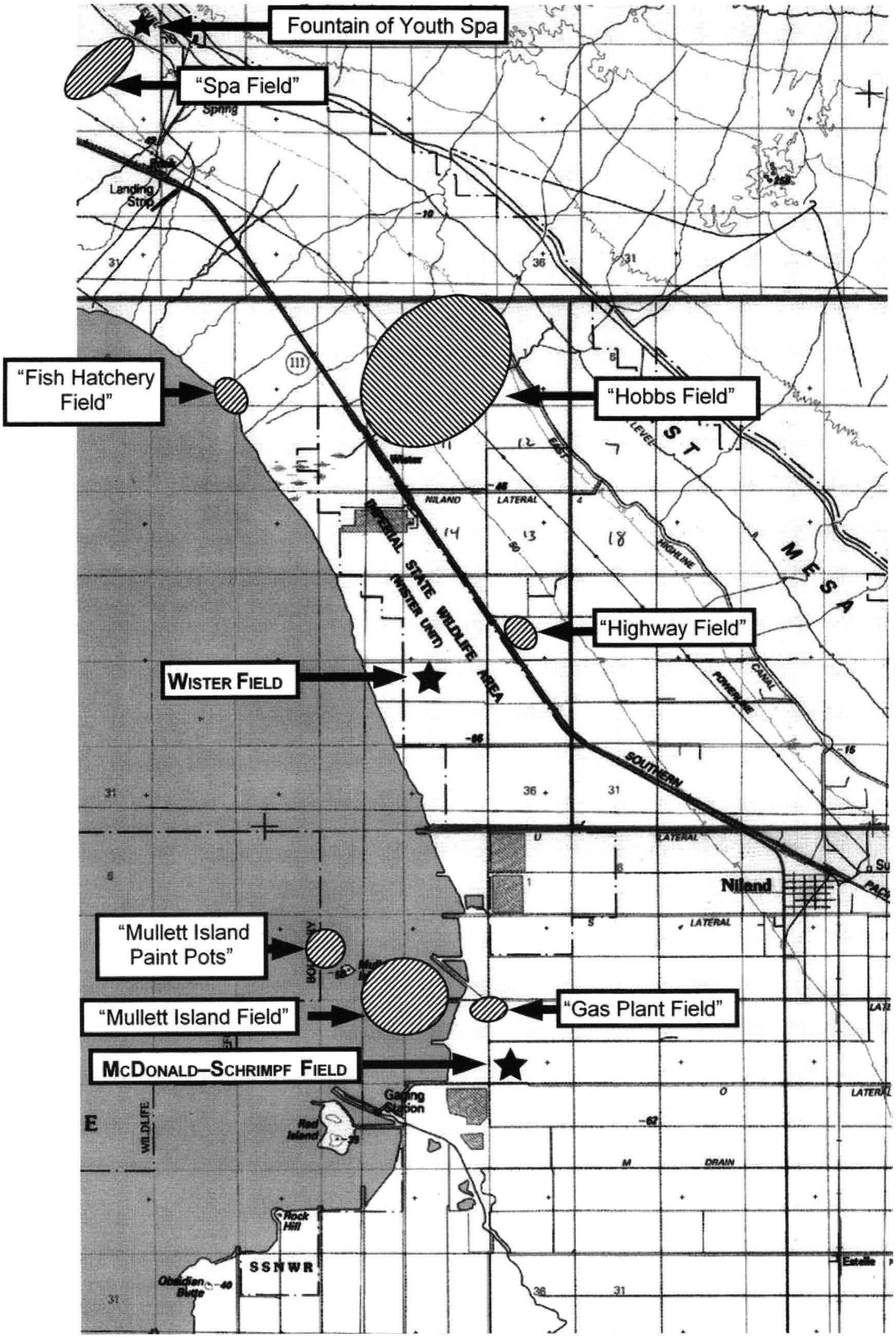
Background

That mud pots exist in at least two localities near the small town of Niland, near the southeastern shore of the Salton Sea in southern California, is well known. Reports about them were produced in 1999 and 2000 for GOSA's *The Geyser Gazer Sput* newsletter by Scott Bryan [1999], by Tom and Genean Dunn [2000] and by Jack Hobart [2000]. Hobart also played "tour guide" for television host Huell Howser's PBS program, "California's Gold." These two mud pot localities are shown with stars and their names on the index map (Map Page A).

Briefly, the northernmost set of documented mud pots is known as the Wister Field. It is located roughly 5½ miles northwest of Niland and about 1 mile west of Davis Road, just south of that road's intersection with Highway 111. This is a public area within the Wister Unit of the state's Imperial Wildlife Area. The mud pots that lie near the end of the access road are within deep, pit–like craters, some of which are surrounded by wooden boardwalks and railings. Additional craters can be found over a wide area west of the active zone, but in late 1998 the activity within that area appeared to be in decline. Many of the former mud pots were only damp, collapsed craters, their throats lined with crystalline salt.

The second field lies between McDonald Road and Schrimpf Road, at their intersection with Davis Road, and is known variously as the McDonald–Schrimpf Field or McDonald–Davis Field. (I prefer to use the first of those names, since the Wister

Figure 1. Landsat Photograph, Number 50203–17462.
This photo shows the entire Imperial Valley and Borrego Valley plus the southeastern portion of the Coachella Valley. Note the USA–Mexico border toward the bottom right of the image. The approximate location of the mud pot areas near the Salton Sea and Niland lies within the patterned oval near the southeast corner of the Salton Sea.



Map Page A. Index Map. Map showing the locations of the known (star symbols) and suspected "new" mud pot areas near and within the southeastern shoreline of the Salton Sea. Base map is USGS "Salton Sea, California" topographic quadrangle map, scale 1:100,000 dated 1985, resized to 1:120,000 for use here. [Extracted from Maptech *Terrain Navigator* CD–ROM, "California — San Diego Joshua Tree" disk] and "Gas Plant" fields are also near Davis Road.) These mud pots are about 5 miles south of the Wister Field via Davis Road, or 3½ miles west of Highway 111 from a point 2 miles south of "downtown" Niland. This is the "better" of the two mud pot areas. Many of them have built up rather large mud volcano cones. This apparently is private land, but it is unposted, unfenced and listed as a tourist attraction by at least one published Imperial County brochure as well as on its tourism website [1997]; it is also included as a stop by at least two commercial tour companies.

Although this is within a high–temperature geothermal area, these mud pots are quite cool. Powered by carbon dioxide and containing little water vapor, they mostly have temperatures of 110°F or less. The CO_2 originates from the thermal alteration of valley fill sediments, which are in large part limestone eroded out of the Grand Canyon. However, this is a thermal zone and on occasion one will find a hotter feature. Temperatures in excess of 150°F have been observed in the McDonald–Schrimpf Field [Sturz, 1998].

That still hotter springs can exist here is shown by the former existence of small geysers near Mullett Island. Now beneath the water of the Salton Sea, these geysers were located about 3 miles northwest of the McDonald–Schrimpf Field mud pots. Accompanied by hissing steam vents, their temperature was surely in excess of 212°F since the altitude here is more than 200 feet below sea level. A bit more about these little–known geysers will be found later in this paper.

New Possibilities

At some point a few years ago, and long after I was aware of the Wister and McDonald–Schrimpf mud pots, I found that additional mud pots are indicated on the California Division of Mines and Geology (CDMG) *Salton Sea Sheet* of the "Geologic Map of California" [revised 1977], a series of 2–degree maps at a scale of 1:250,000. The mud pots are shown by a series of very small "+" symbols labeled as "MUD VOLCANOES" in small capital lettering. In total, there 14 of these symbols. See the CDMG image of Map Page B–2, on which the symbols have been enhanced with superimposed crosses (one symbol, corresponding to the Wister Field, has not been enhanced).

Nine of these symbols lie between approximately 2½ and 4 miles due north of the Wister Field, northeast of Highway 111. Because access to this area would be via Hobbs Road, for this report I refer to this area as the "Hobbs Field."

Two additional symbols are shown adjacent to the east side of the highway very close to the Wister Field. I refer to this locality as the "Highway Field."

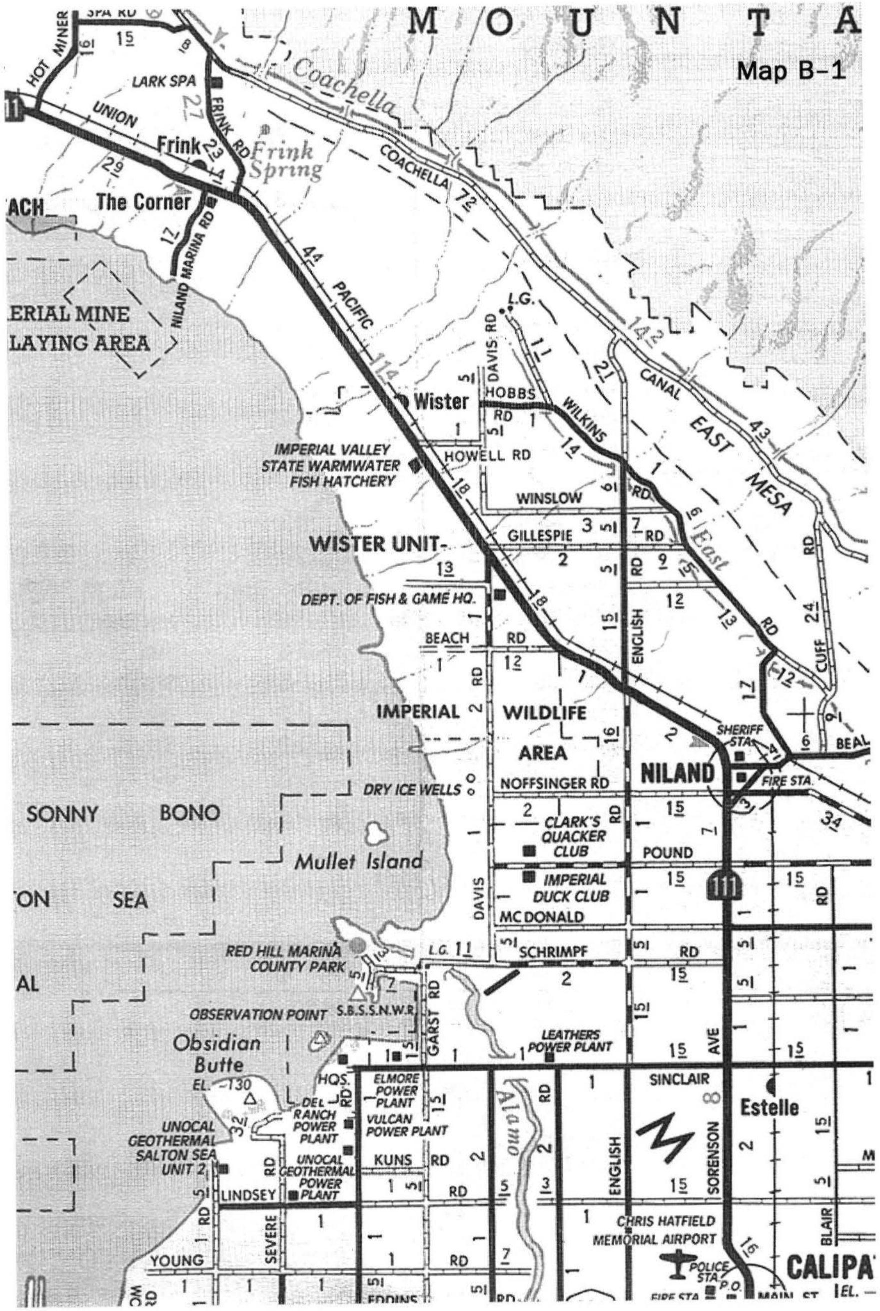
The last two of the 13 symbols are shown about 1 mile northwest of the McDonald–Schrimpf Field. This locality is clearly that labeled as "Mud Volcanoes" in a 1947 *Desert* magazine article written by Harold Weight. Here referred to as the "Mullett Island Field," it is probably near the shore of, but beneath the water of, the Salton Sea. The "Gas Plant Field" of this paper might be considered as an outlier of the Mullett Island Field.

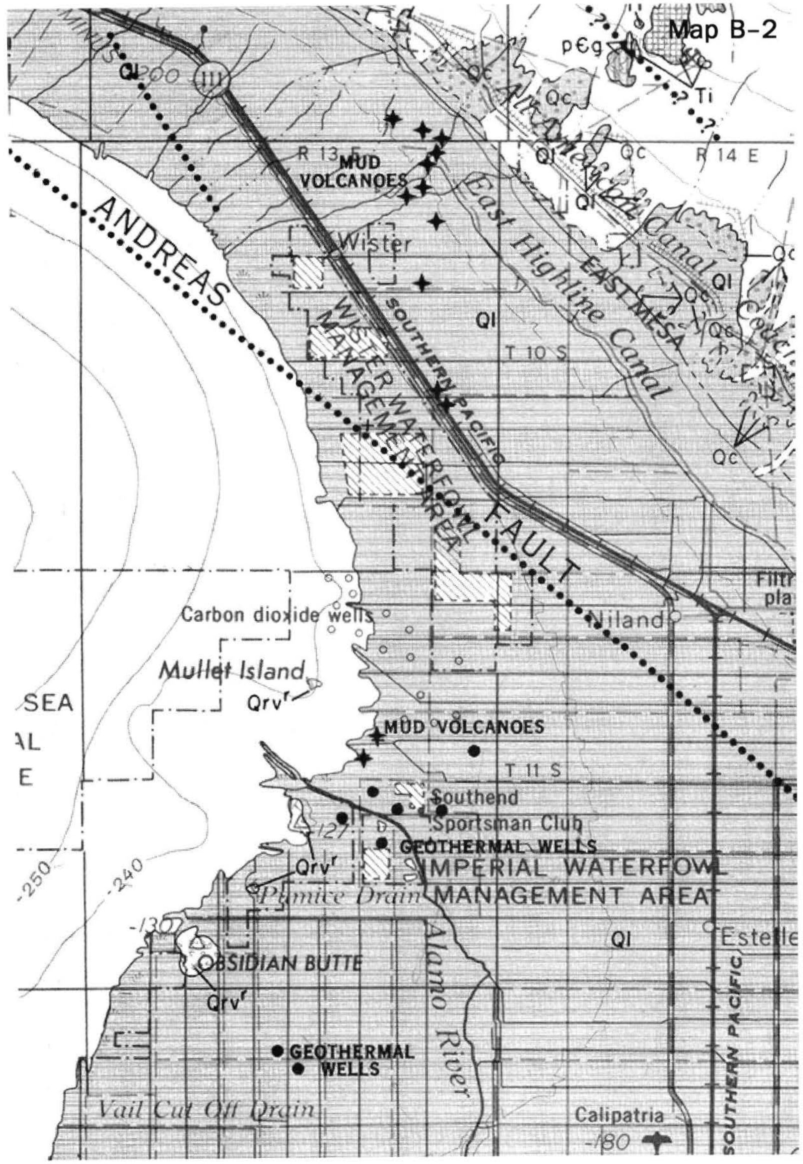
In addition to the above three localities are two other possible mud pot areas. Neither of these is noted on the CDMG map. One, here called the "Fish Hatchery Field," is indicated by a symbol on a map in the *Salton Sea Atlas*. The other is noted in a tourism Webpage operated by Imperial County [1997], which states: "On Hot Mineral Spa Road, just off Highway 111, you will find the Wister Mudpots." This is a problem, because Hot Mineral Spa Road lies fully 9 miles north of the Wister Field. Although I know of no map that indicates mud pots within this area, it is near an area of known warm/hot springs. I call this possible location the "Spa Field."

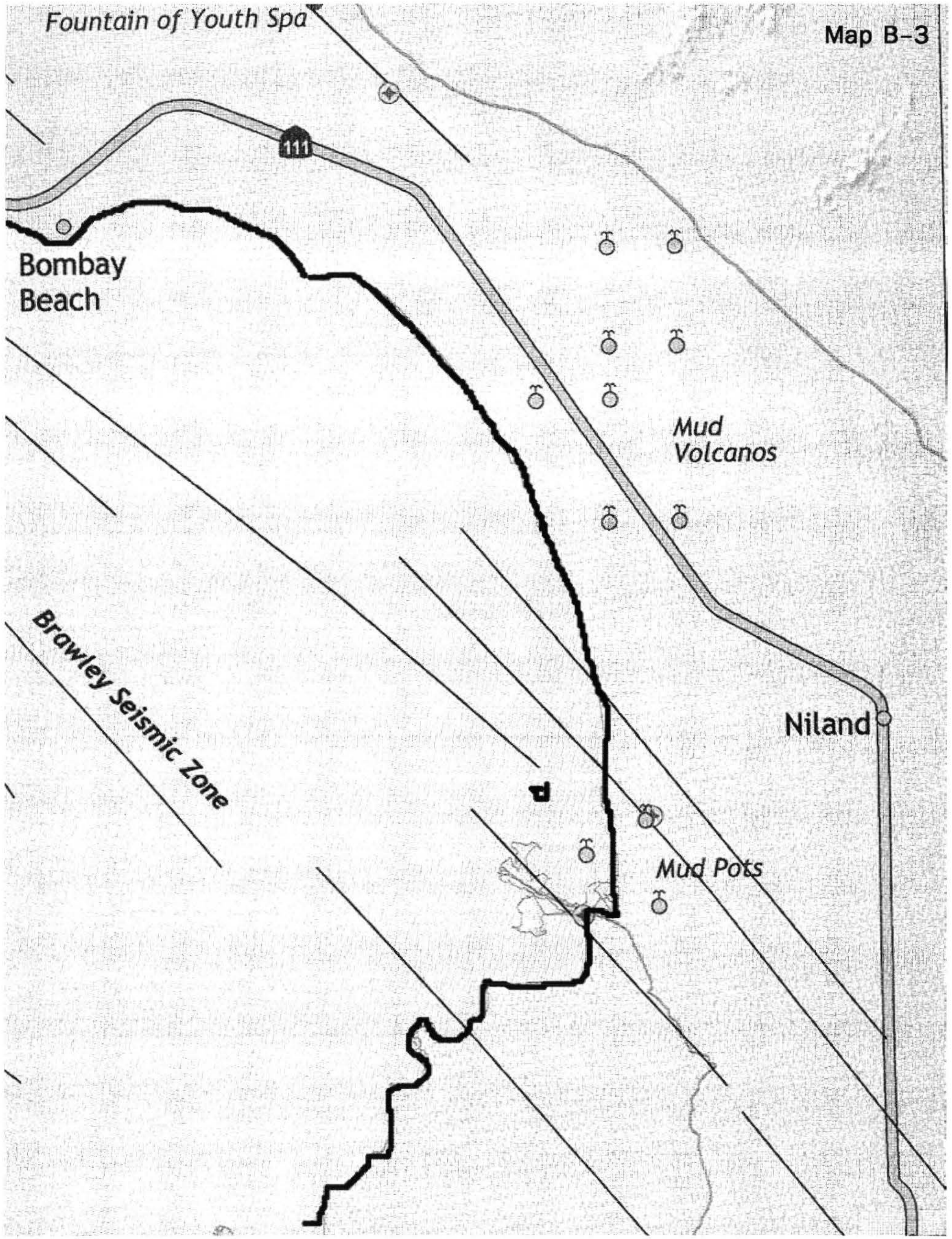
Although I have driven past all of these areas several times, I never felt that mud pots would really exist (or be accessible) in these "new" areas. This is in part because no map that I know of other than the California 2–degree *Salton Sea Sheet* — not AAA, not DeLorme and not even any USGS or other California topographic or geologic map at any scale — showed any indication of these mud pots until 2002. These localities are all indicated on Map Page A.

Recent Maps

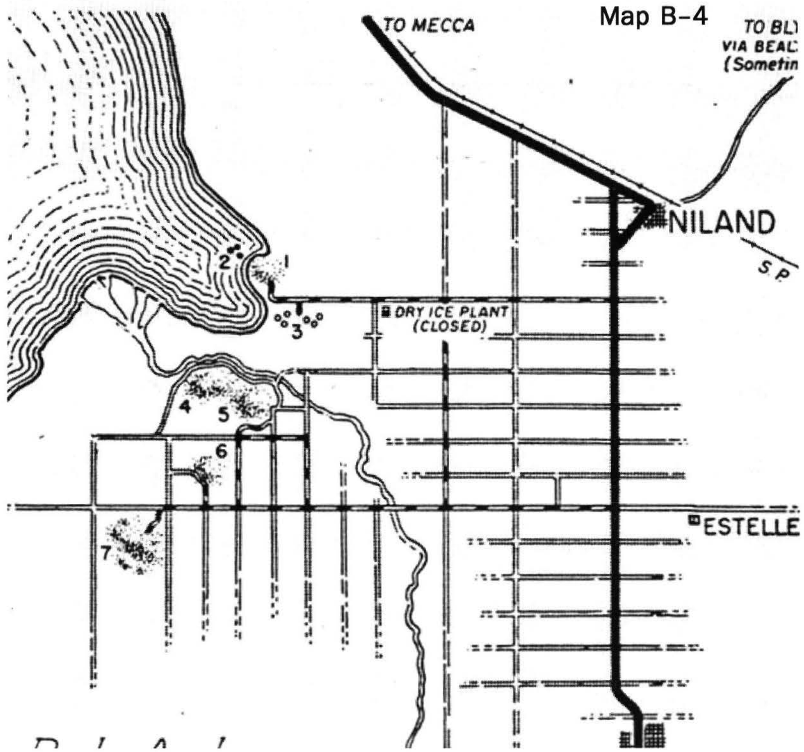
The future of the Salton Sea is a matter of great concern because it is a major, critical habitat for


Map B-1
MOUNTA
Coachella
LARK SPA
UNION
HOT MINER
Frink
FRINK RD
Frink Spring
COACHELLA
The Corner
NILAND MARINA RD
PACIFIC
Wister
HOBBS
DAVIS RD
WILKINS
CANAL
EAST
MESA
IMPERIAL VALLEY STATE WARMWATER FISH HATCHERY
HOWELL RD
WINSLOW
GILLESPIE
WISTER UNIT
DEPT. OF FISH & GAME HQ.
BEACH
ENGLISH
CUFF
IMPERIAL
WILDLIFE
AREA
SHERIFF STA.
NILAND
FIRE STA.
NOFFSINGER RD
DRY ICE WELLS
SONNY
BONO
Mullet Island
CLARK'S QUACKER CLUB
POUND
IMPERIAL DUCK CLUB
MC DONALD
SEA
RED HILL MARINA COUNTY PARK
SCHRIMPF
OBSERVATION POINT
S.B.S.S.N.W.R.
LEATHERS POWER PLANT
GARST RD
Obsidian Butte
HQS.
DEL RANCH POWER PLANT
ELMORE POWER PLANT
VULCAN POWER PLANT
SINCLAIR
Estelle
UNOCAL GEOTHERMAL SALTON SEA UNIT 2
UNOCAL GEOTHERMAL POWER PLANT
KUNS
SORENSON
LINDSEY
SEVERE
YOUNG
CHRIS HATFIELD MEMORIAL AIRPORT
POLICE STA.
BLAIR
CALIPA


Map B-2
MUD VOLCANOES
R 13 E
R 14 E
ANDREAS
Wister
WISTER WATERFOWL MANAGEMENT AREA
SOUTHERN PACIFIC
East Highline Canal
EAST MESA
T 10 S
FAULT
Carbon dioxide wells
Niland
Mullet Island
SEA
MUD VOLCANOES
T 11 S
Southend
Sportsman Club
GEOTHERMAL WELLS
IMPERIAL WATERFOWL MANAGEMENT AREA
Pumice Drain
OBSIDIAN BUTTE
Alamo River
Estelle
GEOTHERMAL WELLS
Vail Cut Off Drain
Calipatria



Map Pages B. Comparative Maps. Shown here are four maps of the mud pot areas, scanned and reproduced at the same scale (approximately 1 inch = 3 miles). They are: **B–1**, AAA "Imperial County" dated 2001; **B–2**, California Division of Mines and Geology, "Salton Sea Sheet" dated 1977 (mud pot symbols computer enhanced); **B–3**, *Salton Sea Atlas* dated 2002 (shoreline and Mullett Island enhanced for clarity); **B–4**, *Desert* Magazine dated 1947.



birds along the Pacific Flyway. The average annual rainfall of the area is less than three inches per year, so natural runoff is nil. The Sea's water level is maintained almost entirely by agricultural runoff from Imperial Valley farms. This runoff bears a substantial quantity of dissolved "salts" that include nitrates and phosphates plus heavy metals. As of early 2002, the total dissolved load in Salton Sea water was nearly 45,000 parts per million.

The only source of agricultural water is the Colorado River, and now a federal quantification process has ordered California to reduce its take of Colorado River water by about 20%. That is more than 800,000 acre feet per year. Various mitigation measures are under consideration (with some estimated costs in excess of one billion dollars), but it seems certain that the Salton Sea will be impacted. One likely result of the water loss will be a fallowing of agricultural lands, and therefore less runoff and a possible drop in the Salton Sea's water level. Some extremely expensive mitigation plans are designed to prevent any decrease in the water level.

As part of the ongoing studies of the Salton Sea environment, the Redlands University Institute, in cooperation with ESRI Press, released a beautiful new book, the *Salton Sea Atlas*, in September 2002. Lo and behold, four of the five "new" mud pot areas are shown on two different maps in the volume: as "*Mud Pots*" for the "Mullett Island Field" (as well as the McDonald–Schrimpf Field), and as "*Mud Volcanos*" [*sic*] for the Wister Field and potential new "Hobbs Field," "Fish Hatchery Field" and "Highway Field." (There is no indication of anything at the "Spa Field.")

It is these recent maps that led to the present study. Numerous other maps were also used. The four most important are shown on Map Pages B. To allow easy comparisons, they have been reproduced all to the same linear scale (1 inch = approximately 3 miles) and aligned with one another.

A Brief History of the Salton Sea

The history of the Salton Sea and its forerunners is interesting and pertinent to the story of the hot springs, so a brief history is worthwhile.

The Colorado River drains much of the western United States. Its major headwaters are in Colorado and Wyoming, and the drainage basin also encompasses portions of Utah, New Mexico, Nevada, Arizona and California. At the present time, the river (that is, what is left of it after all the dams and diversionary canals along its course) drains past Yuma, Arizona and directly into Mexico to the Gulf of California. But it has not always followed that direct route to the sea.

California's Imperial Valley is only slightly separated from the Colorado River by a pile of young sediment that, in effect, is part of the river's delta. The total depth of valley fill in the Imperial Valley is in excess of 18,000 feet. Some of this was brought to the valley by the Whitewater River from the north and a miscellany of small, intermittent streams from east and west, but the great majority was delivered by the Colorado River. It is not terribly inaccurate to say that the Imperial Valley is filled with what once was the rock of the Grand Canyon.

Yuma is only 180 feet above sea level. The divide separating the river near Yuma from the Imperial Valley is barely higher than that. Therefore, in numerous prehistoric times the river escaped its current channel and flowed into the Imperial Valley rather than directly to the ocean. The result was a series of lakes known as Lake Cahuilla (or during the mid–1800s, as Blake's Sea).

Lake Cahuilla was an impressive body of water. Once the river flow reached the Imperial Valley, the basin filled until the water reached a spill point south of Mexicali, Mexico that is 42 feet above sea level. Stated another way, all of the Imperial Valley and parts of the Coachella Valley were filled by a lake whose water surface stood at +42 feet. The lake drained via today's Rio Hardy to the Gulf of California.

The floor of the Imperial Valley, the Salton Sink lakebed beneath the modern Salton Sea, is at an altitude of 278 feet *below* sea level (only 4 feet higher than Death Valley's Badwater, the lowest point in all of the western hemisphere). When full, Lake Cahuilla was 115 miles long north–to–south, as much as 50 miles wide and 320 feet deep. Usually, this was fresh water. Wave cut terraces and "bathtub rings" are easy to find throughout the valleys, as are fields of fresh water clam and snail shells (the probable source of the name of the Coachella, an aberration of the Spanish *conchilla* for "little shell").

The most recent existence of Lake Cahuilla came to its end only a little more than 300 years ago. Per both geological and archaeological evidence, it was still full in the year 1680 but was dry by about 1750. This fits nicely with calculations that indicate the full lake without inflow would evaporate at a rate of five to eight feet per year. This evaporation left behind extensive salt flats on the floor of the Salton Sink.

Considering this natural history, the Salton Sea was "bound to happen." But the Salton Sea is a human accident. In 1905 (years before any dam had been constructed anywhere along the river) a flood washed out a set of dikes along the river south of Yuma. For more than two years, the Colorado River flowed directly into the Imperial Valley via what is now called the New River. Several commercial salt works were drowned and the Southern Pacific Railroad had to move its tracks to higher ground. When the flood was finally stopped in 1907, the new lake surface stood at an elevation of –195 feet. Both the Wister and the McDonald–Schrimpf Fields were under almost 30 feet of water.

From that level, the lake quickly evaporated to a surface below –250 feet. Only with the development of agriculture and its water runoff did the Salton Sea rise once again. It has been more or less stable at an elevation around –230 feet since the late 1970s.

Geologic Background

Along and within the southeast shore of the Salton Sea is the Salton Sea Geothermal Area. Exploratory geothermal wells were drilled in 1927, but nothing of a commercial scale was developed until 1964 [Laflin, 1995]. As of late 2002, ten power plants were being operated by CalEnergy Operating Company, with a combined peak gross electrical production of 330 megawatts (nominal net). Additional plants are planned for the near future.

These power plants operate using a geothermal brine in which geochemical indicators imply a subsurface temperature of at least 680°F. The brine is caustic and carries a significant dissolved load of over 160,000 parts per million, including sulfides of copper, lead, silver and zinc. CalEnergy expected commercial zinc recovery to be fully operational by the end of 2002, with an annual production in excess of 30,000 metric tons (more than 66 million pounds) per year — at the January 2003 price of 38.7 cents per pound, that is a world–class, gross annual value greater than $25 million. [CalEnergy, 2002].

The source of the geothermal heat and metals is magmatic. The area is directly above a documented plate tectonics spreading zone, the same pull–apart system that has separated Baja California from mainland Mexico. The form of this magma is uncertain. Some authorities state that it is a single pluton of batholithic scale, measuring about 20 miles long by perhaps 8 miles wide and oriented in a southwest–northeast direction. Others feel that it is a complex network of developing dikes rather than a single mass. In either case, recent seismic studies indicate that the uppermost magma lies at a depth of less than 20,000 feet.

Some of this magma has occasionally reached the Earth's surface. The most recent expression of this volcanic activity is the Salton Buttes, a series of five rhyolitic domes. From south to north, these are Obsidian Butte, Rock Hill, Red Hill–Pumice Butte (two merged domes) and Mullett Island. All of these now stand at least partly surrounded by the water of the Salton Sea. Although some sources cite these eruptions as having occurred as little as only 400 years ago, potassium–argon dating gives an age of about 16,000 years [USGS, undated Website]. (This age is substantially greater than that given in my earlier article about the mud pots

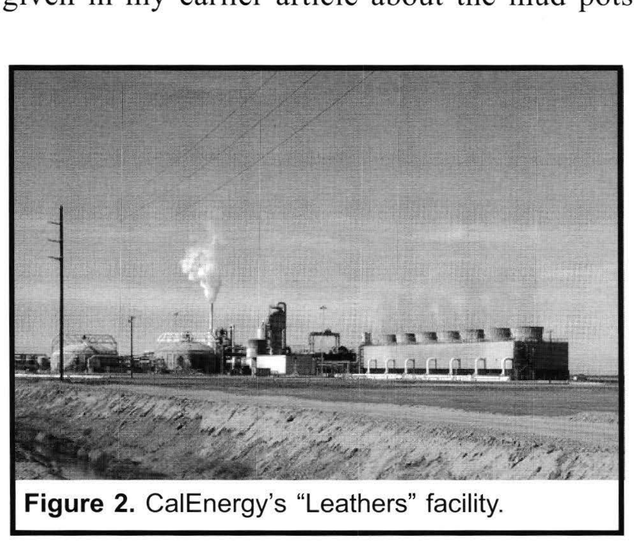


Figure 2. CalEnergy's "Leathers" facility.

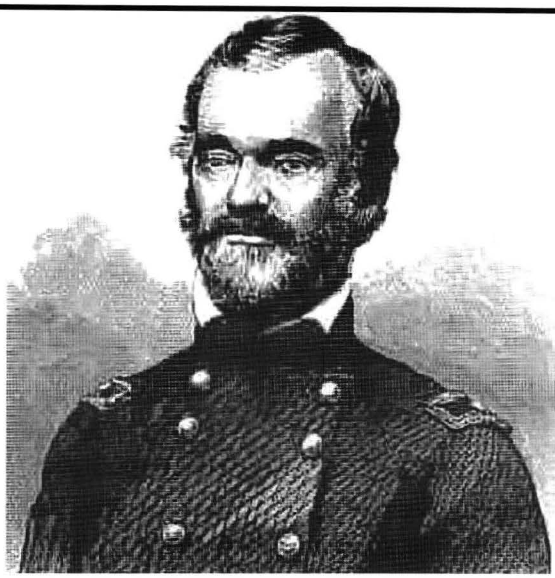


Figure 3. S. P. Heintzelman, the first person known to have described the Salton Sea mud pots, pictured as a major general in a woodcut dating to the late 1860s.

[Bryan, 1999]). The older date is supported by the facts that all of the domes are largely buried beneath valley fill and are marked by numerous wave–cut terraces from prehistoric stands of Lake Cahuilla.

Hot Springs

Hot springs of various kinds in this general area were first visited by Captain Melchior Diaz, formerly part of Hernan Cortes' conquistadores, in 1541. Exactly which springs he saw is uncertain — they might have been the Volcano Springs near Mexico's Cerro Prieto — but in any case he talked of something that caused "...hot ashes to bubble up" [*in* Ives, 1951].

Far more recently, they were seen by Major S. P. Heintzelman, as early as 1848 when he served at the end of the Mexican War with General Kearney, then in 1850 in the company of John LeConte, and once more in 1852 when he was the Commanding Officer at Fort Yuma. Investigating after seeing clouds of steam, he reported:

> "twenty–eight acres of eruptions, shooting mud as much as forty feet."

(Heintzelman's name may be familiar to Civil War historians. He served throughout that war and at its end commanded the defenses of Washington, D.C.)

LeConte's [1855] description is of interest. It reads in part as follows:

> "...we found in the plain numerous circular holes containing boiling mud... Many of them are encrusted with inspissated mud [*that is, "thickened by evaporation" – ed.*], forming cones 3–4 feet high... Four of them eject steam and clear saline water, with great violence, resembling in appearance the jet from a pipe of a high–pressure engine... Another spring was a large basin filled intermittently to overflowing with foam and clear saline water."

The mud pots were also noted in 1853 during the railroad mapping Blake Survey [Williamson, 1856], and they quickly gained more attention. During a visit in July 1857, Veatch [1857] saw large scale mud volcano eruptions and at least one geyser or perpetual spouter of significant size. In part, he wrote:

> "Mounds and cones are composed of mud, varying from three to fifteen feet in height. Out of some of the cones the steam rushed in a continuous stream... In others the action is intermittent, and each recurring rush of steam is accompanied by a discharge of a shower of hot mud, masses of which are thrown sometimes to the height of a hundred feet. These discharges take place every few minutes from some of the mounds..."

Later he says:

> "In one place *a stream of hot water* [emphasis added here] was thrown up from fifteen to thirty feet, falling in a copious shower on every side... It issued from a superficial mound out of an opening about six inches in diameter; but the column of steam and water, immediately upon issuing, expanded to a much greater size. The orifice was lined with an incrustation of carbonate of lime..."

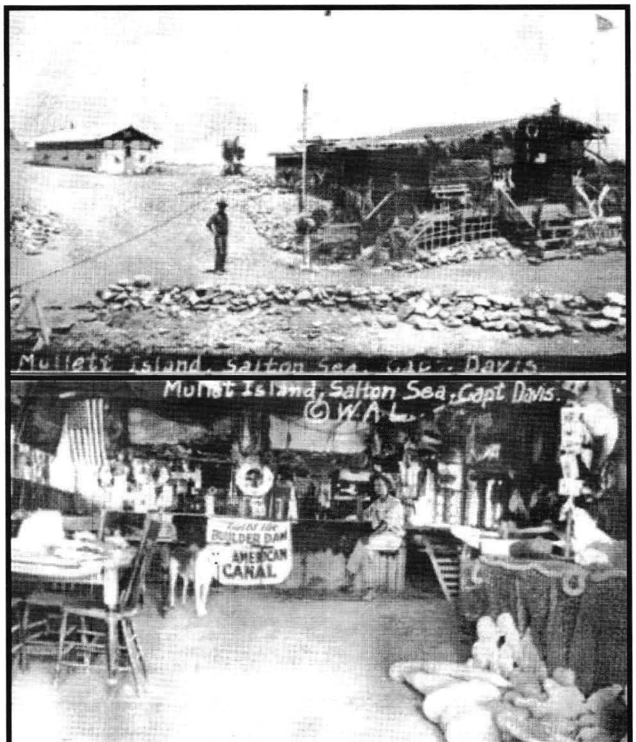
Aside from the early scientific attention, the mud pots were simply a remote curiosity until 1898, when Captain Charles E. Davis laid claim to the rocky dome that is now Mullett Island. At that time, some seven years before the start of the flood that produced the Salton Sea, this was a small hill within the barren salt flats left by the earlier evaporation of Lake Cahuilla. Recognizing the hill as a volcano, Davis gained title, built a cabin and named it Hell's Kitchen. (Of course, Davis Road is named after Captain Davis.)

Surely Davis was present when George W. James visited the hot springs during 1906, although James fails to mention him. Because of extensive flats of salty mud, James needed “skees” to reach the springs, which lay within an area 500 feet long and 350 feet wide. There he found:

> “The smell of sulphur was quite strong, and the bubbling, soughing, hissing, venting and spitting of the water, steam and mud filled our ears. There were over a hundred vents of one kind or another, most of them so small as to be perfectly ridiculous… Watery mud, scalding hot, bubbled and gurgled and frothed in the same way that artesian water bubbles over the top of its casing.”

That was the observation in March 1906. Just three months later, James found: “When I circumnavigated the Salton Sea in June, 1906, the whole volcanic area was under water.”

Figure 6. Mud pots near Mullett Island, circa 1960. Compare the apparent size the island in the background with the view of it in Figure 10 and it is clear that this locality is now under water. The specific date of this photo, by Dick Whittington, is unknown [*from* deStanley, 1966].



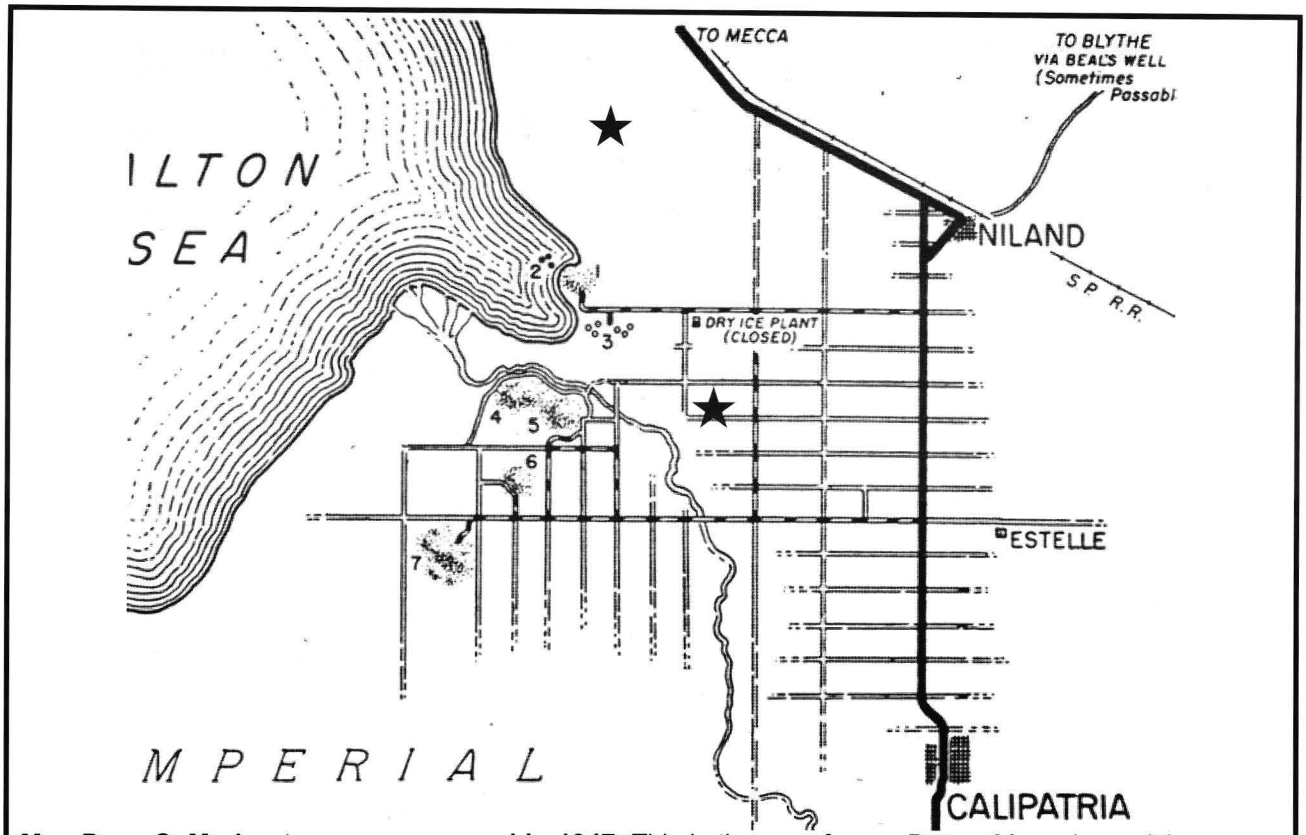
Figures 4 and 5. Life on Mullett Island. The top picture shows Captain Davis standing near his Hell’s Kitchen Cafe, while the lower image pictures him sitting inside the building. Reproduced from Laflin [1995], the identity of the photographer “W. A. L.” is unknown. The date of the photos is also unrecorded except that the sign hanging from the cafe’s counter refers to Boulder (a.k.a., Hoover) Dam, constructed between 1928 and 1935, and the All American Canal, built between 1934 and 1942.

After the flood that created the Salton Sea between 1905 and 1907 was halted, Davis developed his property with a boat landing, café and dance hall. Serving an increasing number of duck hunters and general vacationers, many of whom arrived via the nearby Southern Pacific Railroad, he became quite an entrepreneur. The hot springs were among the attractions that he promoted. Apparently the most active of the hot springs were immediately northwest of Mullett Island and to the southeast between Mullett Island and Red Hill. Both areas are now beneath the Salton Sea.

That the southeastern group of these hot springs included small geysers is certain. In the 1920s, Marcia Rittenhouse Winn lived at Mullett Island. For a 1975 issue of *Westways Magazine* (published by the Automobile Club of Southern California), she recollected:

> “The hissing of steam and the gurgling that came up from some mysterious subterranean discontent were to be an ever present reminder that we were sitting on top of volcanic ground, whose steam vents man could not turn off. The geysers kept a thin layer of moisture on top of the surrounding silt in all seasons …To the south [of Mullett Island] lay an inferno of hissing geysers and boiling mud pots.”

Other travel–oriented articles and booklets were produced about the mud pots from the late–1940s into the 1960s. Weight [1947] devoted most of his writing to the human history of the area but noted



Map Page C. Mud pot areas as mapped in 1947. This is the map from a Desert Magazine article [Weight, 1947] published in April 1947. There are two points of special note here. First, there is a dramatic change in the shoreline of the Salton Sea, so that the volcanic buttes (and hot springs) that were high–and–dry in 1947 are now islands and peninsulas. There have also been numerous apparent changes to the roads, but it was today's Pound Road that provided driving access to Mullett Island. Second, and surprisingly, neither the Wister (upper star, superimposed on original map) nor the McDonald–Schrimpf mud pot field (lower star) is shown on the 1947 map, which accompanied an article about the area's mud pots.

Numbered localities are: "1. Mullett Island; 2. Paint Pots; 3. Mud Volcanoes; 4. Pumice Butte; 5. Red Hill; 6. Rock Butte; 7. Obsidian Butte."

that the mud pot activity was apparently more vigorous before the flooding by the Salton Sea. In 1947 he said:

> "Now they seem content to rise as great boiling mud pots, building themselves higher and higher as the mud pours over the sides and hardens... Steam fusses and whistles upward through the mud in a number of places..."

This was in reference to the springs southeast of Mullett Island. Later in the article, Weight said:

> "The Paint Pots — mud pots from which highly colored clay oozes — are almost under water and ... must be reached by boat."

Mullett Island itself could be reached by road. Mr. and Mrs. E. McFarland, in 1947 the private owners of Hell's Kitchen, charged 50 cents for parking and an additional 20 cents for admission to the mud pot areas.

Briefly, other examples of these publications include:

Ives [1951], whose route description made it clear that his "Alamo River Mud Pots" were the same as my "Mullett Island Field," included several nice photos of mud pots but provided rather little descriptive text other than the opinion that the springs "smell like unwashed feet."

Gist [1952], who visited twice in January 1951, observed several dozen mud pots and, possibly, a geyser or two:

> "Tiny bubbles fizzed upward through small salty lakes, and one beautifully shaped 'vase' burped intermittently."

And Murbarger [1952], clearly much more interested in Captain Davis than in the hot springs, simply noted a field of mud pots.

What I find interesting about these articles is that none of them say anything about either of today's Wister or McDonald–Schrimpf fields, nor are they shown on the articles' maps (Weight's is reproduced as Map Page B–4 and Map Page C).

Geysers

Geyser gazers will note the use of the term "geysers" in Winn's article. Although only published in 1975, her article was about life on Mullett Island in the 1920s. Did she recognize any springs as *geysers* then, or only in later years? If the former case, then that seems to be the first time that geysers, by name, were actually recognized here.

Activity that can only be called geyser–like has been described throughout observations prior to the present inundation of the Mullett Island area by the Salton Sea: LeConte's [1855] observation of a "large basin filled intermittently" in 1850; Veatch's [1857] "discharges every few minutes" and "stream of hot water"; James's [1907] "spitting of the water"; and Gist's [1952] pool that "burped intermittently."

Perhaps 20 years ago, Dr. Donald E. White, of the U. S. Geological Survey, told me [personal communication] that around 1950 and before he observed geysers in the Mullett Island area. The geysers were all small, apparently erupting to heights not greater than a foot or two. But they clearly were true geysers. Unfortunately, Dr. White passed away on November 20, 2002, just two weeks after I wrote him a query on this matter.

To my knowledge, this information appeared in only one formal written report [White, 1955, p. 1122–1123]. In that paper, describing the "Salton Area," White wrote about his observations of April 12–13, 1948:

> "...the thermal features of the area about a mile southeast of the Mullett dome consisted of mud volcanoes, mud pots, muddy bubbling pools, perpetually spouting springs, steam vents, and *at least one active geyser* [emphasis added here]." He continued: "...only the part of the area near board walks was examined because of the treacherous nature of much of the soft mud."

There was also an historically erupting well on Mullett Island itself. White said: "...in recent years the water rose in the well and erupted mildly three or four times a day to a height of several feet." Although he saw no eruptions, White did find evidence of recent overflow and measured a water temperature of about 163°F at a depth of eight feet below the well collar.

It should be noted that until the 1950s or later, Mullett Island was seldom an actual island but, rather, was a peninsula within Salton Sea. Even now the area occupied by these geysers is beneath only a few feet of water (per the "Bathymetry" map in the *Salton Sea Atlas*, not more than seven feet). Boaters routinely see vigorous bubbling on the lake surface. Should the level of the Salton Sea drop because of the present water adjudication process, it is possible that the geyser(s) will be exposed.

Fault Zones and Geothermal Conduits

All of this region lies within active fault zones, the so–called "Brawley Seismic Zone." The McDonald–Schrimpf Field is mapped as lying directly astride one of those subsurface faults. So far as can be clearly documented, the southern limit of the San Andreas Fault proper is in the vicinity of the Wister Field, and numerous additional fault fractures extend to the northeast of there.

Some of these other fractures, northeast of the San Andreas Fault, support the water flow of the Hot Mineral Spa Geothermal Resource Area, where numerous warm (up to about 130°F) water wells serve commercial spas, including the Fountain of Youth Spa resort and campground. One published report [Hunter, 1998] states that about the year 1900, a natural spring in this area flowed at a temperature of 180°F. This is only another 4 to 5 miles north of the mud pot symbols on the maps.

Although it cannot be proven as such, map study and inference imply that the Hobbs Field is probably astride one of these faults. (Unfortunately, the wonderful USGS Map I–1483, *Map Showing Recently Active Breaks along the San Andreas Fault and Associated Faults between Salton Sea and Whitewater River–Mission Creek, California*, ends its coverage about 5 miles northwest of this area of concern.)

In summary, the entire region from south of the Salton Buttes to the Hot Mineral Spa area is a zone of volcanoes, faults, high heat flow and geothermal resources. The existence of largely undocumented hot springs is possible anywhere within this area.

Field Investigations

In late 2002 it had been nearly four years since my last visit to the known mud pots. When the Director of Education at The Living Desert Reserve, where I volunteer, suggested that I lead a field trip there for TLD docents, I decided to investigate the new mud pot possibilities and update the current activity of the previously known areas.

As part of my initial research, I contacted Kevin Marty, geologist with the El Centro Field Office of the Bureau of Land Management. He stated that the existence of mud pots within this area would not surprise him given the general regional geology. However, because he had not personally been there, he was unable to either confirm or deny the existence of any mud pot or hot spring in the vicinity of Hobbs Road.

Therefore, I determined to visit all of the known and potential Salton Sea mud pot areas. This was done on November 21, 2002. Briefly, the findings were as follows, presented in a north–to–south geographical order. See Map Page A for the locations. All photographs of Figures 2 and 7–17 were taken on November 21, 2002.

"Spa Field" — No mud pots (probably)

This is the area referred to in an Imperial County tourism Webpage under the name of "Wister Mudpots" but described as "On Hot Mineral Spa Road, just off Highway 111." Since this area is about 5 miles north of the nearest other possible, new mud pot areas and fully 9 miles north of the actual Wister Field, this is the one potential new area for which I had low expectations.

Although thermal springs and geothermal wells exist in the area, associated with the Fountain of Youth Spa and other commercial RV park resorts, I found nothing to indicate that mud pots might exist here. In a brief conversation with a woman at the Fountain of Youth Spa's registration office, I was simply referred to the Wister Field. She professed no knowledge of any undeveloped natural spring that might exist in the area.

"Hobbs Field" — Mud pots possible but not observed.

According to the symbols on the CDMG map of the area (see B–2 on Map Pages B), mud pots are distributed over a rather wide area but especially near the logical end of Wilkins Road north of Hobbs Road. In exploring the area, I found virtually all properties thoroughly fenced and posted against entry. Wilkins Road is shown on the AAA map as extending 1.1 miles northwest from Hobbs Road, following the East Highline Canal to a locked gate. Driving this unimproved road, I encountered a locked gate at only about 0.7 mile. It, too, was posted against trespassing with obviously–new signs. While driving back out, I encountered a woman driving in who made it clear that I was not welcome to explore the area.

In other portions of this possible mud pot field, I repeatedly used binoculars to examine the fields, looking especially at the many clumps of lush vegetation that must indicate near surface water. Given the opinion of BLM geologist Marty, I suspect that there are mud pots in the "Hobbs Field," but they appear to be thoroughly inaccessible.

"Fish Hatchery Field" — Mud pots possible but of very difficult access.

The "Imperial Valley State Warmwater Fish Hatchery" is not in operation; it appears to have been dormant for a long time. The potential mud pots would lie a short distance northwest of the hatchery buildings. The area is part of the state wildlife area. Although it is not posted against entry, it is an area of very dense shrubbery and tamarisk trees among wildlife ponds. I made only a cursory observation.

Minutes later, when reading the interpretive signs at the Wister headquarters, I encountered a Department of Fish and Game warden who recalled seeing some "muddy springs along the lakeshore a mile or two up that way." That would certainly be the right area.

Wister Field — Mud pots in existence.

The Wister Field is one of the two previously reported. It lies at the end of an improved gravel

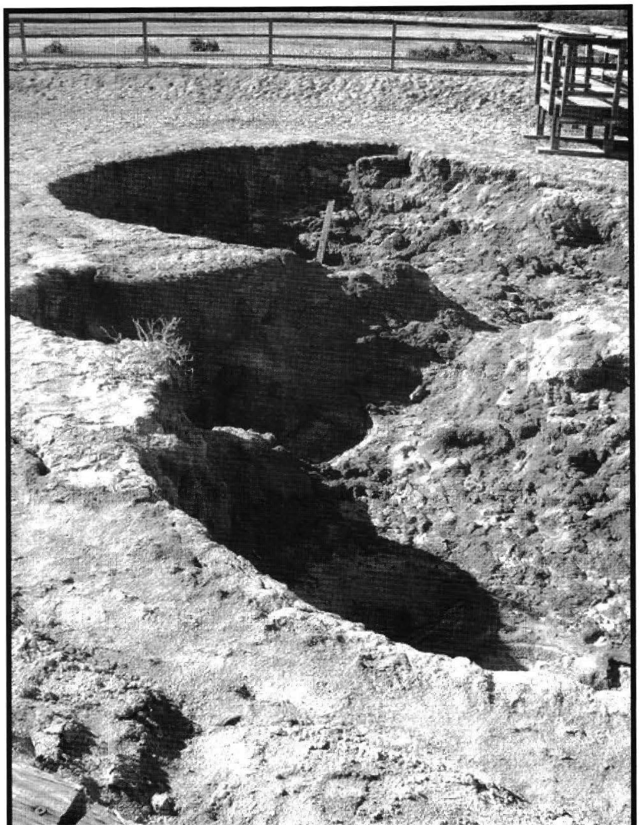


Figure 7. Wister Field. Some of the deep pits that contain mud pots at the Wister Field parking area. In November 2002, the only active mud pot here was at the bottom of the pit in the foreground.

Figure 9. Wister Field, Southwest area. Good mud pot activity was visible at several vents in this, one of six active craters southwest of the parking area.

road about 0.75 mile from the headquarters area of the Wister Unit of the Imperial State Wildlife Area. Technically, this is a fee–use area ($2.50 per day), but registration and payment is on the honor system at a kiosk where a poster announced a bird festival that was dated February 2001; in other words, the entry area is not well maintained.

Figure 8. Wister Field, West area. The only active crater in the area west of the parking lot was the pit near the center of this photo.

The entry road is marked by a small wood sign reading "Mud Pots" with an arrow pointing the way. (There are two roads there. Travelers need the one to the left (south) that begins with some square wooden posts along its left side.) There is a parking area and display at the end of the road. The closest mud pots are surrounded by a fence and short boardwalk. Other mud pots lie across the fields to the west and southwest of the parking lot.

On the November 2002 visit, I found the mud pots within the fence to be nearly inactive. Slight hissing of escaping gas could be heard, but only one small mud pot was active there.

To the west, where in 1998 I found only drying craters with no activity, the situation was much the same on this visit with the exception of one mud pot crater. It was vigorously active from several vents.

The mud pots to the southwest of the parking lot, which were the most active in 1998, were the most active on this trip, too. Bubbling and bursting was seen in each of several craters, and from several vents within two of them.

"Highway Field" — Not investigated.

From Highway 111, no indication of mud pot activity could be seen in this potential area. It was not otherwise investigated because access was across a water–filled drainage ditch, over the busy tracks of the Southern Pacific Railroad and beyond a fence. [*See addendum following the references.*]

"Mullett Island Field" — One feature seen under water.

The "Mullett Island Field" (my name) is the area that was once developed with boardwalks, where an entry fee was charged in the 1940s and where Dr. Donald E. White observed one geyser in April 1948. It probably corresponds in part to the southernmost two mud pot symbols on the CDMG map.

From Davis Road, an extension of Pound Road extends about 0.5 mile to the west; this is not shown on the AAA map but does appear on the CDMG map and also on a DeLorme atlas map (not reproduced in this report). In years past, Pound Road extended all the way to and onto Mullett Island so, if anything of the Mullett Island Field remains to be seen on land, it would be here.

To my surprise, one feature was seen. Just beyond the end of the road, under shallow Salton Sea water, was a round vent. It was bubbling gently when first seen but then not again during the next several minutes of observation.

"Gas Plant Field" — Several active paint pots.

Starting in 1932, peaking in 1942 and closing by 1947, two companies, National Dry Ice Corporation and Natural Carbonic Products, produced dry ice using carbon dioxide gas recovered from 23 wells. The ruins of the Natural Carbonic plant are at the intersection of Pound Road with Davis Road.

I do not recall seeing active mud pots here during past visits, but in November 2002 there were several on both sides of Davis Road. Most or all were powered by gas leakage from the old wells, and were of low temperature. The activity mostly

Figure 11. The ruins of the Natural Carbonic Products dry ice plant, at the intersection of Pound Road at Davis Road.

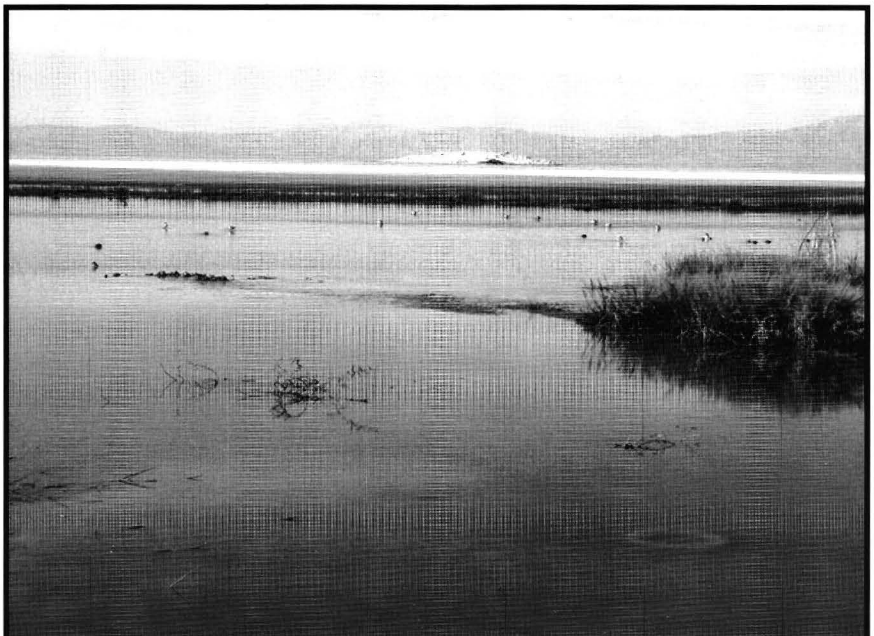


Figure 10. "Mullett Island Field." This is the view from the end of Pound Road. Out across the lake against the backdrop of distant mountains is the white–colored dome of Mullett Island. Under water at the bottom right of the foreground is a round spring vent. Bubbling when first seen, it then sat quietly for the next several minutes of observation.

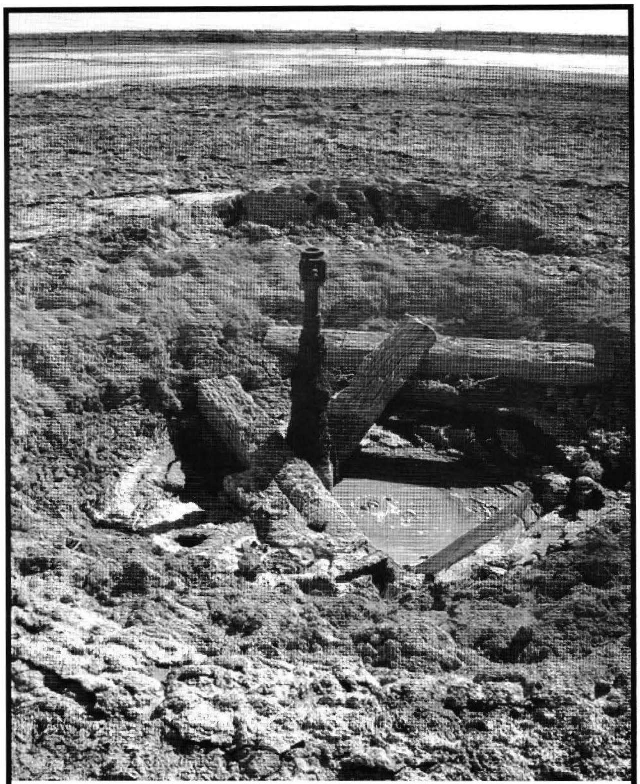


Figure 12. "Gas Plant Field." One of the paint pots bubbling within the crater that it has excavated around one of the old carbon dioxide well heads, west of Davis Road near the Natural Carbonic ruins.

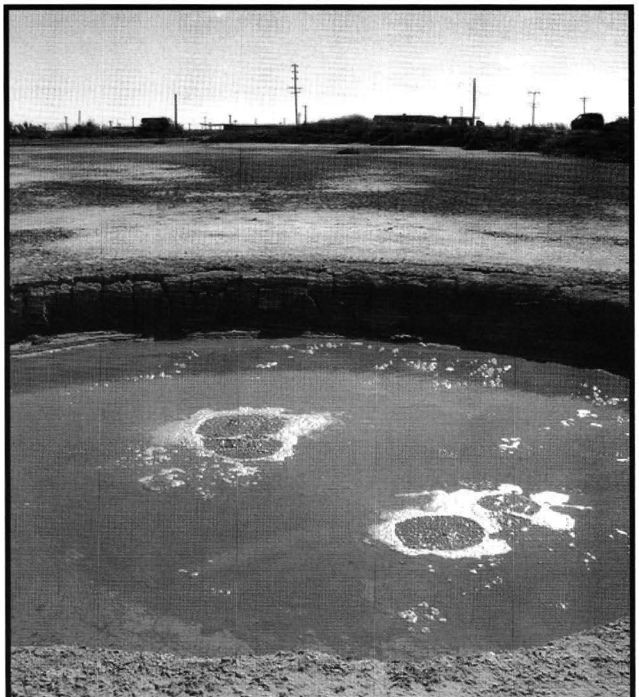


Figure 13. "Pound Road Sizzling Pond," viewed looking toward the Natural Carbonic ruins in the distance. My car is parked on Pound Road extension.

Figure 14. McDonald–Schrimpf Field. Steam, visible in near–90°F heat, could be seen rising from four of the mud volcanoes.

consisted of slight bubbling in muddy water of thin paint–like (rather than thick mud pot) consistency. In addition, much of the area surrounding the old buildings was flooded by water that could be seen seeping from the ground in numerous places. Interestingly, this flooded area and most of the paint pots were bone–dry in January 2003.

Northwest of the road intersection, accessible from the Pound Road extension, is another spring well–removed from the features near the old gas works. It appeared not to rise at an old well head. I called it the "Pound Road Sizzling Pond." It is a circular crater about 20 feet in diameter. Containing gray muddy water, it vigorously sizzled above several vents, one of which was intermittent in its action.

McDonald–Schrimpf Field — Numerous active mud pots, mud volcanoes and one gas geyser.

This is the best known and most active of all the Salton Sea mud pot areas. The activity in November 2002 was more vigorous that that witnessed in 1998. All of the mud volcano cones were active, often from vents on their sides rather than at their peaks. Many were actively producing or had recently produced mud flows down their sides. Several dozen additional mud pots and paint pots were scattered throughout the area. I guess that activity was seen in no fewer than 50 individual vents.

Perhaps most impressive was the fact that steam rose from four of the mud volcanoes. It was enough to see at a distance on a day when the air temperature was approaching 90°F. Unfortunately, I had forgotten to take my recording thermometer with me, but these springs clearly were hotter than any seen in 1998.

The McDonald–Schrimpf Field also boasted one gas geyser. Its water was only luke warm so it was powered by gas other than steam, but it was active as a distinctly intermittent erupting spring. Both the intervals and durations ranged from about 10 to 30 seconds (one interval was closer to 60 seconds). The eruptions varied from simple bubbling to bursting 1 to even 2 feet high.

Red Hill area — One dormant crater?

Upon visiting the Red Hill Marina, I saw a single crater in a mud flat area next to the entry road. To my knowledge, no mud pot activity has been reported at this site. However, since it is only about 1 mile southwest of the McDonald–Schrimpf Field, a mud pot here is obviously possible. This single crater was badly eroded and, if a mud pot, long inactive.

Access

The three localities within which mud pots are definitely known to exist — the Wister, "Gas Plant" and McDonald–Schrimpf Fields — all lie near or adjacent to Davis Road, a north–south road of graded dirt and gravel.

Most visitors will approach the area from the north on California State Highway 111. They will find the north end of Davis Road 6.2 miles south of well–marked Frink Road. The turnoff is indicated by a white–on–brown sign indicating the Wister Unit of the Imperial Wildlife Area.

Figure 15. McDonald–Schrimpf Field. A frothy paint pot, typical of many that were active there in November 2002.

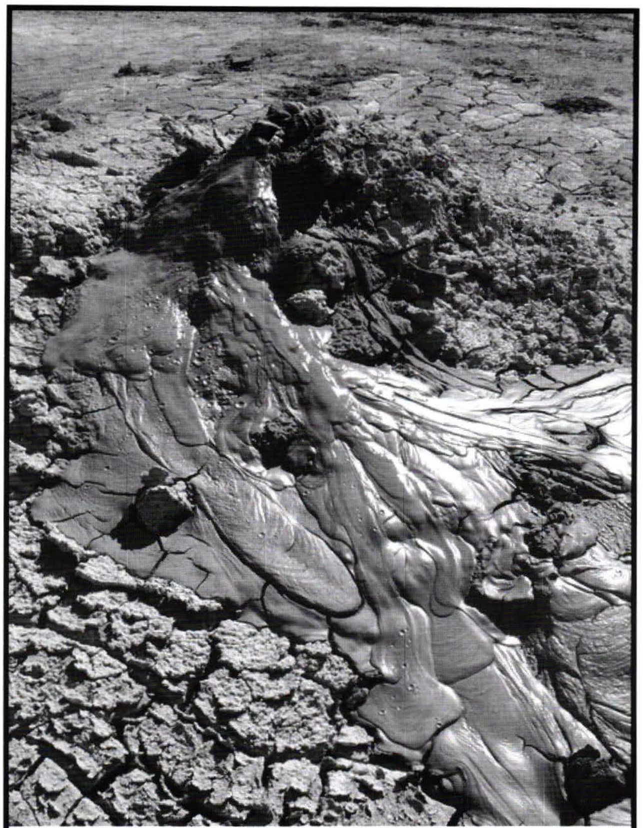


Figure 16. McDonald–Schrimpf Field. One of the mud volcanoes that was actively producing mud flows from a vent near its summit.

Persons arriving from the south drive north from Calipatria on Highway 111 to Schrimpf Road (5.1 miles) or better–marked McDonald Road (5.6 miles). Via either of these graded dirt roads, Davis Road is 3.5 miles west of Highway 111.

Along Davis Road, the distance between the Wister Field turnoff and Schrimpf Road is 5.5 miles. The mud pot fields are located as follows:

The turnoff to the *Wister Field* is just south of the end of road pavement, less than one half mile south of Highway 111. The turnoff is marked with a small sign and the first few feet of the road are paralleled by square wood posts. From the turnoff, it is about 0.7 mile west to the mud pot parking area.

Features of the *"Gas Plant Field"* are located on both sides of Davis Road near its intersection with Pound Road, approximately 4 miles south of the turnoff to the Wister Field, or just 1 mile north of McDonald Road. The "sizzling pond" is visible

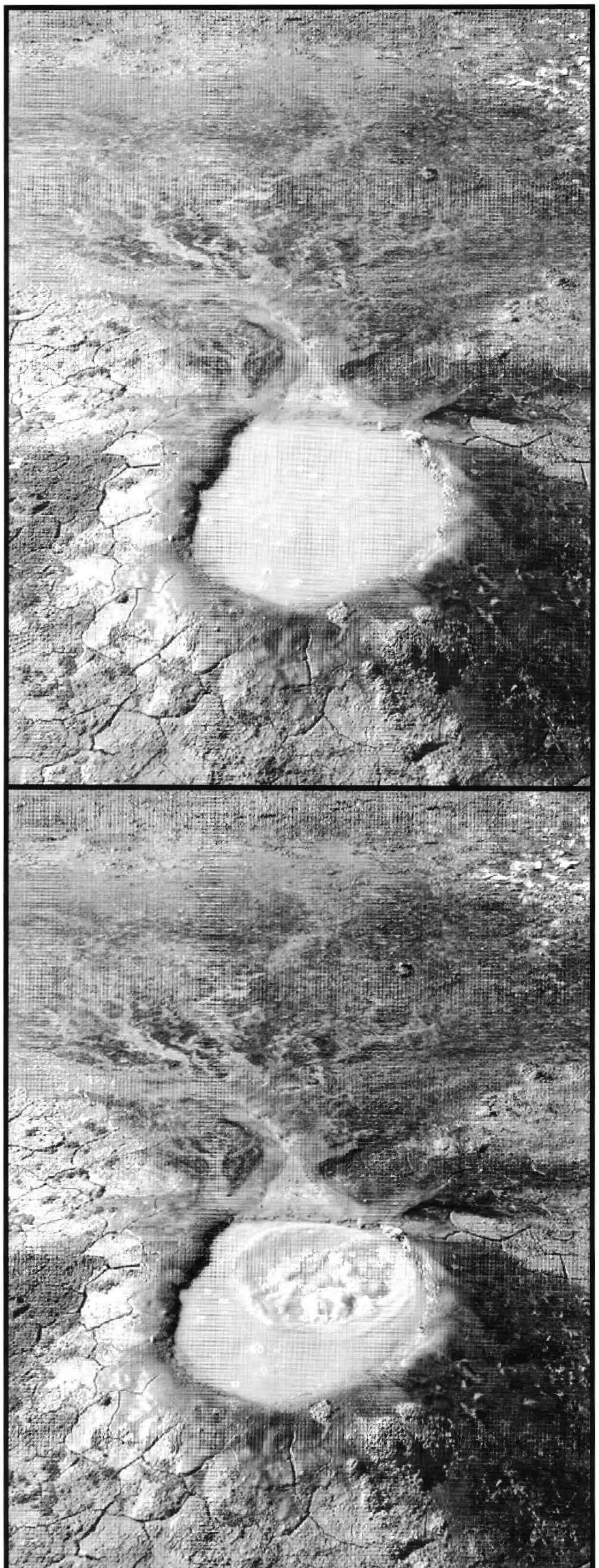


Figure 17. The McDonald–Schrimpf Geyser. This gas–driven geyser generally erupted every 10 to 30 seconds for similar durations. Here I just missed photographing a splash that was about 1 foot high.

from the westward extension of Pound Road, which also leads to a view of the vicinity of the "*Mullett Island Field.*"

The *McDonald–Schrimpf Field* is located between those two roads, in an open field just east of Davis Road.

Note that while gasoline and grocery stores are available in Calipatria and Niland, other commercial services are sparse in both towns.

Acknowledgements

Several people must be thanked for the help they gave in searching out and providing copies of old articles not readily obtained by me. They are:

J. O. Chapple, Debbie Sjodin and Tamsen Hert of GOSA, and Lynda Volman of the AAA–ACSC *Westways Magazine*. Research help was also provided by several staff members at the Palm Desert Branch of the Riverside County (California) Library and at the Palm Springs City Library.

Background information and/or office library access were provided by Bureau of Land Management geologists Steve Kupferman, Palm Springs Field Office and Kevin Marty, El Centro Field Office.

References

Anon., 1999, "Samuel Peter Heintzelman": retrieved from http://www.amcivilwarbiography.homestead.com/

Bryan, T. S., 1999, Mud pots of the Salton Sea Geothermal Area near Niland, California: The Geyser Gazer Sput, v. 13, no. 1 (February 1999), p. 9–11; route correction, v. 13, no. 2, p. 3.

CalEnergy, 2002, "Imperial valley generation" and "Zinc recovery": retrieved from http://www.calenergy.com/

deStanley, M., 1966, *The Salton Sea, Yesterday and Today*: Triumph Press, Inc., Los Angeles.

Dunn, T. and Dunn, G., 1999, Salton Sea geothermal mudpots and mud volcanoes: The Geyser Gazer Sput, v. 13, no. 2 (April 1999), p. 20–21.

Gist, E. S., 1952, Where the Earth burps: Nature Magazine, v. 45, no. 5, p. 245–247.

Hobart, J., 2000, Diamonds from mud: Discoveries at Salton Sea: The Geyser Gazer Sput, v. 14, no. 3 (June 2000), p. 11–13.

Hunter, C. C., 1998, An investigation of the Hot Mineral Spa Geothermal Resource Area, Riverside and Imperials Counties, California; *in* Lindsay, L., ed., 1998, *Geology and Geothermal Resources of the Imperial and Mexicali Valleys*: San Diego Association of Geologists; Sunbelt Publications, San Diego, p. 93–108.

Imperial County, 1997, "Imperial County photo tour": retrieved from http://www.imperialcounty.com/phototur/photo15.htm

Ives, R. L., 1951, Mud volcanoes of the Salton depression: Rocks and Minerals, v. 26, no. 5–6, p. 227–235.

James, G. W., 1907, *The Wonders of the Colorado Desert*: Little, Brown & Co., Boston, v. I of II, p. 19 and 83–86.

Kelly, V. C. and Soske, J. L., 1936, Origin of the Salton volcanic domes: Journal of Geology, v. 44, no. 4, p. 496–509.

Krantz, T. P., Program Director, 2002, *Salton Sea Atlas*: Redlands Institute, University of Redlands, ESRI Press, Redlands, CA., 127 p.

Laflin, P., 1995, Mudpots, geysers and Mullett Island: Part II, Chapter 8 in *The Salton Sea: California's Overlooked Treasure*, The Periscope, Coachella Valley Historical Society, 61 p.; reproduction retrieved from http://www.sci.sdsu.edu/salton/PeriscopeSaltonSeaCh7-9.html

LeConte, J. L., 1855, Account of some volcanic springs in the desert of the Colorado, in southern California: American Journal of Science and Arts, 2nd Series, v. 19, p. 1–6.

MacDougal, D. T., 1907, The desert basins of the Colorado Delta: American Geographical Society (New York) Bulletin, v. 39, no. 12, p. 705–729.

Muffler, L.J.P. and White, D. E., 1969, Active metamorphism of upper Cenozoic sediments in the Salton Sea Geothermal Field and Salton Trough, southern California: Geological Society of America Bulletin, v. 80, no. 2, p. 157–182.

Murbarger, N., 1952, He was monarch of Mullett Island: Palm Springs Villager, May 1952.

Oertle, V. L., 1964, *The Salton Sea Shoreline Guide*: Desert–Southwest Publishing Co., Palm Desert.

Pepper, C., 1994, *Desert Lore of Southern California*: Sunbelt Publications, San Diego.

Robinson, Elders and Muffler, L.J.P., 1976, Quaternary volcanism in the Salton Sea geothermal field, Imperial Valley, California: Geological Society of America Bulletin, v. 87, no. 3, p. 347–360.

Singer, E., 1995, Volcanic activity in the Imperial Valley: Chapter 10, in *Geology of California's Imperial Valley*, unpublished monograph, 10 p.

Sturz, A., German, D. and Putnam, D., 1998, Salton Sea Geothermal Area mud pots: 1991–1998; *in* Lindsay, L., ed., 1998, *Geology and Geothermal Resources of the Imperial and Mexicali Valleys*: San Diego Association of Geologists; Sunbelt Publications, San Diego, p. 109–128.

U.S. Geological Survey, 2001, CVO Website — Salton Buttes, California: extracts from USGS Bulletin 1847, retrieved from: http://vulcan.wr.usgs.gov/Volcanoes/California/SaltonButtes/description_salton_buttes.html

Veatch, J. A., 1857, Notes of a visit to the "mud volcanoes" in the Colorado Desert in the month of July, 1857: California Academy, Natural Science Proceedings, v. 1, p. 104–108.

Weight, H. O., 1948, Nature's freaks on Salton shore: Desert Magazine, v. 11, no. 4, p. 5–8.

White, D. E., 1955, Violtent mud–volcano eruption of Lake City Hot Springs, northeastern California: Geological Society of America Bulletin, v. 66, no. 9, p. 1109–1130.

Williamson, R. S., 1856, *Report of Explorations in California for Railroad Routes to Connect with the Routes near the 35th and 32nd Parallels of North Latitude*: Volume V, Pacific Railroad Surveys, Government Printer, Washington, D.C.

Winn, M. R., 1975, Next door to Hell's Kitchen: Westways Magazine, v. 68, no. 2.

[Author's Note — The following update was provided by Alan Glennon, who visited these mud pots on March 23, 2003. Per my description within the body of this article, I apparently was looking for these mud pots at a point perhaps one–half mile south of the actual location. TSB]

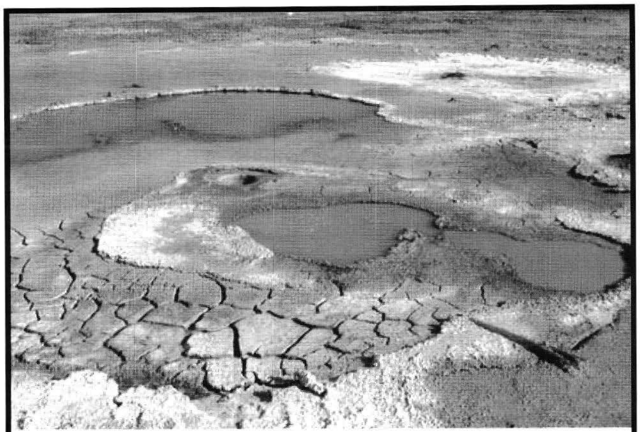
"Highway Field" — Several effervescing pools and paintpots.

The Highway Field is located approximately two hundred meters northeast of the intersection of Highway 111 and Davis Road. Looking to northeast from Highway 111, two broad, low, barren mounds are visible. The two mounds are separated by a distance of approximately forty meters.

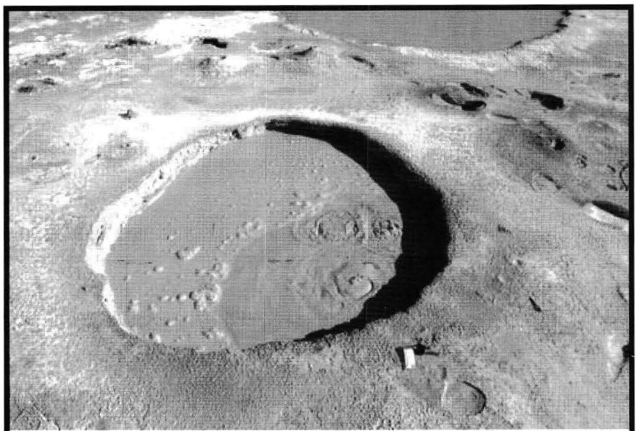
An effervescing, muddy, oblong pool approximately 2.4 meters long and 1.8 meters wide lies atop the southern-most mound. With minimal disturbance to the pool's surface, carbon dioxide gently bubbles from a single location within the pool. Water temperatures throughout the Highway Field were cool to the touch (probably less than 30 degrees Centigrade). The pool is the southern mound's dominant feature, but several minute cones and tiny fissure seeps lead away from the pool toward the northern, more active mound area.

The northern springs are dominated by three effervescing pools ranging from two to three meters in length. Each of the pools appears to be developed from the coalescing of two or more smaller, round pools. Several shallow, round, craters (from 0.3 to one meter in diameter) edge the pools and operate as paintpots. Consisting of steady bubbling from watery mud, these paintpots are the Highway Field's most active features. At least ten small cones dot the field; their heights are on average ten centimeters, but one cone is three times that height. Water and weak bubbling was noted in four of these cones.

Of the entire Highway Field, very little surface water discharge was apparent. Tiny seeps emit water throughout the field, but in immeasurably small amounts. Nevertheless, the two largest pools possess zones of seemingly overflowing moisture with algal growth. Overall, a well-developed runoff channel originates from the spring area, however, it may be a result of the mounds' slightly higher relief.



A complex of muddy pools within the north portion of the "Highway Field." [Photo by Alan Glennon]



One of the more active mud pots in the north portion of the "Highway Field." [Photo by Alan Glennon]

The largest of the pools in the south portion of the "Highway Field." [Photo by Alan Glennon]

About the Contributors
to The GOSA Transactions, Volume VIII

T. Scott Bryan (M.S., Geological Sciences from the University of Montana) retired in 2001 from twenty years as Professor of Geology and Astronomy at Victor Valley College, in Victorville, California. Starting with the summer of 1970, Bryan held seasonal positions in Yellowstone for 14 summers, including ten as Ranger–Naturalist at Norris and Old Faithful. He has visited the geysers of California, Nevada, Oregon, Mexico, Kamchatka, Fiji and New Zealand. He is the author of *The Geysers of Yellowstone* and several articles in the previous volumes of *The GOSA Transactions*, plus a number of travel–based articles in commercial trade publications. He was one of the founding Directors and served as the first President of GOSA, was the creator of *The Geyser Gazer Sput* newsletter, and edited this and several other volumes of *The GOSA Transactions*.

Carlton Cross, an electrical engineer by training, is Professor of Engineering at Walla Walla College, in College Place, Washington, where he has been teaching for 22 years. Previous to that, he was employed at the Bell Telephone Laboratories. As "the family logistics and equipment person," he helped coordinate geyser studies and provided resulting data as well as several photos for three of the articles in this volume.

Jeff Cross first visited Yellowstone at the age of four, in 1979, and he began serious observations of geysers in 1988. He received the Bachelor of Science in Chemistry from Walla Walla College in 1998, and is presently pursuing graduate work in Organic Chemistry at Colorado State University.

Tara Cross became interested in geysers as a child on family vacations. Although she enjoys all geysers, her main interests are Fan and Mortar Geysers and Yellowstone's backcountry areas. A May 2001 graduate with a Bachelor of Arts in History from Southern Adventist University, she currently serves as the Library Director at the Yellowstone Research Library, in Mammoth Hot Springs.

J. Alan Glennon received the degrees of Bachelor of Science from Texas A&M University and Master of Science from Western Kentucky University in geoscience, and is now a doctoral student in geography at the University of California, Santa Barbara. In 1999, he co–founded the Western Kentucky University Hoffman Environmental Research Institute, and served as its Assistant Director for four years. From 1998 into 1999, he worked as a Research Hydrologist for the Center for Cave and Karst Studies. In past years, he worked eight seasons as a Ranger–Naturalist at Mammoth Cave National Park, Jewel Cave National Monument and Great Basin National Park.

Mike Keller has lived and worked in Yellowstone National Park since 1987. He is currently the Location Manager of the Old Faithful Inn. Mike received a degree in Geological Engineering from Montana Technical College in 1991. His geyser specialties are the activity of the Giant Geyser Complex and the Myriad Group, both of which he has studied in detail. With his wife, Cynthia, he serves as a thermal volunteer for the National Park Service, primarily assisting with the monitoring and cleaning of thermal features.

William P. (Will) Moats holds a Bachelors degree in Geological Engineering and Geology from the New Mexico Institute of Mining and Technology, and a Master of Science in Geology from Arizona State University. He works as the Albuquerque Group Manager of the Permits Management Program, New Mexico Environment Department Hazardous Waste Bureau. He has also previously worked as an engineer and estimator in highway, industrial and heavy construction and as a project geologist in minerals exploration. He has enjoyed geyser gazing since 1996.

Rhonda Pfaff holds the Master of Science in Geoscience from Western Kentucky University as well as a Bachelors degree in Political Science. In 2001, she was a cartographic technician for the Spatial Analysis Center in the Yellowstone Center for Resources, at Yellowstone National Park. Research interests include karst landscapes and hydrothermal systems, and recent work has included a Geographic Information System (GIS) analysis of Mammoth Cave, Kentucky, the geochemistry of Narrow Gauge Terrace at Yellowstone's Mammoth Hot Springs, and the hydrothermal activity of the Andes Mountains in South America. She presentlyis a GIS software documentation specialist for the Environmental Systems Research Institute (ESRI) in Redlands, California.

Dr. Donald E. White had a long and sterling career with the U. S. Geological Survey, where he specialized in geothermal topics. Recipient of numerous high–level awards and of worldwide fame, he enjoyed the pasttime of geyser gazing. In memory of his passing in November 2002, this volume includes transcriptions of two memoranda he wrote about the preservation of geysers and related hot springs.

Marie Wolf became a dedicated geyser gazer in 1972 when summer seasonal employment in Yellowstone brought her to the Old Faithful area. She quickly became known as 'Daisy Marie' because of the intense scrutiny she paid to Daisy Geyser and the other members of that complex. The paper she wrote about the early–1970s rejuventation of that group of hot springs is reproduced here in her memory.

Photographers

Kit Barger	Rhonda Cartee
Cyril Cavadore	L. C. Daugherty
Ralph Friz	Shane Fryer
Stacey Glasser	Alan Glennon
Mike Keller	Chris MacIntosh
Bill Massella	Clark Murray
Mike Newcomb	Paul Strasser
Mary Beth Schwarz	Pat Snyder

Helen (Mrs. 'Jo') White

List of Readers

Holly Zullo	Lee Whittlesey
Kristian Wang	Ralph Taylor
Paul Strasser	Lynn Stephens
Mary Beth Schwarz	Rocco Paperiello
Clark Murray	Kevin Marty
Dan Larson	Alan Glennon
Tara Cross	Jeff Cross
Nancy Cross	Gordon Bower

and several others who are unknown to the editor or who wish to remain anonymous.

Also remembering...

John Muller

1924 – 2002

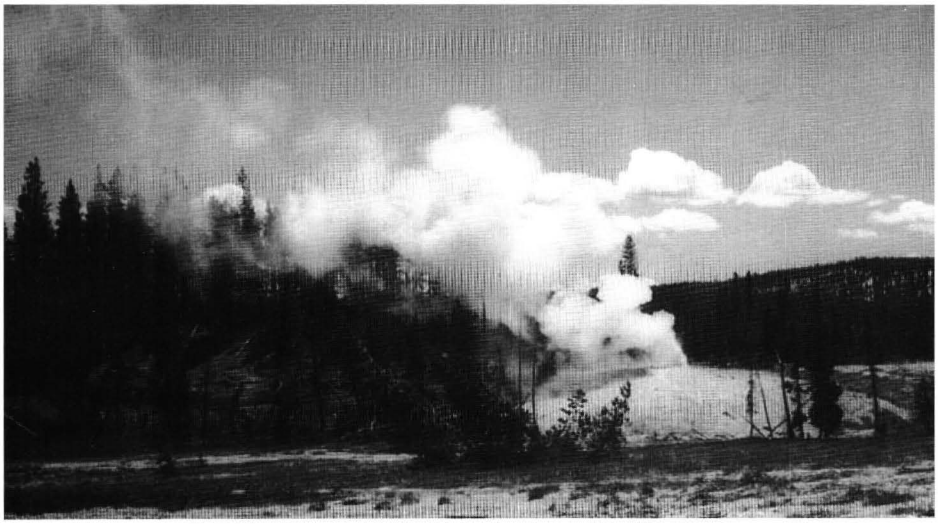
Accompanied by his trusty walking staff, John often sat at Oblong Geyser, one of his favorites.

John conducting his Thermal Volunteer duties across the boardwalk from Scalloped Spring. (Above two photos by Ralph Friz)

At Geyser Creek, near Labor Day 1989. "Big Bowl" (a.k.a., "Necklace") Geyser is in the background. (Photo by Karen Koka)

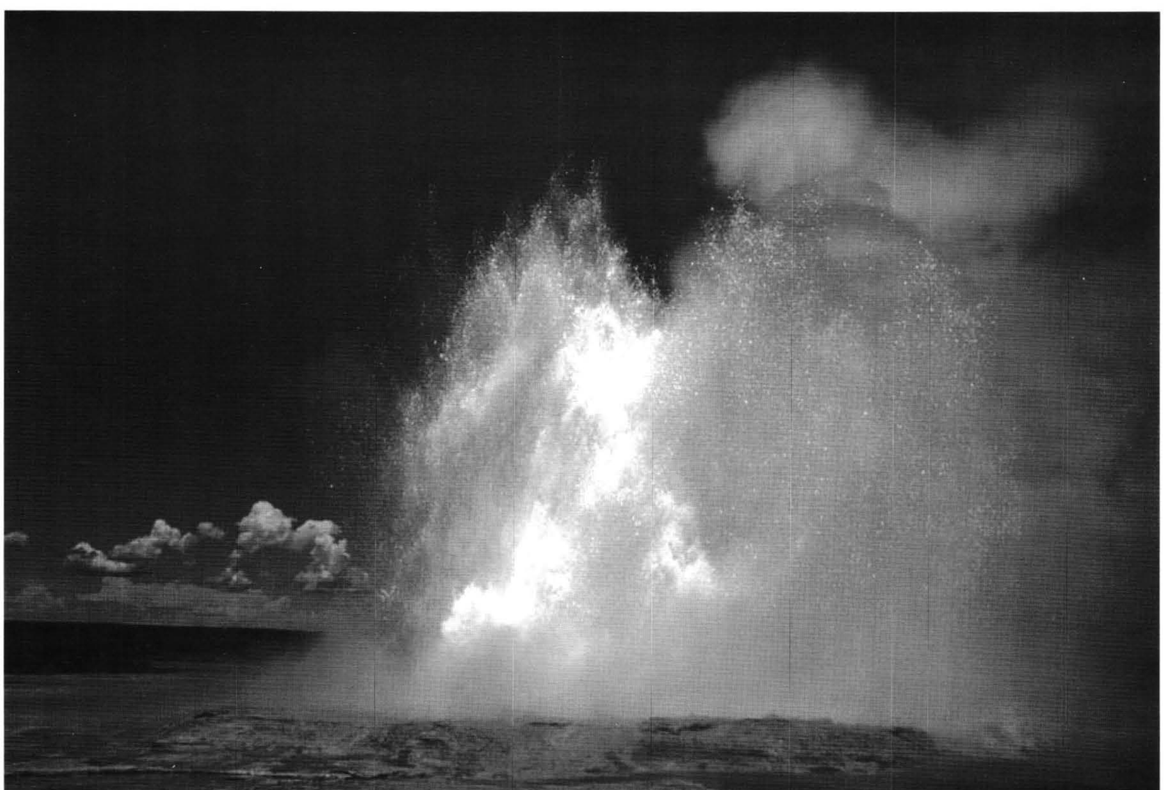
Three Extraordinary Photos by Clark Murray

"**Incline Geyser**," a member of the Porcelain Terrace Springs in the Norris Geyser Basin, was at its best in 1990. Some of the eruptions cleared the slope (out of the photo to the right) and neared Nuphar Lake — meaning that during its brief existence, Incline was one of the larger geysers in all of Yellowstone.



Taurus Spring, in the Shoshone Geyser Basin, in eruption on July 5, 1997. Previously active only shortly after the 1959 earthquake and than again (unseen) in July 2003, this picture by Murray might well be the *only* existing photo that shows Taurus in eruption.

A small spring in the "Westside Group" of the Upper Geyser Basin became active for the first known time in May 1998. Informally called "**Maelstrom Geyser**" because of the violent nature of its 6–foot eruptions, Murray's photos might be the only ones in existence. Maelstrom has not been active since 1998 and, in fact during 2003, its water stood quietly at a level several inches below overflow.



Fountain Geyser, May 27, 2003. (Photo by Pat Snyder)

Researchers are encouraged to produce articles for *The GOSA Transactions*, Volume IX, which is expected to be published during 2004–2005. Please advise the Editor about your article topic and anticipated length at the earliest possible date. Submissions guidelines are available upon request.

The GOSA Transactions
Volume VIII, 2003

The Geyser Observation and Study Association

contents continue on the inside of this cover

GOSA