THE GOSA TRANSACTIONS

GOSA

The Journal of the Geyser Observation and Study Association

VOLUME XIII 2016

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

Cover photograph: Morning Geyser, May 28, 2013. Photo by Graham Meech.

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

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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

This publication's goal is for readers to understand the article information without being bogged down or confused by unfamiliar measurement units. Therefore, GOSA publications prefer using the English measurement system for measuring distances and heights; that is, units of feet, yards and miles, rather than the metric system. Although some feel we should adopt the metric system, the fact is that the majority of our readers, as well as most Americans, do not readily understand metric units. However, please note that articles using the metric system are published as is, using metric measurement units.

Time Measurements and Time Measurement Abbreviations

Units of time are straightforward in nearly all cases. In general discussions, where specific data is not involved, time units are spelled in full ("hours" or "minutes," for example). Within specific data, however, the use of abbreviations is preferred. The units are as follows: d = days; h = hours; m = minutes; s = seconds. To avoid confusion, punctuation-type abbreviations are not used, and longer time units, such as "years" and "months," are always spelled in full.

Other Abbreviations

A number of additional, geyser-observation-standard abbreviations are used within some articles, most consistently within data tables and in text directly associated with specific geyser data. These abbreviations include the following:

I or i = interval; IBE = interval between eruptions; D or d = duration; ie = observed in eruption; and the tilde (~) may be used to note approximate time value. When these terms are used in isolated incidents within an article, they may be spelled out.

Past Tense and Present Tense

Almost without exception, a discussion about geyser activity is based on past observations; therefore, articles have been written in past tense.

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Botryoidal Spring erupts in the White Creek area of the Lower Geyser Basin. Top photo taken Sept. 10, 2015 and bottom photo taken Aug. 30, 2012.

See the article about Botryoidal Spring on page 24. Photos by Pat Snyder.

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Rare and Historical Photographs

Compiled by Jeff Cross

Abstract: Photographs and descriptive text are provided for several of the lesser-known geysers of Yellowstone. These geysers are either rare, are difficult or impossible to access today, or have been dormant for decades. These photographs and text provide a unique record of their activity.

PHOTOGRAPHS BY T. SCOTT BRYAN

The following series of photographs and text (pages 6 through 11) were provided to *The GOSA Transactions* by T. Scott Bryan, who had the opportunity to photograph the eruptions of many lesser-known geysers in the course of his duties working for the National Park Service.

UPPER GEYSER BASIN

"Marmot Cave" ***(above)***

July 17, 1998: "Marmot Cave" Geyser (a.k.a., UNNG-GHG-11) lies in the small pool in front of a cave-like opening in the geyserite on Geyser Hill, Upper Geyser Basin. Eruptive phases were relatively common during the 1990s, but eruption intervals were erratic and generally hours long. The bursting play reached 2-to-6 feet high over durations of a few seconds.

Mottled Pool ***(above)***

Mottled Pool lies within a deep crater near the boardwalk at the top of Geyser Hill in the Upper Geyser Basin -- the only Geyser Hill feature of higher elevation is the summit of nearby Dome Geyser. Usually nothing of Mottled's action can be seen from the walk because its pool lies fully six feet below the crater rim and most splashes are only 2 to 3 feet high; in years past, however, bursts of 10 feet or so were seen. Probably one of several springs originally named "Oyster," Mottled Pool gets its name from ranger Charles Phillips who in 1926 referred to it as "an extinct vent" (Whittlesey 1988). The modern activity apparently dates to the 1959 Hebgen Lake Earthquake and probably is perpetual.

Round Geyser ***(above)***

July 1974: Round Geyser, in the Myriad Group of the Upper Geyser Basin, first came to light as a geyser after the 1959 earthquake (reports of action in 1933 are somewhat questionable). It has undergone several rather brief active phases since then, the best taking place in the mid-1970s. During 1974, intervals averaged around 14 hours. All eruptions lasted less than 1 minute, but they sent a steady, "Old Faithful-like" jet fully 150 feet high followed by a powerful, loud steam phase.

UNNG-ORG-5 ***(right)***

August 1986: A geyser known only by Bryan's designation as UNNG-ORG-5 is a member of the Old Road Group of Biscuit Basin. Its vent is situated next to a runoff channel belonging to Cauliflower Geyser near the midpoint between Demise Geyser to the south and UNNG-ORG-3 to the north. Its only known eruptions occurred during 1986 and 1987. Intervals were erratic and ranged from 40 minutes to a few hours. Durations as long as 8 minutes burst water as high as 15 feet from two vents. The activity in 1987 threw rocks and enlarged the vents so that the final eruptions were nothing more than gushing overflow.

 

Spectacle Geyser

July 1974: Spectacle Geyser was first seen to a few feet high out of a small hole in 1928. Because water from adjacent Abuse Spring was used in the laundry and kitchen of the Old Faithful Inn, Spectacle's vent was immediately filled with sand, and the eruptions stopped. Subsequent activity gradually blew out the sand, enlarging the vent into a jagged crater several feet across. Eruptions 15 to 40 feet high have taken place during several active phases. Some of the best performances took place in 1974, when several days of action saw intervals of 20 minutes and durations of around 3 minutes. More special was the action of May 1976, when over a 10 day period Spectacle played as a truly major geyser fully 75 feet high in company with Abuse Spring, which simultaneously exceeded 90 feet.

Honey's Vent ***(left)***

August 1983: Honey's Vent (the word "Geyser" is an optional part of the name) is a member of the Kaleidoscope Group in the Lower Geyser Basin. The crater was formed by a steam explosion in 1960, when it was named by George Marler in allusion to nearby Honeycomb Geyser. It is frequently seen by observers on the Fountain Overlook boardwalk.

Frolic Geyser ***(above)***

July 1986: Frolic Geyser, an outlier of the Fountain Group in the Lower Geyser Basin, was first seen to erupt in 1964. It is at best minimally active in most years, but it was very active during the mid-1980s when some eruptions reached 50 feet high.

Angle Geyser

1986: Angle Geyser is the namesake member of a complex of hot spring vents within the Sprinkler Group of geysers, in the Lower Geyser Basin. This photo shows what is probably the original Angle Geyser, as described and named by George Marler in 1959. During the years since 2000, several new eruptive vents have formed within the complex, and whether or not Angle itself is still active is uncertain.

Sunday Geyser ***(left and above)***

August 1981: Sunday Geyser might have been active as early as 1926, but it was named by ranger Bill Lewis following its first known eruption that took place on Sunday, July 12, 1964. Never a consistent performer, probably its best active phase was in 1981-1982, when eruptions recurred every few minutes and reached as high as 50 feet.

Medusa Spring ***(left)***

August(?) 1984: Medusa Spring is located in the southernmost corner of the Back Basin of Norris Geyser Basin. It is far from any public trail, but if you know where to look, it can be seen from the road south of Norris Junction. Medusa was first described as a numbered feature by A. C. Peale in 1878, then given its name by the Hague survey in 1887. The name no doubt arose because of snake-like runoff channels that sometimes lead away from the spring, though another possible hypothesis is that natural objects such as pine needles and insects are quickly petrified with silica after falling into its pool. Medusa often stands as a quiet pool below overflow, but eruptive episodes might be fairly common—observations of it are infrequent at best. Also, during major Norris area disturbances, Medusa has been known to erupt muddy water over 10 feet high.

MYRIAD GROUP

Photographs by George Marler, courtesy of Tom Perry Special Collections at Brigham Young University.

Myriad Geyser

Round Geyser

Myriad Geyser, along with Round Geyser *(see page 7),* is found in the Myriad Group of the Upper Geyser Basin. This photograph shows it erupting during its single active phase, which took place in 1954 and 1955, when it erupted to 80 to 100 feet every 5 to 13 hours. (Bryan 2008).

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UNION GEYSER

Photograph by George Marler, courtesy of Tom Perry Special Collections at Brigham Young University. Text by Jeff Cross.

The largest geyser in the Yellowstone backcountry, Union Geyser has not erupted since 1977 (Bryan 2008). Historical quantitative eruption data is scant, but shows that Union erupted in series. These occurred about every 5 days, with two to four eruptions per series occurring at lengthening intervals. Paperiello (1992) collected available data for Union

Table 1. Summary of quantitative data on Union Geyser collected in Paperiello (1992).

	Min	Max	Mean	n
Interval (initial-to-initial):	5.0 d	5.7 d	5.5 d	6
Interval (first in series):	2.8 h	4.0 h	3.1 h	9
Interval (second in series):	6.1 h	8.5 h	7.4 h	5
Interval (third in series):			11.3 h	1
Height (center cone):	70 ft	120 ft	99 ft	9
Height (north cone):	50 ft	66 ft	56 ft	6
Height (south cone):	steam	20 ft	7 ft	7
Duration (total):	26 m	85 m	54 m	10
Duration (water, ctr. cone):	3.4 m	10 m	6.6 m	14
Duration (water, N. cone):	7.5 m	13 m	10.1 m	11
Duration (water, S. cone):	0 m	2 m		
Delay (N. cone follows ctr.):	0 m	3.6 m	2.0 m	8

dating from 1872-1887, 1950 and 1973-1976. A summary of that data is in Table 1 *(above).*

Although Martinez cited initial-to-initial intervals as short as 3 days, he does not give data that can be included in this table (Martinez, 1974). The six intervals that can be used include two double intervals of 11.0 days (2 x 5.5 days) and 11.5 days (2 x 5.8 days) from 1976. The series of Union Geyser have an unusual form, where the intervals within the series lengthen as the series progresses. This suggests a series mechanism where the recharge rates for heat, water, or both, decrease as the series progresses. It stands in contrast to eruptive series that maintain uniform intervals. Also interesting is the delay that sometimes occurs between the start of the eruption from the center cone and the start of the north cone. That a delay occurs implies that these two vents, though certainly connected, are somewhat independent. Similar delays occur in the eruption of Vent Geyser during the eruption of Grand Geyser, and the onset of major activity from Mortar Geyser during the eruption of Fan Geyser.

Only once has the rate of filling been studied at Union Geyser. In 1878, Peale (1883) recorded filling rates following two eruptive series. In both cases, water was first visible in the vent 24 hours following the start of the series, despite the first series consisting of three eruptions, and the second series consisting of only two. Following the first series, the first splashes out of the center cone were observed 86 hours after the start of the series, whereas this required 96 hours following the start of the second series. Overflow was reached 110 hours after the start of the first series, having risen from 4 feet below overflow over a period of 66 hours, which calculates to a refill rate of 0.73 inches per hour. By the time Peale's party left Shoshone Geyser Basin six days after the second series, Union was full of water and boiling, but no eruption had yet occurred.

The hole in the flank of the center cone, the result of vandalism, was reported in 1948 (Paperiello, 1992). Since that time, the hole has expanded via erosion along a seam between an outer resistant shell that forms the present surface of the cone, and a resistant nucleus, as illustrated in the photograph on page 15.

The cone of Grotto Geyser (photo on page 15) has weathered in the same fashion with a resistant shell remaining after the removal of erodible material beneath it.

Union Geyser's Cone 1965. Credit: National Park Service photo.

Grotto Geyser's Cone. Credit: National Park Service photo.

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LITTLE GIANT GEYSER on 03 October 1959, and **DOUBLE GEYSER**
Photos by Robert McIntyre, National Park Service. Text by Jeff Cross.

Little Giant Geyser

Double Geyser

Little Giant Geyser is one of the most enigmatic geysers in Yellowstone. The only reference giving quantitative data is Peale's report in Hayden (1883), who noted nine eruptions at intervals varying from 4.1 to 24.3 hours. At first glance, Little Giant would seem to erupt at irregular intervals. However, most of the intervals fall into the 16.9 to 24.3 range. If the single interval of 9.7 hours is taken as a true interval, and all longer intervals are treated as double intervals, then Little Giant can be said to have erupted, on average, every 10.3 hours. This is not improbable, as single eruptions of Little Giant could have been missed during the night. Placing hypothetical eruptions halfway between the documented eruptions gives times ranging from 23:03 to 03:24, hours during which eruptions of Little Giant could easily be missed. A similar argument, using the 4.1-hour interval, is likely not valid, as it would require

Table 1: Eruptions of Little Giant Geyser recorded by Peale in 1878. Double intervals are calculated, as are the times of hypothetical eruptions. Notably, all the hypothetical eruptions occur at times when an eruption of Little Giant could easily be missed.

Date (August 1878)	Time	Interval (h)	Double Interval (h)	Hypothetical Eruption
14	1617			0324 (08/15)
15	1430	22.2	2 x 11.1	0206 (08/16)
16	1342	23.2	2 x 11.6	2303 (08/16)
17	0825	18.7	2 x 9.4	
17	1805	9.7		0233 (08/18)
18	1100	16.7	2 x 8.5	2310 (08/18)
19	1121	24.3	2 x 12.2	
19	1527	4.1		0044 (08/20)
20	1000	18.6	2 x 9.3	

Mean interval: 10.3 hours (assuming mostly double intervals)
Duration: 13-28 minutes (mean = 20 minutes)
Height: 15-50 feet

Peale to have missed numerous daylight eruptions. Four durations were recorded by Peale, of 13 to 28 minutes with a mean of 20 minutes. Three heights were recorded, ranging from 15 to 50 feet. *(See Table 1 above).*

The activity of Double Geyser, which erupts from a vent near Little Giant, has often been assigned as the reason why Little Giant has remained inactive for most of the known history of Shoshone Geyser Basin. Indeed, Double and Little Giant are closely connected, as Little Giant can experience minor splashing eruptions to a few feet during and after eruptions of Double. The hypothesis is that Little Giant ceased having major activity at some time after 1878, and that Double began erupting instead.

This hypothesis is likely to be false. A photograph taken in 1959 shows Double in eruption. Another photograph, also from 1959, shows Little Giant in eruption. Clearly, both geysers were active in 1959. That Little Giant was active in 1959 before and after the 17 August 1959 Hebgen Lake earthquake is implied by the statement in a post-quake report by Al Mebane that "Little Giant Geyser plays more frequently than before the quake." (Mebane 1959). Since that time, significant activity from Little Giant was observed only in 1976, when an eruption to around 6 feet was seen, in 1988, and 1991, when heavy wash around the vent was noted (Bryan, 2008 2014). These were isolated events, and not part of any typical pattern of activity.

More recently, the activity in these thermal features has waned. Little Giant stopped having minor eruptions in 2005, and Double fell dormant in 2009. It was active in 2011, but fell dormant again in 2012. In 2010, a vent immediately west of Little Giant began to enlarge, and in 2013 and 2014, it was erupting to 2 feet at intervals of 41 to 54 minutes for durations of 16 to 24 minutes (Cross 2013; Cross 2014).

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Activity of North Goggle Geyser During 2012

Demetri Stoumbos

Abstract: North Goggle had a year of high activity beginning on February 12, 2012, continuing through the summer, and having its last observed eruption of the year on October 9, 2012. It was found that North Goggle is intimately related to Lion Geyser, having eruptive series of minor and major eruptions during, or immediately following one of Lion. An intricate, yet regular, pattern of fill cycles was also observed.

Introduction

North Goggle Geyser[1] reactivated on February 12 2012 for a year of high activity. I was able to observe and study its behavior from mid-June through the end of August. I learned that the geyser doesn't have a simple eruptive cycle, but a complex one with many different parts. Even so, it is quite regular in its patterns. I will describe:

1) the relationship between nearby Lion Geyser's series and that of North Goggle;
2) North Goggle's activity outside of a series;
3) its cycles of fill and drain;
4) extended fills;
5) how the system gains/loses "potential";
6) how that potential affects inter-eruptive activity;
7) minor eruptions and the activity following one;
8) the events leading up to a major eruption; and
9) the major eruption I witnessed.

North Goggle and Lion Geyser

North Goggle's eruptive series during the summer of 2012 were intimately related to those of Lion Geyser. Comparing recorded North Goggle times to the Lion electronic times from geysertimes.org [2013] of 2012 starting from April 4 (there was a logger failure up until that date), it can be seen that North Goggle series would typically start three or more hours into a Lion series, and could last until about five hours after the last Lion eruption. It should be noted that there were two cases where North Goggle was recorded erupting outside this window and before Lion even had its initial eruption; both these cases were times taken from webcam observations.

A North Goggle major eruption on July 1, 2012, showing the pulsing jetting nature of the eruption. Photo by LC Daughtery.

Fill cycles and "eruptive potential"

Outside of a Lion series, North Goggle would have 11 to 12 minute cycles. These cycles would begin when water reached overflow, at which point

1. Editor's Note: While Goggles Spring is an official Yellowstone place name, "North Goggle Geyser" is one of several names that has been applied to the small cone to the north that is the subject of this article. Earlier names "Triangle Hot Spring" (Ansel Hall, 1926), "North Goggle Spring" (George Marler, pre-1959), and "Gurgling Geyser" (Germeraad, 1959) did not receive common use, and the accepted name for many years was North Goggle Geyser. Park Historian Lee Whittlesey has advocated for the name "North Goggles Geyser," as the noun "goggle" does not technically exist. The author uses North Goggle Geyser here because of its prior common use and because, as a single vent, it could be seen as a single "goggle" rather than a pair of goggles, which originally inspired the name of Goggles Spring.

Another picture of the July 1, 2012, major, with Goggles Spring in the background. Photo by Devin Cooper.

there would be a heavy flood of water, without boiling, that would quickly die down to a near-overflow rocking of the water. The entire "fill" would last about two minutes. Afterwards, the water would drain to about halfway down Goggles Spring, and slowly rise back to overflow over the next 9-to-10 minutes. I will define these cycles as having zero "eruptive potential," henceforth referred to in this article as "potential," the term being used to describe the overall energy of the system.

During a Lion series, North Goggle had the chance that a fill could last longer than the normal 2 minutes. I will call these "extended fills" and refrain from using the term "overflows", because in special cases there would not be any overflow at all. Water holding for longer than 2½ minutes signaled an extended fill, which lasted anywhere from around six minutes to over an hour. They increased the potential of the system, with longer fills adding more potential than shorter ones. Though the length of the extended fill did not seem to be predetermined, the durations did seem to cluster, with many of the fills dropping after 16-to-17 minutes, and a large number of them dropping around the 28-minute mark. When the water levels finally fell (and to a lower level than normal), it took longer to recover than the typical 9 to 10 minutes. For a shorter extended fill of 16 minutes, I estimated the next fill to start about 10 to 12 minutes after the drain; 16 to 18 minutes was needed for a fill of 28 minutes, and wait times more than 20 minutes for longer fills.

The potential that these extended fills gave to the system did not appear to significantly wane over time, even if North Goggle continued on its regular cycles. Potential would only begin to diminish in North Goggle once Lion finished a series. After the failed roars from Lion, each successive fill from North Goggle would have less and less potential. North Goggle could hold potential for up to five hours after the last eruption of a very long Lion series.

A minor eruption of North Goggle. Minor eruptions tended to not have as much form to the plume, and were often lopsided as in the picture. Photo by Micah Kipple.

Signs of increased potential

North Goggle and Goggles showed many signs of increased potential by changes in their fill cycles. Foremost was the boiling that would occur in both features while they were between fills or at the beginning of a fill. The more potential, the more boiling there was, sometimes looking much like the post-eruptive play of Depression Geyser deep in Goggles Spring. The increased boiling at the very start of a fill was most prominent in North Goggle. In the moments preceding a fill, the boiling would temporarily cease, save for a string of small bubbles if there was sufficient potential. Then, as the fill began in earnest, there would be a sudden rush of bubbles from North Goggle, sometimes doming the water by more than a foot. This intense boiling would quickly die away for the remainder of the two minutes, and then the deep boiling would resume once the water level dropped.

Increased potential could also be observed in four other characteristics of a fill cycle. First, a normal fill would begin when water was already near overflow, whereas with potential, the water would begin rising quickly from a few inches below the rim. Second, Goggles usually initiates a fill, pouring water into its side basin followed by North Goggle reaching overflow a few seconds later. With some potential, North Goggle would begin its flood before Goggles Spring reached overflow. Third, the amount of water the flood put out of North Goggle was less than when the system had no potential; less water seemed to be ejected per cycle. Fourth, the average interval for fills shortened slightly to 10 to 11 minutes, the lower limit being a few seconds below 10 minutes.

Minor eruptions

A minor eruption could be initiated once enough potential had built up in the system. Sometimes this required multiple extended fills, whereas other times one exceptionally long fill lasting an hour or more could give enough potential for a minor. The occurrence of one minor did not necessarily mean that there was enough potential for subsequent ones, but it seemed that once North Goggle had two successive minors, there was sufficient potential for a series of minors until the end of the Lion series killed the system.

All of the minors I observed were initiated by the rush of bubbles at the beginning of a fill. They were maybe 5 to 10 feet in height, lasted no longer than a few seconds, and ended with water dropping out of sight, in both North Goggle and Goggles, to the sound of heavy boiling deep in the system.

If Lion was still in series, then minors would start mere seconds after the rush, but as the end of a Lion series reduced potential, North Goggle had an increasingly difficult time initiating minors. As potential waned, the rush would be delayed by a few seconds after the fill started, and the force of the eruptions decreased in magnitude. Initiation of a minor, a few hours after the last Lion, sometimes took a minute of rolling boil in North Goggle, and resulted in a small, weak minor.

There were two conditions under which North Goggle would fail to initiate a minor at the start of a fill, despite the system having enough potential for one. The first arose from the system having two recovery periods: one to resume fill cycles, and the other to resume minors, the first recovery time being shorter than the latter. After an extended fill or minor eruption, the system could resume cycles after a time, but still not be recovered enough for a minor. These cases were characterized by North Goggle barely reaching overflow, if at all, at the beginning of a fill. Instead, the rush of bubbles would come when the water level was just below the rim, limiting the amount of overflow. The second possibility for a failed minor was when the amount of potential in the system was barely sufficient to initiate one. The intensity of the rush of bubbles varied slightly even for a certain amount of potential, so one fill could have a modest rush without erupting with the next rush being large enough to trigger a minor.

Fill cycles following a minor eruption

The patterns between a minor and the next fill were very interesting. Immediately following a minor, water would usually rebound in Goggles Spring. Rarely, this would instead happen three minutes after a minor. During these "quick comeback" fills, water would rise quickly to about halfway up in Goggles Spring and rock around for only one minute before dropping. These fills seemed to have a higher chance of turning into extended fills, needing to hold for only over a minute and a half in order to become "extended". The resulting extended fills were characterized by low water rocking in Goggles (which is why I refrain from calling them overflows) while rising slowly. The system reached overflow in Goggles Spring after a few minutes. As with other extended fills, the duration of these extended fills varied widely, some dropping even before Goggles reached overflow.

If the quick comeback fills failed to hold, then another fill would begin seven to eight minutes after a minor. It would start with water very low in Goggles Spring, and rise quickly to completely fill Goggles Spring within a minute. North Goggle would not overflow during these fills, because the system was still recovering from the minor, and instead would just boil a few inches below the rim, as described above. The duration of the seven-minute fills was typical of other fills: about 2 minutes before dropping or turning into an extended fill.

Minor intervals

Though the system needed only seven minutes of recovery to begin fill cycles, it took about 30 minutes to completely recover and allow for another minor. This resulted in many minor-to-minor intervals

North Goggle near the end of a major, as water gives way to a weak steam phase. Photo by Kate Parry.

falling around 37 to 40 minutes: 7 minutes for the first fill, and 10 to 11 minutes for each of the next three cycles (see Figure 1). Shorter intervals could happen when the fill cycles took slightly longer. This gave the system a bit more time to recover and be ready by the third fill after a minor (discounting any quick comeback fills). One exceptionally short interval happened when there was increased potential in the system, and North Goggle ended up erupting 27 minutes after its previous minor. If a minor failed to initiate in the first 5 or 6 fills after the previous one, it was unlikely that North Goggle would minor again unless it had another extended fill.

The exception to these interval times was during the unusually long series of February 12 and 13, 2012, when 27 of 43 observed intervals were shorter

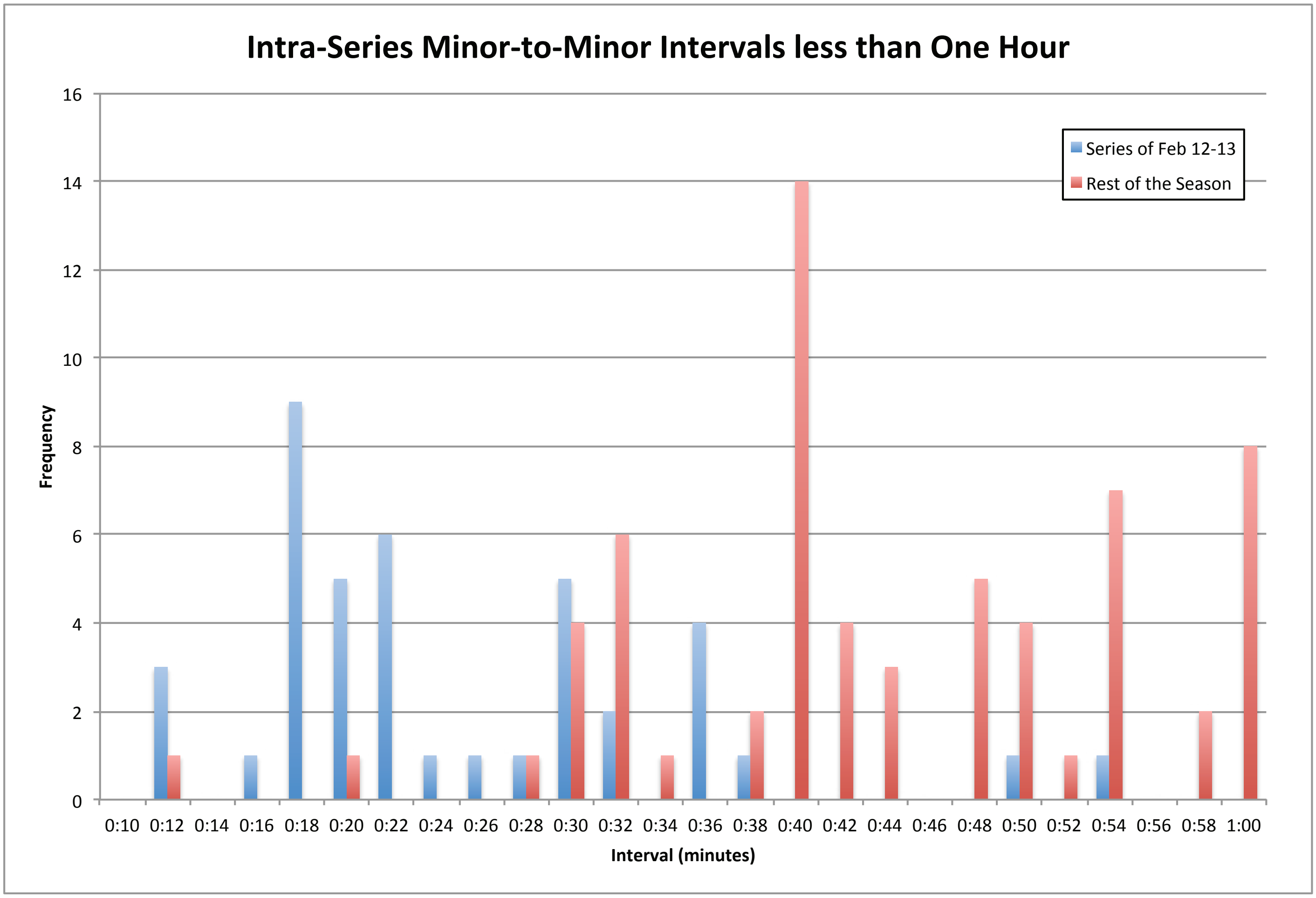

Figure 1: *Histogram of minor-to-minor intervals. Several instances of intervals longer than an hour are not shown here.*

than 27 minutes (GeyserTimes). Of these shorter intervals, many fell between 16 and 22 minutes, which could correspond to the first fill after the seven-minute one (see above).

Events leading up to a major eruption

After the rush of bubbles at the beginning of a fill, the boiling would stop very quickly. Throughout extended fills, the boiling would slowly recover, getting to a rolling boil in both North Goggle and Goggles Spring. The time needed for the boiling to resume depended on how much potential the system had when the extended fill started. I saw one fill that started from zero potential, and after an hour the only boiling was in the form of some stray bubbles in North Goggle. With other extended fills that began after a minor, North Goggle and Goggles Spring would be back to continuous boiling within 45 minutes. The boiling was not steady, but instead would wax and wane. It seemed as if, earlier in extended fills, the two would alternate boiling heavily so that when North Goggles boiled the most, Goggles Spring boiled the least, and vise-versa. Later on in the fills, the moments of increased boiling would coincide, as if Goggles and North Goggle were pushing simultaneously instead of alternatingly, like the way Gold and High vents of Fan Geyser begin to pulse in unison as the system goes into lock.

Like the boiling of the rush, North Goggle would flood out a lot of water at the very beginning of a fill, but then overflow would quickly die down. The water would then hang just at overflow in Goggles. This was also true of quick comeback extended fills once the water level of the system had recovered. As the fill progressed, it became apparent that Goggles went through cycles of rocking a little bit higher than normal, and rocking a little bit lower than normal, switching every couple of minutes.

Major eruptions

The one major eruption I witnessed on July 1, 2012 at 9:09 was initiated 51 minutes into an extended fill. An especially large boil came from North Goggle, which didn't seem to push much water out,

The beginning of a North Goggle major. Photo by LC Daugherty.

yet it happened the instant before North Goggle began bursting and the water column rose to its full height. The eruption itself consisted of a jetting unlike the burst-like motion of the minors. The height was maintained for the majority of the 3 ½ minute eruption, waning at the end to a weak steam phase. Goggles Spring drained at the start of the eruption and then began throwing bursts of water every few seconds up to 4 or 5 feet from very deep down and sharply angled towards the Lion benches. After the major, it took 80 minutes for water to reappear deep in Goggles Spring, and 99 minutes until the next fill cycle, which had no potential, save for a few bubbles. The water that refilled the system after the major looked a tinge cloudy, and green in color.

Of the fourteen recorded majors, two were seen to have continued the series afterwards, with major to minor intervals of 32 minutes and 59 minutes. Only three of the majors had no observed minors leading up to them (GeyserTimes). The chance of getting a major fell mostly within the same window of Lion's series as that for minors, except that majors could not happen as soon after a Lion initial as minors could.

The frequency of majors dropped markedly around mid-June 2012. In the three months prior, there were eleven recorded majors, yet afterwards there were only three. The last series with a major occurred at the end of August. Only two minors, in separate Lion series, were seen after August, making the overall activity eight months total in length from mid-February to early October.

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Botryoidal Spring: A Summary of Activity from 1996 to 2013

Stephen Michael Gryc

Abstract: Botryoidal Spring, located in the lower White Creek thermal area of the Lower Geyser Basin, underwent a dramatic change in 1996 when it began erupting explosively and frequently. This paper summarizes eighteen years of observation of Botyoidal Spring with a listing by year of the geyser's average intervals and durations. A complete log is given for the author's two and one-half hour observation of Botryoidal Spring on June, 30 2013. Note is also taken of other geyser activity in the lower White Creek area seen during the same observation.

Description and Recent History of Botryoidal Spring

Botryoidal Spring has been an object of fascination for geyser enthusiasts since 1996 when it changed its eruptive activity from a superheated pool with occasional small eruptions to a regular and explosive geyser with unique characteristics. Hobart (1998, p. 50) suggests that the change may have been a response to several earthquakes earlier that summer.

George Marler (1973, p. 195) describes the geyser's crater and earlier activity:

> "This spring was named Botryoidal in view of the fact that the sinter which has formed on the shoulders about the crater is in the form of botryoidal nodules. The sinter at the crater's edge is highly colored with iron oxide; it is raised and ragged, indicating a relatively long period of boiling activity. The crater is about 9 x 9 feet with a 5 foot extension on the southeast side.
>
> Botryoidal is a superheated spring, the temperature being 201^{0} F. The water is in a constant state of ebullition, except for a short period following an eruption of A-2 [Geyser]. That Botryoidal has occasional eruptions of more than average vigor is indicated by a ring of fragmental sinter which partially surrounds the crater. Eruptions which have been observed were about 6 to 8 feet in height. The length of the intervals is unknown."

In 1996 eruptions of Botryoidal Spring became frequent and regular with play recurring with a mean interval of just 1m54s. Durations were brief with a mean of 14.58 seconds (Hobart 1998, p. 51). Both intervals and durations lengthened during the ensuing 17 years, but the nature and size of the eruptions have remained very similar to those of 1996.

No water can be seen in Botryoidal Spring between eruptions. The initial burst of Botryoidal's eruption is characteristic of this geyser. Play is initiated by a sudden rise of water that initially takes the form of a rounded mass of large bubbles. These bubble masses were first described and photographed by Hobart (1998, p. 50-56). The bubble mass rapidly expands and explodes into droplets that may be propelled to heights of 12 feet (or about 4 meters) as reported by Hobart (1998, p. 50) or more (up to 20 feet) as described by Bryan (2008, p. 196). The first burst is always the largest and tallest while all successive bursts are significantly smaller. To enjoy the geyser's bubble mass and explosive initial burst an observer must stare fixedly at the crater before an eruption commences. Since the geyser erupts frequently, vigilance is not difficult to maintain for the very few minutes between eruptions.

Photo 1 shows the beautiful rounded form that a bubble mass can take. Several bubbles of different sizes can be seen. Photo 2 shows one of the largest and tallest eruptions of Botryoidal Spring that the author has observed. Photo 1 was taken in 2008, and Photo 2 is from 2006.

Eighteen Years of Eruption Data

Since it began explosive eruptions in 1996, Botryoidal Spring has been observed and studied by many geyser enthusiasts. To compile an eruptive history for the geyser for the years 1996 to 2013, I

Photo 1: Each eruption of Botryoidal Spring commences with the rising of a rounded mass of bubbles. Photo taken on July 2, 2008 at 17:05 by Stephen Gryc.

Photo 2: The initial burst of Botryoidal Spring's eruption has always been observed to be the largest. The height of this burst is around 20 feet, commonly given as the maximum for this geyser. Photo taken on July 9 of 2006 at 08:44 by Stephen Gryc.

BOTRYOIDAL SUMMARY BY YEAR

Year	Mean Interval	Number of Intervals	Mean Duration	Number of Durations	Observers
1996	1m54s	34	14.6s	35	Hobart (1998)
1997	2m51s	120+	17s	16	Hobart/Gryc (Dunn 1997a & b)
1998	3m01s	17	20.5s	20	Tara Cross (2013)
1999	2m55s	24	19s	23	T. Cross (2013)
2000	2m52s	21	18s	22	T. Cross (2013)
2001	3m03s	4	23.6s	5	T. Cross (2013)
2002	4m12s	7	25.6s	9	T. Cross (2013)
2003	4m09s	47	26.4	49	T. Cross (2013)/ Reeves (2005)
2004	4m26s	35	26.4s	36	Reeves (2005)
2005	4m23s	8	26.4s	9	Reeves (2005)
2006	4m40s	72	30.3s	27	Reeves (2006)/ Bower (2006)
2007	4m35s	28	27s	29	T. Cross (2013)/ Reeves (2007)
2008	4m33s	67	24s	11	Jeff Cross (2013b)/ Stephens (2008)/ Whinery (2008)
2009	4m15s	unknown	24s	unknown	Bower (Tara Cross, 2009)
2010	4m46s	8	30.8s	10	J. Cross (2013a)
2011	4m33s	12	25s	10	T. Cross (2013)
2012	4m35s	33	29s	11	J. Cross (2013b)/ Stephens (T. Cross & Stephens, 2012)
2013	4m34s	32	28s	33	Gryc

have gathered interval and duration data from every year from several observers. The actual number of eruptions for which I have found data varies greatly from year to year, with as many as 120 eruptions observed in 1997 and as few as 5 in 2001. Acknowledging the scarcity of data in some years, this provisional history of Botryoidal Spring's eruptions gives a general, if rough, outline of the geyser's behavior over an extended period.

The summary above shows mean intervals and durations for each year as well as the number of intervals and durations on which those averages were based. Also noted are the last names of the observers from whom the data was obtained.

The chart below graphically displays the trends in Botryoidal Spring's intervals and durations of eruption over an eighteen-year period.

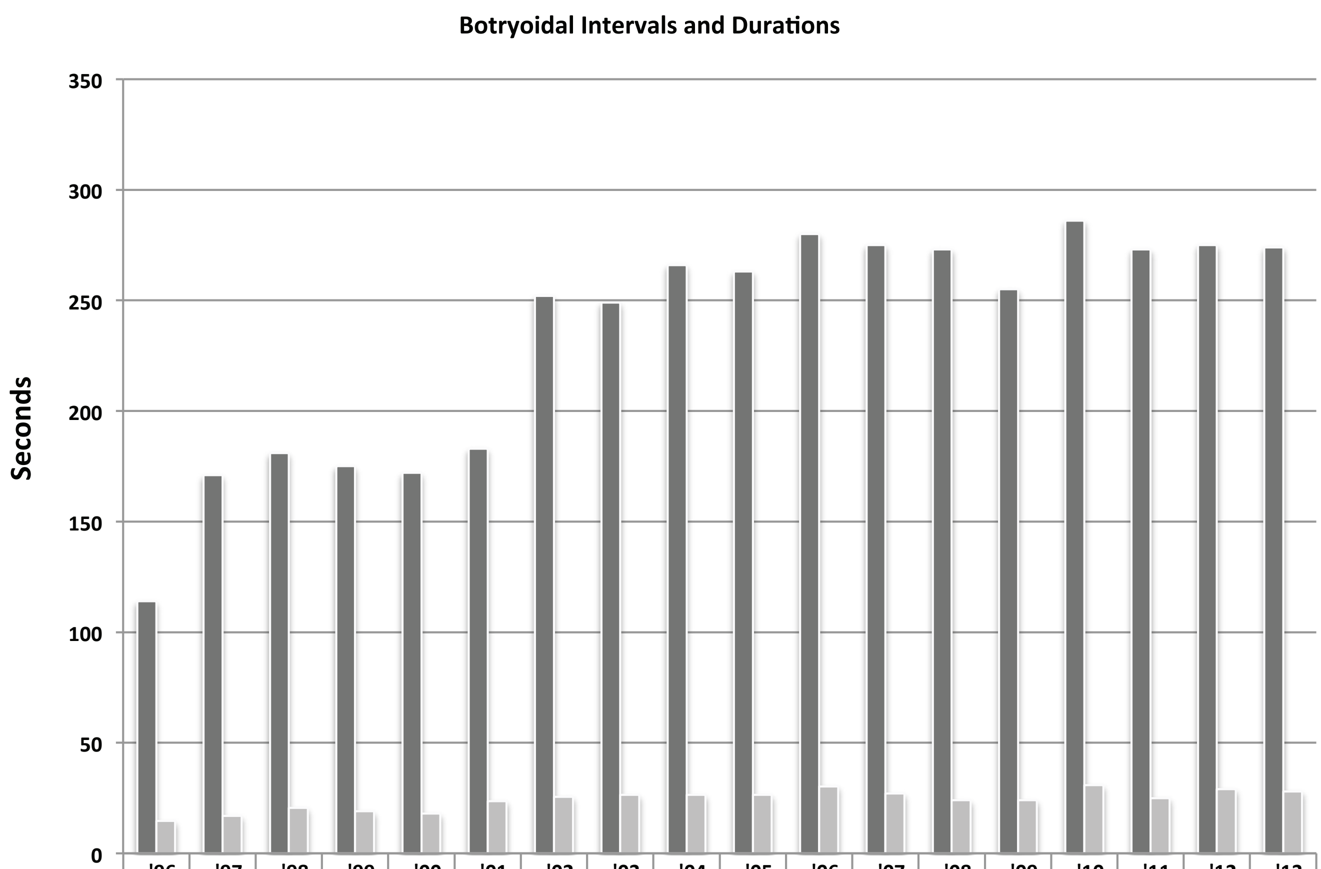
Durations lengthened as intervals increased to and above the 250-second mark, but the duration's percentage of an interval decreased. From 1996 to 2001 durations ranged from 10.5% to 14.5% of the interval with the average duration being 12.2% of the interval. From 2002 to 2013 durations ranged from 8.8% to 10.8% of the interval with the average duration being 9.3% of the interval.

Observations in 2013

On June 30 of 2013 I witnessed 33 consecutive eruptions of Botryoidal Spring. Intervals were measured from the first sight of water. Durations ended with the last sight of any water. The mean interval was 4m34s with a standard deviation of 23.5 seconds. The mean interval was close to the median interval of 4m35s. Intervals ranged from the shortest of 3m41s to the longest of 5m23s. Both the mean and median durations were 28 seconds with a standard deviation of 2.5 seconds. The shortest duration was 21 seconds, and the longest was 33 seconds. No attempt was made to estimate the height of individual eruptions, but it appeared to me that Bryan's (2008) range of 12 to 20 feet remained reasonable. The entire record of observation is shown on page 28.

Observation of Other Geysers in the Lower White Creek Area

An observer situated in the Surprise Pool parking area has a panoramic view of most of the hot springs in the lower White Creek thermal area. As I was taking data for Botryoidal Spring, I also witnessed five consecutive eruptions of A-0 Geyser which is much closer to the parking area. Most eruptions attained a height of about 6 feet. The mean interval was 27m36s, and the mean duration was 45 seconds. The mean interval and duration as well as the eruption's height were close to what I had observed from this geyser in other years during the



	'96	'97	'98	'99	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	'10	'11	'12	'13
Interval	114	171	181	175	172	183	252	249	266	263	280	275	273	255	286	273	275	274
Duration	14.6	17	20.5	19	18	23.6	25.6	26.4	26.4	26.4	30.3	27	24	24	30.8	25	29	28

Year

TABLE OF OBSERVATIONS ON JUNE 30, 2013

Start	End	Duration	Interval
09:09:17	09:09:45	00:28	
09:14:40	09:15:06	00:26	05:23
09:19:34	09:20:04	00:30	04:54
09:24:07	09:24:36	00:29	04:33
09:28:49	09:29:16	00:27	04:42
09:33:10	09:33:40	00:30	04:21
09:37:15	09:37:45	00:30	04:05
09:41:40	09:42:10	00:30	04:25
09:46:00	09:46:26	00:26	04:20
09:50:29	09:50:57	00:28	04:29
09:54:54	09:55:23	00:29	04:25
09:59:36	10:00:05	00:29	04:42
10:04:13	10:04:41	00:28	04:37
10:09:10	10:09:36	00:26	04:57
10:14:03	10:14:31	00:28	04:53
10:19:00	10:19:25	00:25	04:57
10:23:37	10:24:05	00:28	04:37
10:28:44	10:29:13	00:29	05:07
10:33:10	10:33:37	00:27	04:26
10:38:27	10:38:54	00:27	05:17
10:43:07	10:43:38	00:31	04:40
10:47:32	10:47:59	00:27	04:25
10:52:31	10:53:01	00:30	04:59
10:57:18	10:57:48	00:30	04:47
11:01:24	11:01:50	00:26	04:06
11:05:39	11:06:06	00:27	04:15
11:10:17	11:10:48	00:31	04:38
11:14:44	11:15:06	00:22	04:27
11:19:28	11:19:57	00:29	04:44
11:23:28	11:24:01	00:33	04:00
11:27:09	11:27:40	00:31	03:41
11:30:58	11:31:19	00:21	03:49
11:35:29	11:35:54	00:25	04:31

past two decades. The data log is shown on page 29.

Between A-0 Geyser and Botryoidal Spring is a small depression with a cluster of vents that have seen intermittent eruptive activity over the past few decades. Bryan identifies the feature as UNNG-WCG-6 (Bryan 2008, p. 196). I observed a single small burst of water from this area at 11:37:30. The height was between one and two feet. No eruptive activity from A-1, A-2, or Logbridge Geysers was witnessed.

A-0 OBSERVATIONS ON JUNE 30, 2013

Start	End	Duration	Interval
09:35:06	09:35:50	00:44	>26:00
10:02:13	10:02:58	00:45	27:07
10:30:04	10:30:50	00:46	27:51
10:58:31	10:59:19	00:48	28:27
11:25:30	11:26:12	00:42	26:59

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The Development of Hydrothermal Features at Rotomahana after the 1886 Tarawera Eruption—A Historical Review

R.F. Keam and E.F. Lloyd

Abstract: No comprehensive, nor even any extensive, description of the post-1886-eruption development of surface geothermal activity in and around the Rotomahana Crater has previously been prepared, and what is presented here does not pretend to remedy such an omission. However, we do assemble at least an outline history of surface geothermal features of this area of New Zealand, and this has revealed where the greatest gaps in the story remain.

BACKGROUND

Over the past 70 years scientific studies have established in considerable detail just where subterranean hot water is to be found at shallow depths throughout the Taupo Volcanic Zone (Figure 1) of New Zealand. Geographically this is a well-defined band of country, averaging about 30 kilometres across, and extending from just south of Ruapehu volcano near the centre of the North Island in a north-northeasterly direction towards and beyond the Bay of Plenty coastline. Offshore the continuation includes many submarine and island volcanoes in the Pacific Ocean, and, in global terms, is an integral part of the Pacific Ring of Fire. Most of New Zealand's major intensive geothermal systems[1] and also a majority of its active or potentially active volcanoes occur within the Taupo Volcanic Zone. Structurally this is a graben largely filled with stratified tephras, ignimbrites, lavas, and volcanogenic sediments, and is estimated to have a maximum depth/thickness of about 4 kilometres (Modriniak and Studt 1959), (Rogan 1982). Scattered throughout the infill are intrusions and volcanoes, many of the latter having been partially or completely buried subsequent to their formation. A related structural effect, apparent from the geology, has been gradual widening of the graben boundaries in west-northwest/east-southeast directions. Geodetic monitoring in recent years has shown this to be continuing currently and taking place at about 0.7+/-0.3 mm/year, somewhat smaller than continental-drift rates (Darby et al 2000).

The geothermal systems are aquifers containing hot water (and perhaps steam) whose fluids are convecting as a result of temperature-originating density inhomogeneities. Typically convection cells are ten kilometres in diameter with their upflow zones being about half that width. Each is more or less cylindrical with a vertical axis, but often their shapes are considerably modified by the local topography, by the permeability and three-dimensional geometry of rock formations hosting the fluids, and by just how hot the up-flowing geothermal plume is. From one to another they can vary considerably in total up-flow and in the areal density of their geographical distribution. Where they are close together the waters from distinct up-flows can merge and aggregate to form regions where hot water can be encountered at shallow depth almost anywhere in an area as much as ten kilometres across. The detailed three-dimensional geometry of the systems, including the location and form of deep supply plumes, is so far only approximately defined.

Once established, a geothermal system is robust, and its total fluid up-flow at depth can become dynamically almost steady-state. It can survive major disruptions - even quite large volcanic eruptions through part of the same three-dimensional region that it occupies. There are of course limits to the degree of disruption that can be withstood, but, in the case of the 1886 Tarawera eruption, while these limits have been exceeded within a relatively small part of the geothermal system established there, the system as a whole continues its activities and seems to be adjusting towards a new quasi-stable state (Simmons et al, 1993). Note that the presence of permanent gases (particularly carbon dioxide) in the geothermal fluids is increasingly becoming regarded as

[1] An intensive geothermal system is one in which near-surface geothermal fluid temperatures can be found at or above the boiling point for the local surface atmospheric pressure.

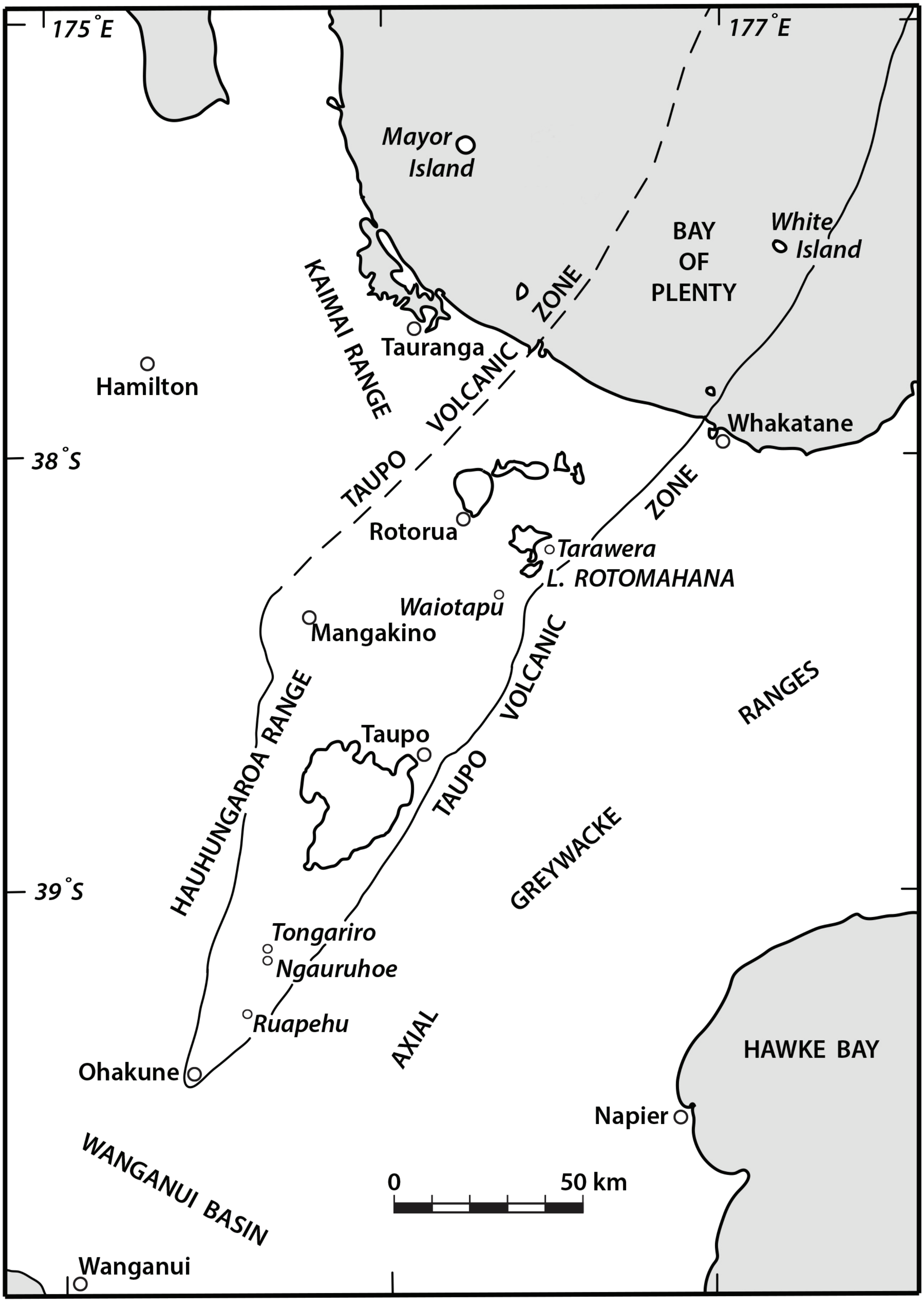

Figure 1. Outline map of the Taupo Volcanic Zone of New Zealand. (After Wilson et al, 1995, p.3, Figure 2)

important but will not be considered here.

Figure 2 *(below)* shows geothermal systems in the central part of the Taupo Volcanic Zone from Rotorua and Lake Tarawera in the north to Ohaaki in the south. Lake Tarawera lies in the Okataina Volcanic Centre, and Ohaaki in the Reporoa Volcanic Centre. The surface geothermal features at Rotorua, Rotomahana, Waiotapu, Waikite, Reporoa, Te Kopia, Orakeikorako, and Ohaaki were discovered by the early Maori people and had been used minimally by them for cleanliness, comfort, recreation, laundry uses, cooking, drying berries, and more latterly as an economic basis for entertaining tourists. It has, however, been only recently that electrical resistivity measurements have started to show the detailed underground extent of the geothermal systems connected with these groups of springs. The shading shows the areas beneath which the electri-

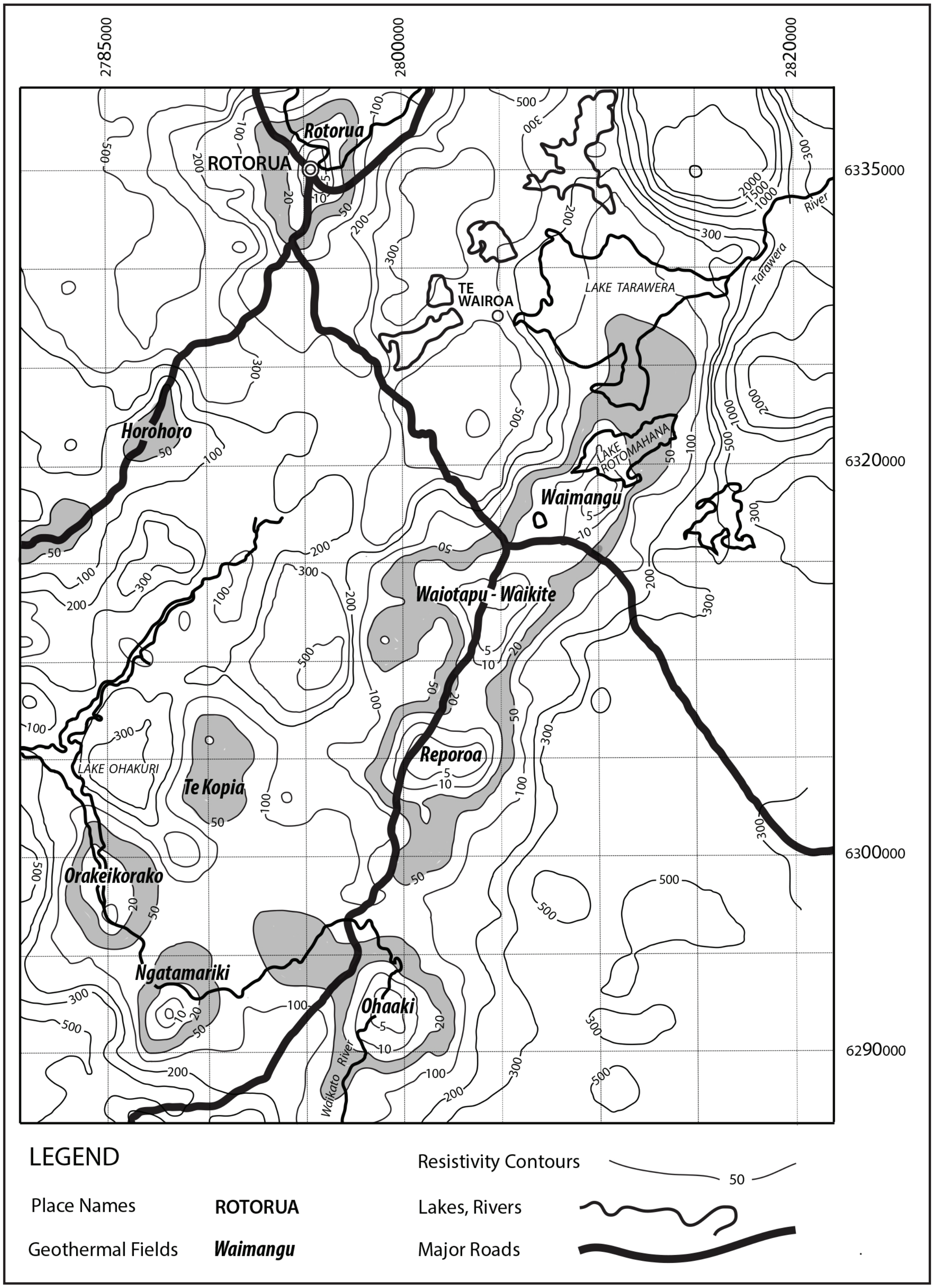

Figure 2. Map of shallow depth electrical resistivity measurements in the central Taupo Volcanic Zone of the North Island, New Zealand (adapted from Stagpoole and Bibby 1998). Smoothed iso-resistivity contours are labeled with their resistivity values given in ohm-metres. The nominal exploratory array spacing is 500 metres and thus loosely represents an average resistivity value to that depth. Scale: Small grid squares are 5 km x 5 km.

cal resistivity lies between 20 and 50 ohm-metres. These values conventionally define the shoulder band enclosing low resistivity concentrations which indicate the places where at shallow depth ionized salts are present and high temperature fluids lie. It is immediately obvious that the boundaries of geothermal systems sometimes overlap and in fact include here the largest area of continuous geothermal fluid existing at shallow depth in New Zealand. Note particularly that the Waimangu/Rotomahana system extends significantly beyond places where direct evidence of surface manifestations has been found, and that it overlaps to the south the large Waiotapu/Waikite system.

THE 1886 TARAWERA ERUPTION

[**Note:** During the time this paper was in preparation, active research by the author revealed that the following 'classical story' of the eruption should be replaced by an almost entirely different sequence of processes. The resulting new account, still actively being developed, is outlined in the Addendum to the present article. q.v.]

During the sudden explosive basaltic 'Tarawera' eruption on 10 June 1886 the long-established geothermal system that had supplied heated fluid to the famous White Terrace (Te Tarata) (Figure 4) and Pink Terrace (Otukapuarangi) (Figure 5) and

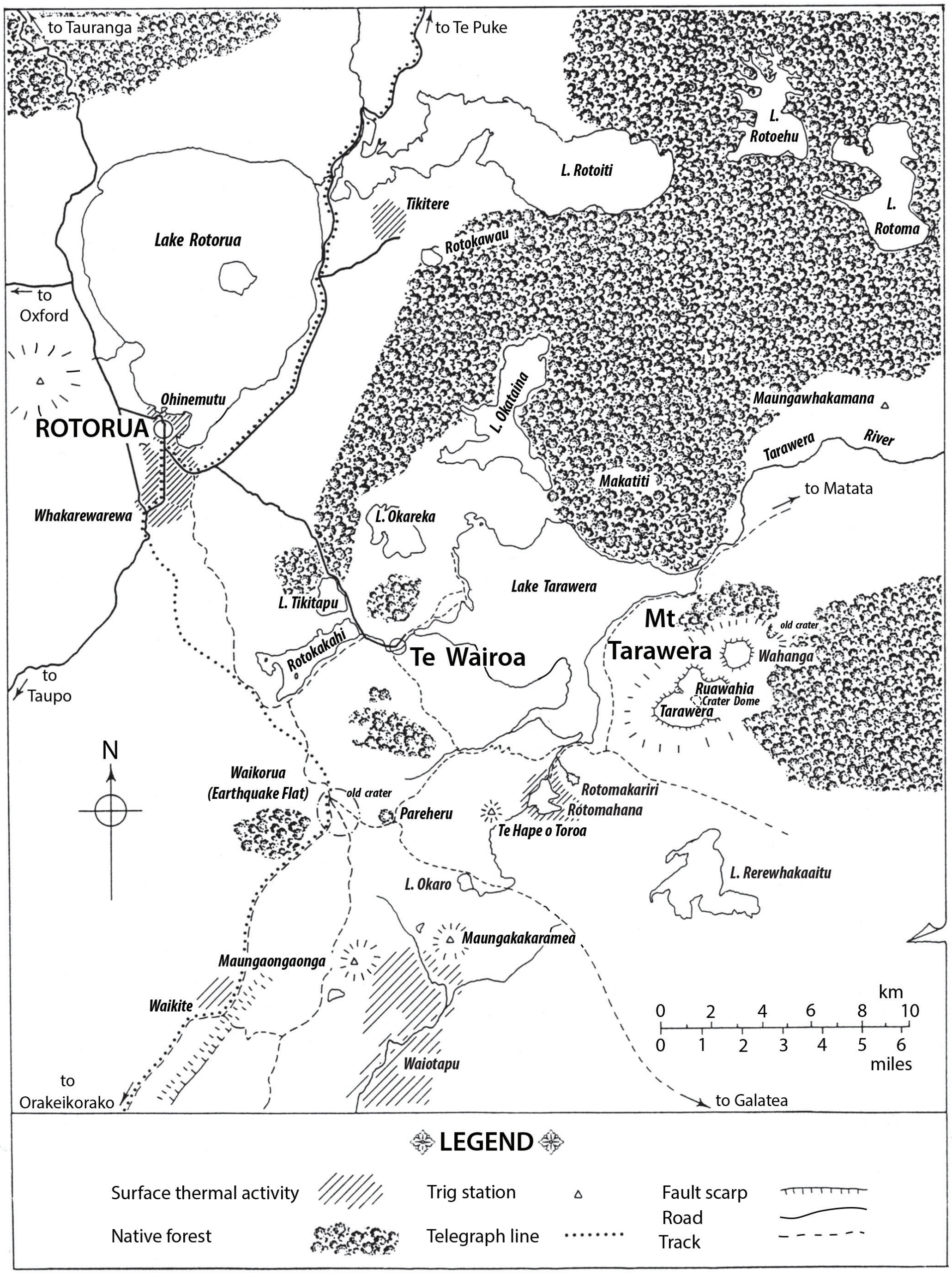

Figure 3. Map of Rotorua district as it was just before the Tarawera eruption in 1886.

Figure 4. Te Tarata, the White Terrace. The arc of the view spans directions clockwise from approximately southeast to southwest. Charles Spencer photograph, 1881.

Figure 5. Otukapuarangi, the Pink Terrace. The arc of the view spans directions clockwise from approximately north to east. The distant mountain is Tarawera. A small steam cloud just in front of it indicates the position of Te Tarata cauldron and just to its left there appears a glimpse of the White Terrace itself. Charles Spencer photograph, 1881.

their attendant phenomena at Rotomahana underwent major near-surface modifications. Indeed, an hour and a half after Mt Tarawera began erupting, rising basalt magma intruding into the geothermal system triggered an enormous hydrothermal explosion. And it was the stored geothermal energy residing in the relatively shallow parts of the geothermal system itself that was the dominant source of the mechanical energy expended during this climactic initial stage of the outbreak at Rotomahana. It caused a massive pyroclastic flow (at geothermal temperatures) of comminuted rhyolitic country rock and laid down a distinctive, oatmeal-coloured, flour-like dry deposit containing almost no basalt that covered a disc-shaped region approximately six kilometres in radius centred at the site of the former lake Rotomahana. The inner portions of the disc were themselves covered later in the eruption by greater total volumes of less-energetic discharges quite rich in basaltic ash.

When this focus of activity was first reached by explorers three days after the upheaval, no sign could be seen of the Terraces, and it was widely (but not universally) believed that these wonders had been completely destroyed. In place of a small, shallow, warm, somewhat irregularly-shaped lake, with linear dimensions of a kilometre or so, there was to be seen an approximately circular basin-shaped

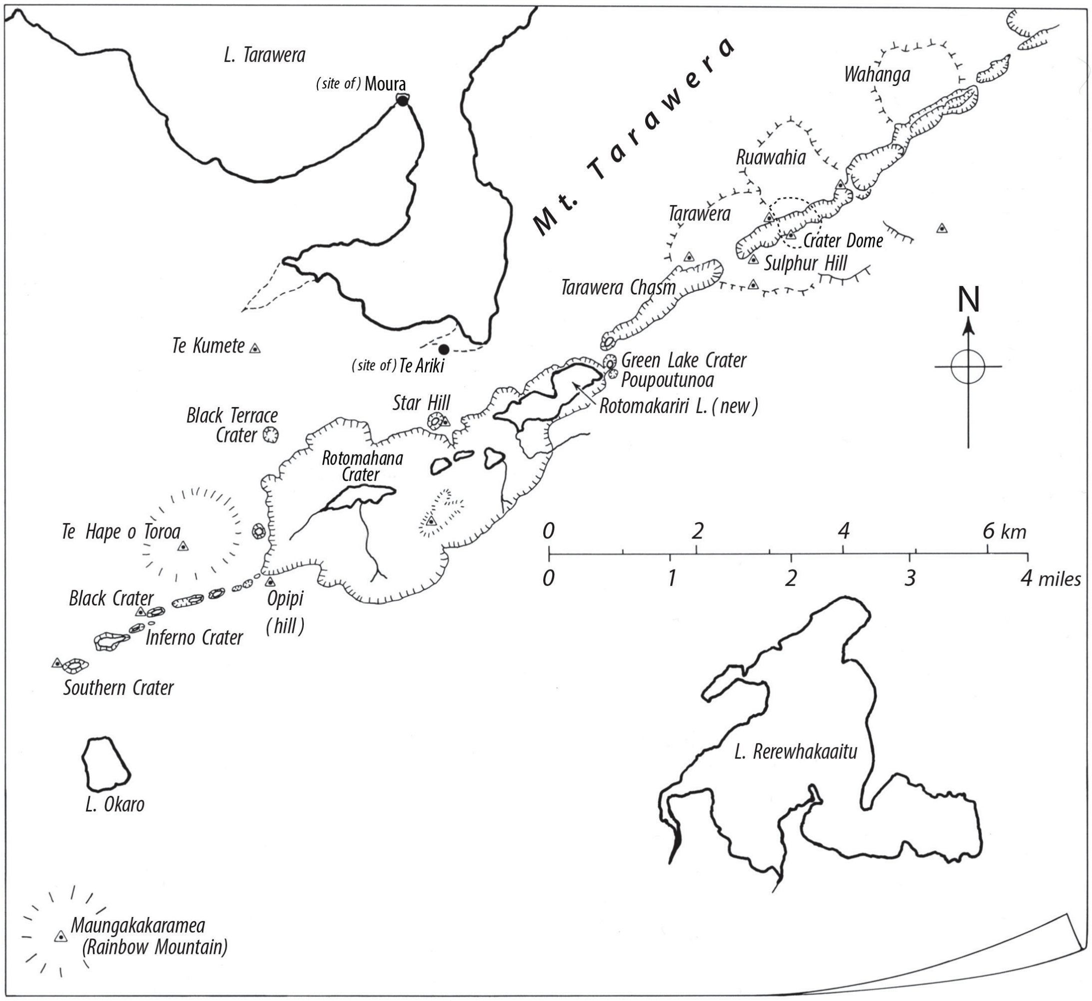

Figure 6. The 1886 Tarawera Rift showing the lakelets and other features as they were at the end of July 1886 (Keam 1988 p.329 modified from maps in the official reports by Smith 1887, and Thomas 1888).

hollow about 2.5 kilometres in diameter cored out to a greatest depth of about 170 metres (Smith 1887 p.56) *see appendix*. Much of the geothermal-fluid-saturated sediments and other rock that, until the eruption began, had occupied the region just below this space was the direct source of the climactic pyroclastic flow material. The basin was immediately christened the 'Rotomahana Crater'. Distributed over its floor were many vents, some already quiescent, but many others still intermittently ejecting rocks and mud. Jets of steam hissed and roared from uncounted orifices and crevices all over the crater floor providing an inescapable auditory accompaniment. A dust- and ash-covered adjacent hill, Te Hape o Toroa (see Figure 3), southwest of Rotomahana Crater provided the explorers with a convenient viewing platform, but the mild earthquakes that repeatedly shook this eminence understandably generated some anxiety in the party about their personal safety. From the abyss before them enormous steam-clouds rose several thousands of metres into the sky. Dimly seen occasionally through gaps in the lower parts of this canopy a tiny mud-coloured lakelet could be discerned occupying the deepest part of the crater. This was the vestigial remnant of the former shallow lake and also the precursor of what has grown gradually into today's large and deep Rotomahana lake, extending from almost the foot of Te Hape o Toroa to the foot of Mt Tarawera.

The Rotomahana Crater sensu stricto (Figure 6) occupies only a 2.5-kilometre segment of a 15.9 km long line of craters which formed during the Tarawera eruption. The line's length and straightness indicates that the craters form the surface expression of a fairly deep-seated structural break and this has been named the 'Tarawera Rift'. Because of the hydrothermal system which the Tarawera Rift intersected at Rotomahana, and the explosions generated there, this is its widest part.

Structure of the Tarawera-Rotomahana-Waimangu Area

A brief description of the different structural relationships along the Rift will now be presented (refer to Figure 6):

The highest parts of Tarawera mountain comprise one hidden and three visible rhyolite domes that formed during the Kaharoa eruption, the penultimate volcanic event that had occurred during an interval of about five years at about A.D. 1315 at this location (Nairn et al 2001), (Hodgson and Nairn 2005). The inferred dome vents are aligned at (052°N)[2] - approximately southwest to northeast. Their summits sagged slightly in the course of their extrusion and subsequent cooling, and therefore are flattened to some extent, and they all solidified at almost the same elevation. This gave the post-Kaharoa mountain summit region, viewed from across Lake Tarawera, the appearance of being an almost level ridge interrupted by one slightly lower saddle. While the whole edifice is commonly referred to as 'Tarawera', in Maori usage the visible domes, in order from the northeast to southwest, are distinguished with the separate names Wahanga, Ruawahia, and (sensu stricto) Tarawera. The hidden 'Crater dome', largely concealed beneath Ruawahia, is revealed there in the walls of the Rift. A tiny replica of the mountain, also formed during the Kaharoa eruption, was extruded southwest of Tarawera. This domelet, perhaps forty metres high, has been blessed with a plethora of at least five names, including Poupoutunoa (Maori), Little Tarawera (English), Green Lake Plug (Geologists)..., thus ensuring it will never be forgotten by leaving a compensatingly proportioned legacy of confusion.

The Tarawera Rift, at (057°N), runs almost parallel to the axis of the mountain. Its northeastern extremity consists of two slightly elongated craters, end to end, traversing the plinth, as it were, of the domes. Proceeding thence to the southwest along a crater traversing the eastern edge of the first dome, Wahanga, one next encounters the first of a series of aligned and connected craters that extend almost unbroken to the southwest end of the summit ridge. The superficial width of the Rift here ranges between 150 and 250 metres. Next there follows a section of about 270 metres of intact pre-eruption (buried) surface. Southwest of this gap a long continuous section (the 'Tarawera chasm') extends down the mountain slope almost to the lowland craters. Beyond the end of this, and separated from it by only a few tens of metres, lay a single crater ('Green Lake Crater') and offset to the south a smaller isolated crater in the top of Poupoutunoa. Here, and extending almost to the foot of Te Hape o Toroa, the 1886 eruption craters are now drowned by the new Rotomahana lake. Partially connected with Green Lake Crater there was next visible a continuous two-kilometre-long rift that, when discovered late in July 1886, was already occupied with water, and formed the largest lakelet ('Rotomakariri') that had collected within the craters up to that time. Further to the southwest the crater edges, bounding this feature and also bounding a densely packed distribution of vents beyond it, gradually diverge. Ultimately the outer crater edges separate sufficiently to merge with the perimeter of Rotomahana Crater. Southwest of the latter the Rift is represented by a 2.5 kilometre chain of separated craters extending to its superficial termination at 'Southern Crater'. These southwesterly vents were originally called the Okaro craters, (after a nearby small pre-existing lake of that name) but, because Waimangu Geyser later developed within one of them, they are now referred to collectively as the Waimangu section of the Rift. 'Black Crater' (Figure 6), mid-way along the southwesterly vents, remained vigorously in eruption for about a week.

Assistant Surveyor-General S.P. Smith and his party were within seeing distance of Black Crater from 13 to 15 June and he described its activities during that period as follows:

> ...it constantly appears, in full eruption, vomiting forth large quantities of stones, sand and mud, the ejecta rising frequently to between 400ft. and 500ft. in the air. Most of the stones &c., fall back again into the crater, though every now and then a column shoots up in an oblique direction, discharging large quantities of stone on the outside of the cone it is gradually building up with a noise like the rattle of musketry, and leaves them smoking on the surface. The shape of the columns when charged with stones and sand is most elegant, and looks like grand pyramidal geysers, darkened by the sand and mud so as to stand out in relief against the accompanying masses of rising steam.

A good photograph showing one of its explo-

2
The convention for direction being used is degrees of arc clockwise from geographical North.

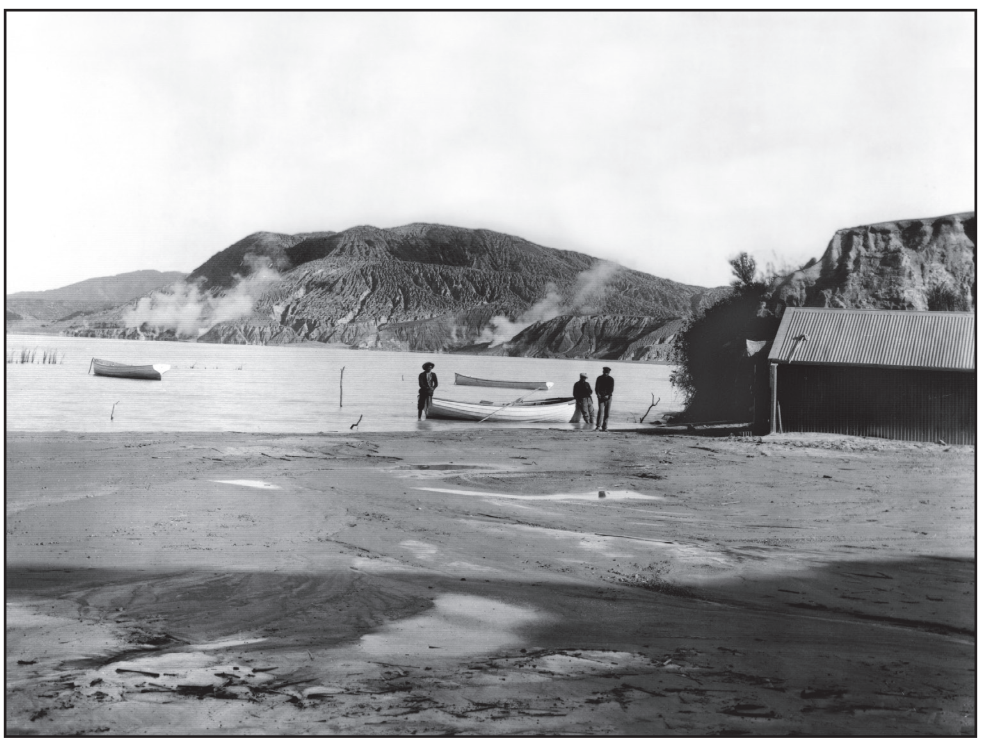

Figure 7 *(above).* The northwestern end of Rotomahana Crater. G.D. Valentine photograph 133, early November 1886. Compare with Figure 8 taken about seventeen years later from a nearby location.

Figure 8. Western shoreline of Rotomahana seen from the north: the steaming areas are Donne Cliffs/Awarua Cliffs to the left, Otukapuarangi Bay to right. Te Hape o Toroa is the high rounded hill behind the steaming areas, and the distant partially hidden hill is Maungaongaonga (see Figure 3). W. Hammond photograph, ca 1903.

sions was secured by Charles Spencer sometime between 15 and 18 June 1886 (Keam, 1988, p.215). This shows a dark band of ejecta in excess of 100 metres high disappearing into a thick steam cloud above. The column itself was approximately half that in width. Much of the ejecta evidently consisted of rhyolite blocks. The activity declined over several weeks, and Black Crater's final known discharge occurred on 4 August 1886 (Smith 1887 p.60).

ACCOUNTS OF HOT SPRING ACTIVITY AND DEVELOPMENT OF TOURISM 1886 - 1903

Almost nothing is known of any hot springs that developed in the floor of the Rotomahana Crater and perhaps persisted until they were submerged by the progressively growing lakelet. The one exception is an observation by Smith, whose topographic survey team worked throughout the eruption-devastated area for a fortnight in late July and early August 1886. Smith's official report (Smith 1887 p.56, plan 3) states:

> The southern 'bay' [of Rotomahana Crater] had ceased to be active, except in a few places where steam issued from the sides of [a] little river draining down into the central lake. This river was hot – indeed, almost boiling – where it issued from the ground, which it did with great noise and volume, its waters so strongly impregnated with iron as to colour the rocks with a bright-yellow ochreous deposit, though the water was quite clear.

At a location about 200 metres northwest of the confines of Rotomahana Crater a significant hydrothermal eruption occurred between 31 July and 6 August 1886 and continued until at least 15 August. Smith named the new vent 'Black Terrace Crater' (Figure 6) after a small pre-eruption hot spring situated approximately at its site[3] (Smith 1887 p.59).

With lengthening days as spring approached, photographers and artists began preparations to exercise their talents in the Tarawera / Rotomahana region to be able to present to a still-fascinated public pictorial representations of the changes that had been wrought so suddenly and rapidly by the volcanoes.

Earliest upon the scene was the talented landscape artist Charles Blomfield who before the eruption had on different occasions visited and camped out at Rotomahana and assembled an unmatched portfolio of paintings of the Terraces and the other wonders to be seen there. He settled in from the beginning of October for three weeks, with his tent in the fern at Pareheru (see Figure 3) at the edge of the main eruption deposit west of the craters, and made many forays across mud, sand, rocks and ashes to the choice of vantage points available to him. His excursions included not only visits to the relatively nearby Okaro craters, but also exhausting climbs to the bottom of the Rotomahana Crater and to the top of Mt Tarawera itself, and his assemblage of post-eruption views became almost as impressive as that of his earlier pre-eruption trophies. With geological changes still continuing rapidly – if less violently – these pictures are uniquely valuable scientifically as well as pictorially.

During November 1886 photographer G.D. Valentine and surveyor John Blythe took several photographs of the Rotomahana Crater (Hall 2004 p.67). Only along the western wall of Rotomahana Crater, south of Black Terrace Crater, did vigorous steam evolution continue for more than a few months, so hereafter attention will be focused on this region since it forms the main visible topographic context for the developing hot springs and geysers. Valentine took two almost identical photographs (his numbers 133 and 134, see Figure 7) of this area from the northern rim of Rotomahana Crater early in November at a place almost directly above where the Kaiwaka stream had flowed on its way from Rotomahana to Lake Tarawera before the eruption. A modest embayment of the crater rim is clearly visible. This is close to where the Pink Terrace had lain. But apart from steam clouds rising from within it this feature, which we refer to as 'Otukapuarangi Bay', is too far away for any individual hot springs to be distinguishable. Dense steam clouds also obstruct any view of the distant crater rim further south along the western side.

The eruption disrupted the drainage system for rainwater falling within the approximately 83

3 Almost certainly this event is explicable in terms of falling pressures in the hidden part of the Rotomahana geothermal system at this locality – a relatively short distance back from the Rotomahana Crater edge – and caused by the sinking water table as ground water gradually percolated through to that deep and essentially empty neighbouring basin.

km^2 area[4] (Paterson 2003 p.5) comprising the Rotomahana catchment and it took about eighteen months to re-establish. The largest two re-establishment events were (1) the overflow of Okaro lake which occurred in mid- to late October 1886; and (2) the discharge of Rotomakariri crater lakelet directly into the Rotomahana Crater on 2 July 1887 (Mair 1887). Natural surface drainage of the new Rotomahana lake itself was never re-established. The pre-eruption valley occupied by the Kaiwaka stream, which had discharged Rotomahana into Lake Tarawera, had been completely buried to a depth of about 60 metres of tephra. This barrier of eruption debris has resulted in Rotomahana being dammed and its level eventually rising to approximately 50 metres higher than it had been before 10 June 1886. Suspicious glances have always been cast at this barrier, with concern being expressed about its stability, and in April 1974 an outlet culvert was constructed at the saddle where natural overflow would have commenced had the lake ever risen sufficiently. This construction reduced (but did not eliminate) the seeming danger, and in 2003 a report was commissioned to consider all the influences which could possibly contribute to barrier instability (Paterson 2003). So far as we had been aware no sustained overflow through the artificial outlet actually began until 15 August 2012.[5] The Kaiwaka Hou (New Kaiwaka), here fifty metres above the site of its precursor, thus can now be recognised. Inspections on 9 October 2012 revealed that though a stream of about 200 litres per second was seen to be flowing, no erosion was taking place and the valley walls and bed along the course of the stream were stable. Subsequent dry weather led to a fall in lake level and, unsurprisingly, Kaiwaka Hou turns out to be an intermittent phenomenon.

In the immediate post-eruption period visitors to the Rotomahana Crater normally approached it from the north by boat across Lake Tarawera to near the site of the buried village of Te Ariki (see Figure 6), and walked thence up to the crater rim. Alternatively, like Blomfield, they approached from the west, crossing the ash-fields to the summit of Te Hape o Toroa, where they could enjoy a more distant but panoramic vista.

Before the eruption the New Zealand Government Survey Department had been planning the route of a coach road from Rotorua to the Urewera country some 60 kilometres to the southeast. This had been intended to pass close to Rotomahana. The eruption rendered such a direct route impractical so an alternative running south from Rotorua was chosen, and construction commenced. This road passed across three very old[6] sediment-floored volcanic craters, the most southerly of which, Waikorua (see Figure 3), was known also as Earthquake Flat. It was realized that a branch road could be built from there over somewhat higher ground, through the area called Pareheru where Blomfield had camped, and thence, continuing in an easterly direction, it could provide a convenient tourist route to a terminus on the lower western slopes of Te Hape o Toroa. So, over the next couple of years 'McIntosh's road' was built (Figure 10).

The Urewera line of road continued southwards from Waikorua for about 4 kilometres, there closely hugging the western edge of Maungakakaramea (Rainbow Mountain)(Figure 3) with its large area of then almost-bare geothermally-tinted slopes, and then turned to a more easterly direction heading towards its ultimate destination. Such progress with developing the Rotorua district road network opened yet another opportunity, namely, a more southerly direct route from Rotorua to Taupo in the geographical centre of the North Island. So, selecting this road-line also became a Survey Department responsibility, beginning at a junction with the Urewera road at the place where the latter veered to the east at Rainbow Mountain.

With the Pink and White Terraces having disappeared during the 1886 eruption, New Zealand had lost the crown jewels of its Thermal Region. The resulting nostalgia was almost palpable, with images of the lost wonders continuing to be published as pictorial postcards and even within a series of pictorial postage stamps. Arguments as to the Ter-

4
Nairn has, instead, 77.5 km^2 (Nairn, 2002, Table 7, p.124)

5
B.J. Scott (Personal communication) informs us that there had indeed been an earlier outflow – presumably shortly after the culvert had been built - but in traversing the whole course of the outflow from culvert to Lake Tarawera in 2003 I (RFK) did not recognize any sign that this had occurred so we suspect it was low volume and short-lived.

6
About 61,000 years (Wilson et al 2007)

races' possible survival were debated from time to time, and projects to seek their potential recovery by excavation from within the eruption deposits were discussed – with enthusiast and tourist guide, Alfred Warbrick even estimating a cost of £2750 for lowering Rotomahana to the level of Lake Tarawera to facilitate such an endeavour (Warbrick 1909). But surely elsewhere in the New Zealand thermal region there were other geothermal features that echoed the beauty of the vanished Terraces and could ameliorate the loss to some extent?

Until the 1886 eruption the Waiotapu thermal area, next to the south from Rotomahana, had remained unvisited by tourists and, indeed, at that time it was almost unexplored by Europeans. In fact it possesses many features that reflect what had been seen at Rotomahana, even having one considerable surface expanse of siliceous sinter - the Primrose Terrace. This, though considerably smaller in area and volume than either of the Rotomahana Terraces, nevertheless does have a broad silica-sinter platform, and, leading from this, a sinter-rippled rather than a sinter-terraced gently sloping surface. The large hot spring (Champagne Pool) at its apex, like those formerly atop each of the Pink and White Terraces, occupies a small hydrothermal eruption crater. Waiotapu has also a number of boiling springs, a few small geysers, and many other hydrothermal explosion craters mostly holding cold green lakelets. Several of these seem to be about the same age as old explosion basins at Rotomahana, and two of them (Lloyd 1959), though mostly cold, are one of the rarest type of geothermal feature, worldwide, in possessing molten sulphur[7] within their plumbing systems. Professor A.P.W. Thomas inferred the probability of this in his report on the 1886 eruption (Thomas 1888, pp.10-11). Waiotapu also exhibits a compact suite of a dozen or more subsidence pits scattered over a hectare of ground, and is without doubt the most colourful thermally active locality in New Zealand.

So, during the late 1880s and the 1890s, Waiotapu gradually became a tourist resort. Two people who had acquired significant experience with the tourist trade at the Maori village of Te Wairoa, the main pre-eruption gateway to Rotomahana and the Terraces, became crucially, but separately, involved afterwards with the promotion and development of tourism at Waiotapu. First on the scene, in December 1888, (Stafford 1988 p.332) was Francis Bernard Scott [Frank Boyd Scott: (Vaile 1939 p.36)] who set up a 'Bungalow' accommodation villa at the junction of the Urewera and Taupo roads under construction at the southwestern extremity of Rainbow Mountain. Scott's wife, Ramarihi, was a member of the local Maori hapu (sub-tribe) who from time to time had established and dwelt in scattered settlements in this area, and who themselves set up for a short period a tourist whare (shelter) close to the Primrose Terrace. Scott and others had noticed that there were widespread occurrences of hydrocarbon seeps in and around the northern hot springs at Waiotapu, and attempted (unsuccessfully) to launch a company to exploit, commercially, the supposed concentrated sources. Second was John Falloona, a survivor of the destruction at Te Wairoa during the night of the volcanic eruption. His involvement at Waiotapu began a little later than Scott's, but on a larger scale. In September 1896 he called for tenders (Stafford 1988 p.333), and over the next few months built the first local hotel accommodation about four kilometres south of the Bungalow close to the new Taupo road, then under construction.

Another development at Waiotapu, and nothing to do directly with tourism, arose from recognition that that part of the nutrient-poor pumice soils extending thence southeastwards across a wide plateau was more suitable for forestry than agriculture. This realisation was combined with a very enlightened Government initiative to create an open prison for suitable inmates. Such an institution was therefore built at Waiotapu with its prisoners becoming the work force planting the forest trees and experiencing considerable freedom and a relatively relaxed social environment. As a result the prison's first supervisor, J.C. Scanlon, and some of his charges, became the Europeans whose residences were located nearest to the site of Waimangu geyser – though at a distance of about 8 kilometres from it, and with their view in that direction partly impeded by intervening Rainbow Mountain and a lower hill just to the east of that. Planting began in early 1901.[8]

While tourist interest in craters of the 1886 erup-

7
The only similar feature we are aware of is Cinder Pool in the Norris geyser basin of Yellowstone National Park.

8
And this undertaking, with its early prison connection long since severed, has become the basis of a major New Zealand commercial enterprise.

Figure 9. Waimangu Geyser probably formed late-1900 in a sub-crater at the north-eastern end of Echo Crater - the flat area in front of the geyser. Here it is erupting to 180 to 200 metres. Rarely it reached twice that height. It ceased activity in 1904. Inferno Crater is left of the geyser, and the skyline at far left is Mt Tarawera. A. Iles, photograph, 1903.

tion never ceased, it appears that use of McIntosh's road to Te Hape o Toroa decreased during the 1890s. With Waiotapu becoming an increasingly popular attraction, the regular tourist routine evolved into a coach drive along this spur road only about half way to its terminus. There, from Pareheru, a panoramic view could be obtained taking in a sweep of the ash-fields from the hills towards Lake Tarawera and clockwise round to Rainbow Mountain. This interesting and time-efficient detour would normally be undertaken en route either when traveling from Rotorua to Waiotapu or when returning.

The first launching of a boat on the new Rotomahana took place on 15 February 1900 through the efforts of J.A. Pond, the Auckland-based Government Analyst, and fellow-explorer and Aucklander, Dr Humphrey Haines (Pond 1902), (Keam 1962 p.30).[9] These two scientists were interested widely in the post-eruption developments that were occurring around Rotomahana and also particularly in the lakelet in Inferno Crater, one of the Okaro group. They returned for further investigations two months later, and on 25 June and 19 November 1900 Pond gave public lectures about their work before the Auckland Institute. Unfortunately only limited records of both talks have survived.

In the meantime on 6 October 1900 Surveyor E. Philips Turner and his assistant, while surveying from the top of Haparangi mountain southwest of Rotorua, had seen steam clouds from two eruptions rising above hills in the direction of the Okaro craters. Turner's duties followed by a bout of typhoid fever, prevented him from investigating further. His chance of discovering the cause of the phenomenon was thereby lost to Haines who arrived back at his and Pond's hunting ground early in the New Year.

Waimangu Geyser (Figure 9) was discovered by Haines on 31 January 1901. The main public announcement of its existence and the opportunity for giving detailed descriptions of this new geothermal prodigy was accorded to Mrs Haines. She was honoured to present contemporaneously in the 23 March 1901 issues of all three of The New Zealand Herald (Supplement), The Auckland Weekly News (illustrations pp.10, 11), and The New Zealand Graphic XXVI (pp. 547, 557; illustrations pp. 546-547, 550-551) a detailed account of her and her husband's experiences and observations.

Because of the great height to which Waimangu Geyser erupted, and the accompanying forma-

9
This event received no publicity at the time and a later 'first launching' was claimed in mid-1901 by a group including Harold Blomfield. *Vide infra*

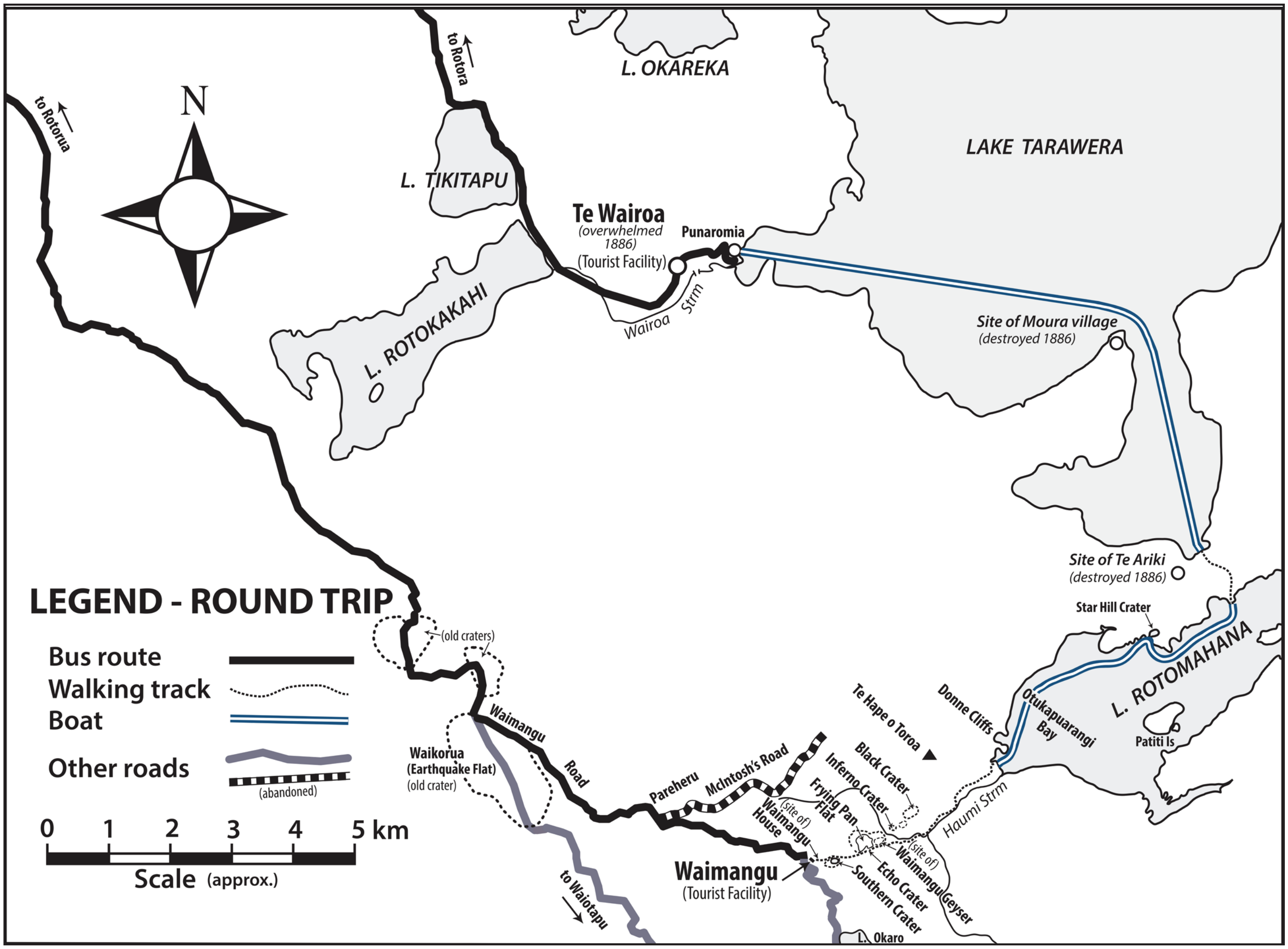

Figure 10. Route of the Round Trip. This map is largely constructed by tracing from a loose pocket map of the Tarawera Survey District included in (Grange, 1937). To some extent it is ahistorical and is modified to show elements of interest from earlier and later dates. For instance the line of the Round Trip is drawn more or less as it is today rather than for the period between 1903 and ca. 1920 when the walk across the Rotomahana / Tarawera isthmus lay somewhat to the west of its present route.

tion and persistence of steam clouds rising into the sky afterwards, Scanlon, his staff, and the prisoners at Waiotapu were able to see the white masses drifting above the intervening hills, and the gaoler's name appears frequently in news reports over the months following the geyser's discovery, especially when anything unusual was observed. For instance, in early April 1901, he was quoted as having '...witnessed a splendid eruption by moonlight, the steam ascending quite 3000 feet above the highest peak of Karamea [sic Maungakakaramea: (Rainbow Mountain)]' (New Zealand Herald, 9 April 1901).

Especially interesting so far as the main subject of the present article is concerned is part of a somewhat curious report published in the New Zealand Herald on Thursday 11 July 1901:

> Mr Scanlon says that there is no reason to doubt that another geyser has broken out in the Rotomahana Valley which throws up a volume of steam quite as big as Waimangu.

The fact that Scanlon was quite definite that there was another[10] major geyser needed checking. Three local Rotorua residents were determined to investigate, so, at the first opportunity, on Saturday 13 July 1901, they set off and camped in the vicinity of Waimangu for two nights. The expedition members were the photographer Arthur J. Iles, and

10
However, Rotorua historian, the late D.M. Stafford tacitly assumed Scanlon was mistaken and that the source of steam was Waimangu Geyser (Stafford 1988 pp. 44-45).

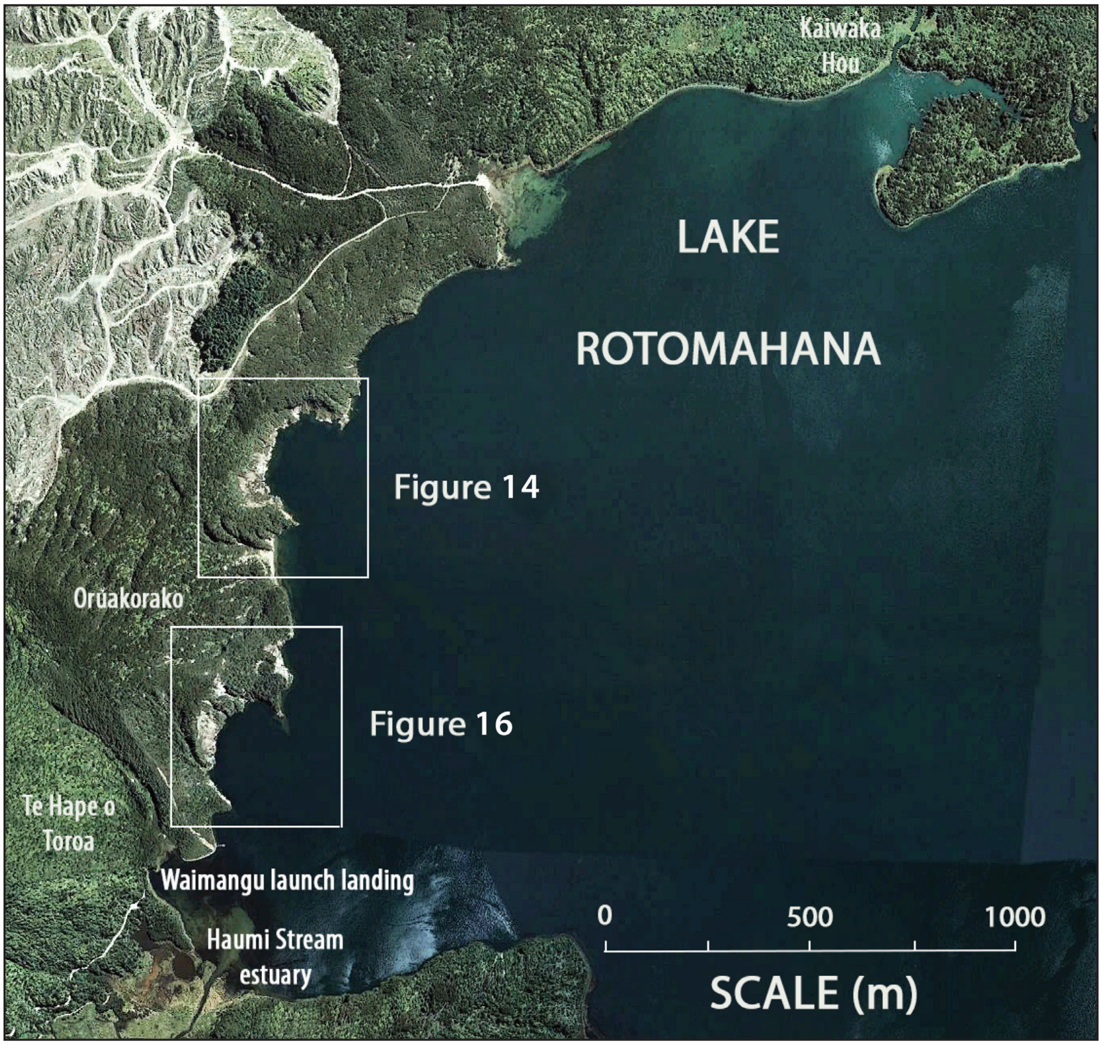

Figure 11. Map of the western shore of Rotomahana lake. Modified from Google Imagery.

Figure 12. Donne Cliffs, Donne Crater, from the south. C. Spencer photograph, ca 1903.

Messrs Paget and Wi Duncan. Nothing unexpected was discovered in the near vicinity of Waimangu geyser basin so it appears that next they decided to continue their searches in the direction of Rotomahana Lake. A very brief report in the New Zealand Herald of Wednesday 17 July 1901 states: '…after some very rough traveling they found there was a fresh outbreak on the site of the Pink Terrace. There had been a very severe eruption, and a great deal of water ejected, which had denuded the rocks of their covering of mud, leaving the rocks bare. They saw one eruption of steam which ascended to a height of 1000 feet.'

One notes the mention above of the 'site of the Pink Terrace'. No topographical survey had been conducted at Rotomahana before the eruption, so the precise location where it had lain was not identifiable. Nevertheless the 'site' would certainly have been within 200 metres of where the Pink Terrace had been, and the embayment in the shoreline of Rotomahana where Iles et al explored has been recognised by the authors of this article habitually using the informal name Otukapuarangi Bay, mentioned earlier, for this geographical feature.

A manuscript entry enlarges somewhat upon what the explorers saw, namely, a crevice about fifteen feet wide extending from the top of a small hill from which the geyser rose to the lake. 'Steam rose in a column about 1000 feet high from it.' Muddy water rushed down the crevice to the lake. When the eruption subsided Duncan found a 'hole 50 feet to 60 feet deep in which the water was gurgling and boiling.' A thin coating of pink sinter had been deposited. There is no mention of the water being thrown to any great height, and, impressive as the vapour cloud no doubt was, the activity seems not to have been very violent.

This was just the start. A few weeks later Iles and Duncan were joined by Harold Blomfield, Messrs D. Griffiths, Stewart, C. Shepherd (another photographer), and some Maori friends for a more thorough exploration. The group sailed two boats across Lake Tarawera and the smaller one was carried across the narrow isthmus to Rotomahana on the shoulders of six of these stalwarts. Blomfield prepared an account of the expedition and this was published (Blomfield, H., 1901). The text was accompanied with eleven photographic illustrations, most of them taken on the trip, but with one pair providing comparative pre- and post-eruption photographs taken from somewhat equivalent positions. While the trip's primary aim was to explore the western shoreline of Rotomahana lake, recreational pursuits – climbing Mt Tarawera and pig-hunting – were also included in the programme and the illustrations.

The transported boat first had to be lowered about twenty metres from the crater rim before it could be launched on Rotomahana. Condensing Blomfield's account somewhat, he then says [pp 11-13]:

> On the western side [of the lake] thermal activity was very pronounced, and the new geyser recently discovered, though not playing, roared with tremendous force…. Crossing the lake, the party landed in the vicinity of the site of the Pink Terraces… but the steam was so dense that little or nothing could be seen from the land…. [The party then]…rowed over a portion of the lake that was boiling…. A huge torpedo exploding at intervals near the boat made the danger imminent… A wonderful steam paddle-wheel geyser was discovered. At some little distance the sound was an exact imitation of a ferry steamer… Going closer to the bank where this peculiar geyser was situated, it was found in a small cave, the water being thrown out at each beat. The steam, however, was so dense that it was impossible to find out the cause of this peculiar phenomen[on]…. The new geyser…was next examined. It lies close to the water's edge, and as far as can be proved is the old cauldron which existed on the top of the Pink Terraces.[11]

And that is the disappointing end of the hot springs descriptions!

About this time Captain Gilbert Mair, famous in New Zealand for exploits during the wars of the 1860s, later a Parliamentary translator, and an end-of-the-century pastoralist, had commenced farming in the vicinity of Rerewhakaaitu Lake (see Figure 3), a short distance south-east of Rotomahana. In mid-August 1901 he launched his own boat on Rotomahana, taking soundings where he judged

11
The final sentence is a bold and unsupported assertion.

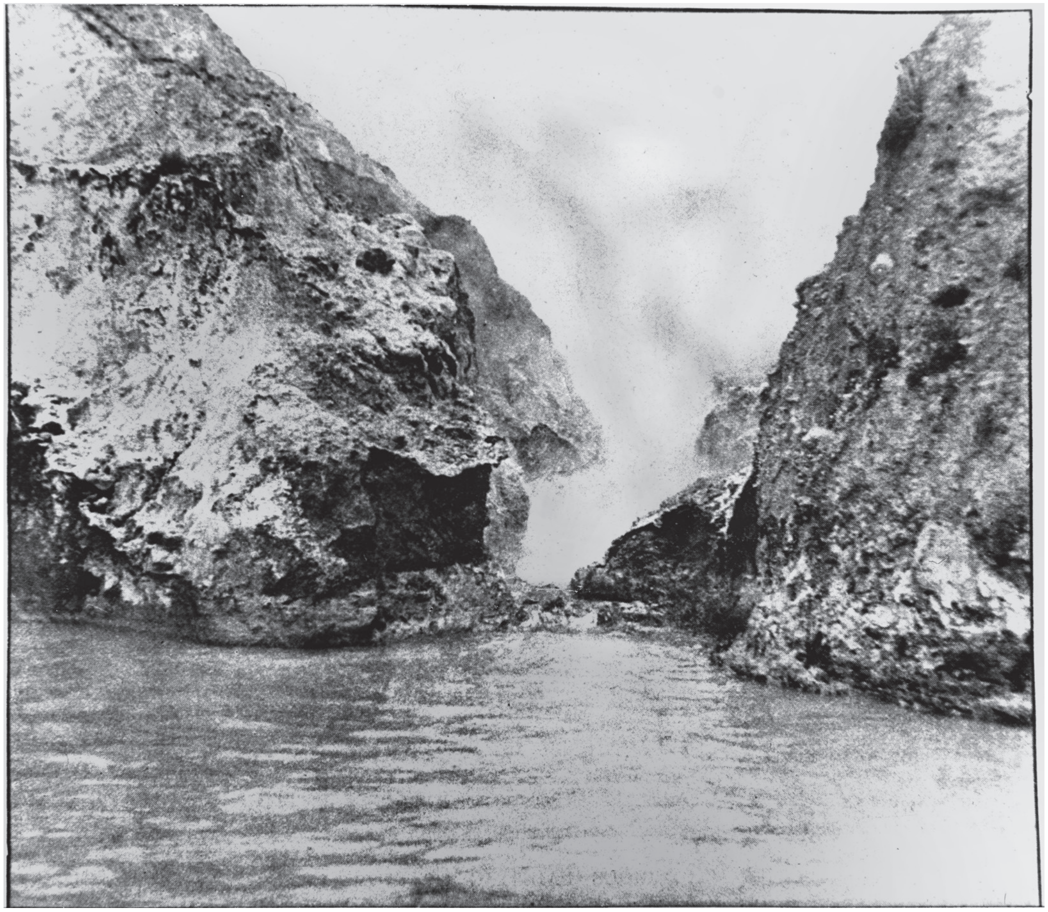

Figure 13. Te Waari Geyser, Otukapuarangi Bay. This unremarkable image is the only captioned photograph of this feature so far found, New Zealand Graphic, 11 April 1903. Unidentified photographer,

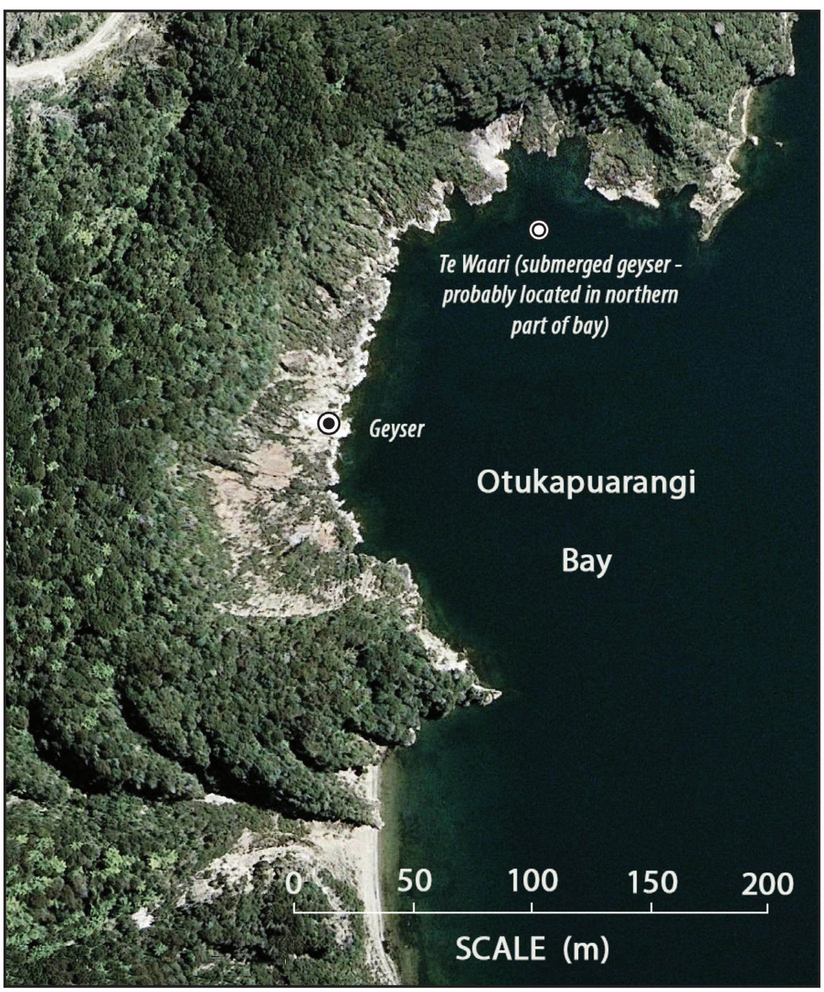

Figure 14. Map of Otukapuarangi Bay. Modified from Google Imagery.

Figure 15. Upton Geyser at Donne Cliffs. R.F. Keam photograph, 29 January 1981.

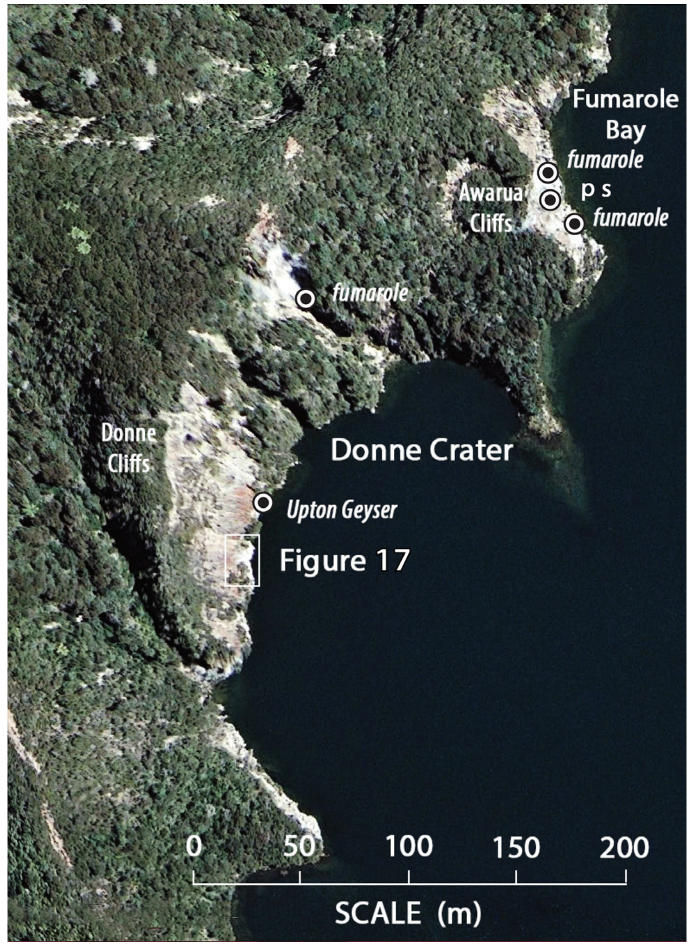

Figure 16. Map of Donne Crater Bay and Fumarole Bay. Modified from Google Imagery. 'p s' denotes persistent spouter. Modified from Google Imagery

each of the Terraces to have been situated ([Mair] 1901). He found a depth of 47 fathoms (86 metres) at his White Terraces site, 36 fathoms (66 metres) at his Pink Terraces site, and a greatest overall depth in the lake of 67 fathoms (123 metres) (New Zealand Herald, 20 August 1901).

Apart from the very few photographs taken by the Iles et al parties during the second expedition, it seems remarkably few images of the Rotomahana hot springs were secured by anyone, and certainly the main two Auckland-based illustrated weekly periodicals published none until 1902. Written descriptions of hydrothermal activities exhibited by the features were just as sparse – Waimangu Geyser and its immediate environs seemed to be all that mattered. The April 1901 description by Scanlon of his distant observations, which had triggered the explorations enthusiastically undertaken shortly thereafter, seems to have revealed near the Rotomahana shoreline only disappointing geysers and springs. Another difficulty seems to have arisen from false attributions as to where any inferred violent geyser discharges were originating. As another instance, it was presumably prisoners returning from their plantation work who reported seeing a magnificent geyser at about 5 p.m. on 22 August 1901 rising from the foot of Mt Tarawera (New Zealand Herald, 24 August 1901). One suspects again that this was Waimangu Geyser itself being viewed from an unfamiliar location and at an unfamiliar angle – perhaps with only the highest shots or even just its steam-clouds being visible above the sky-line, and perhaps after these clouds had drifted far from their source.

Limited detail is available about the initial development of Waimangu as a tourist resort. This is despite the coincidence that the Department of Tourist and Health Resorts was created in February

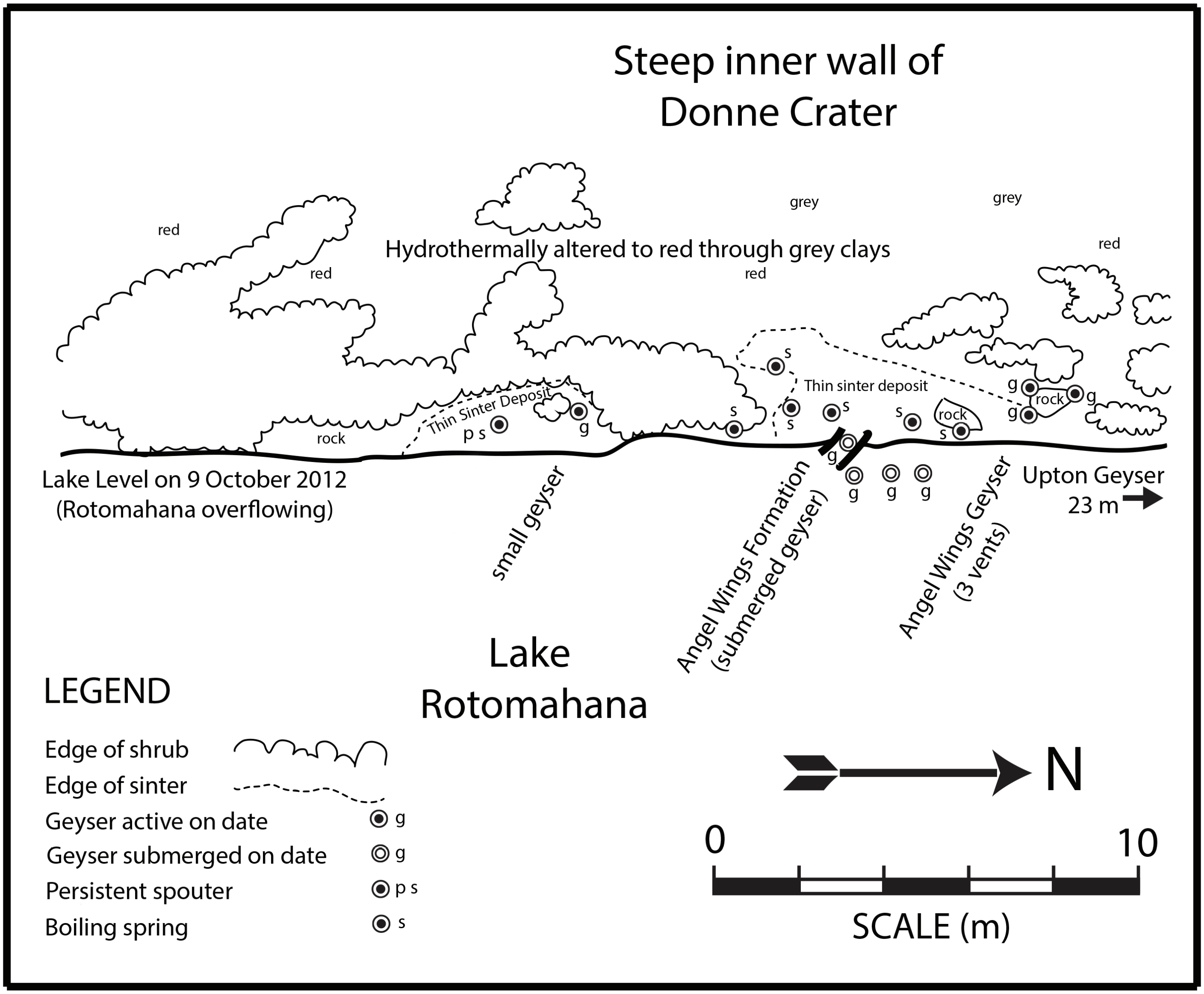

Figure 17. Sketch-map of greatest concentration of geysers and boiling springs, Donne Cliffs. Note that the scale is approximate only. 9 October 2012.

1901, within days of when Waimangu Geyser was discovered. It has nothing to do with record keeping in the new Department, but it does have something to do with subsequent handling of those records. The file indexing system indicates that files earlier than those that survive today clearly were at one time assembled, and one of us [RFK] first found they were missing at the time of an initial search made in 1963. It seems certain these no longer exist and they are definitely not held by Archives New Zealand, the organization currently responsible for the care and preservation of Government records. Information about head office involvement from the years 1901 and 1902 is thus limited and one has to rely on other sources to trace the background for the establishment of the 'Round Trip' (Figure 10). This new tourist trip consisted of travel by coach from Rotorua along McIntosh's road as far as Pareheru, thence along a branch extension to Waimangu, a walk along a newly constructed track past Waimangu Geyser and onward to the shores of Rotomahana, thence a short voyage along the lake's western shoreline to a landing in a northern embayment, a walk to the shores of Lake Tarawera, a voyage to Punaromia on the western shore of that lake, a walk up a track to The Buried Village (Te Wairoa), an opportunity for examining the ruins at that locality, and a coach trip back to Rotorua. Or the trip could be made in the opposite direction.

Various features along the route were given names at this time and the new trip opened, apparently on 1 January 1903. Because the main public interest centred on Waimangu Geyser and its activities, little detail was published about the lesser geothermal features. Nevertheless, on a rather small-scale map published about this time one notes four newly-named features on the western side of Rotomahana. From south to north these were 'Pat['s] Geyser', 'Donne Cliffs', 'Awarua Cliffs' and 'Te Waari' geyser (Papakura, 1905, appended map). Donne Cliffs comprise the western rim of a minor crater formed in the 1886 eruption and initially separate from Rotomahana Crater. The rising lake submerged the eastern rim before the Round Trip was inaugurated and the cliffs now rise steeply from the shores of Rotomahana to a height of about 30 metres. They are gradually being subjected to chemical alteration by the steam and hot sulphur gases emerging from numerous places on the face. T.E. Donne was the first General Manager of the Department of Tourist and Health Resorts and this energetic and administratively resourceful man clearly was very effective in exploiting the adventitious development of Waimangu Geyser into its becoming a major tourist attraction in New Zealand. In the course of time the description of the steep Rotomahana shoreline involved omission of the name 'Donne' and its replacement with simply 'The Steaming Cliffs'.[12] Pat's Geyser seems to have been a feature towards the south end of Donne Cliffs, but with continuing lake level rise it presumably is now well submerged. Awarua Cliffs appear to be the backdrop to Fumarole Bay (described later). Te Waari geyser (Figure 13) was located in Otukapuarangi Bay (Figure 14). Its site is now drowned and it was probably the original geyser found by Iles and his co-explorers. Its name is a Maori transliteration of 'Ward', surname of [Sir] Joseph Ward, the Minister responsible for several Government Departments, at that time including the fledgling Department of Tourist and Health Resorts.

No doubt Ward's support complemented the enthusiasm of his friend and administrative head, Donne, in establishing the Round Trip, and his name deserves equally to be revived if the 1903 geyser could ever be identified.

The cessation of Waimangu Geyser's activities in 1904 no doubt quickly reversed what had been up till then a rapid growth in the number of tourists who had been flocking to the Waimangu area to see its eruptions. Thereafter, while photographs of features in the area continued to appear in the New Zealand illustrated magazines, their frequency gradually declined and after a while it was largely just when sudden unexpected geothermal events occurred that one finds them. Indeed, after about 1920 they almost entirely disappeared.

THE ERUPTIONS OF 1926 AND 1951

To our knowledge only two important eruptive events have been reported as having occurred at Rotomahana since 1886. These were both sub-lacustrine hydrothermal eruptions.

The first occurred sometime between late afternoon 17 November 1926 and early the following morning. W. Penno, in charge of the Rotorua Office of the Government Department of Tourist and Health Resorts, reported to the head office as follows (Penno 1926):

> …. A fairly large upheaval occurred along the foreshore of Lake Rotomahana between the site of the old Pink Terrace and the southern landing stage… It is apparent that in all, five or six large blow-outs occurred at different points, blowing off the ends of several projecting points. One fairly large peninsula which was previously a few feet above lake level is now a few feet below, and at the point of activity a deep channel has been made, capable of allowing a launch to pass through. The lake in the vicinity rose about seven or eight feet and uprooted all the ti-tree and shrubbery along the foreshore and within reach of the surge. Except for profuse boiling at certain points, and the discoloured state of the water around the landing stage the position is now quiet.

The description of the changes at 'one fairly large peninsula' suggests that the main explosion occurred just off the point there, and that the potentially navigable channel that opened resulted from the peninsula tip and an attached mass of lake-bed slumping several feet down-slope into a sub-lacustrine crater produced by the upheaval. That several other blow-outs occurred focused precisely at the ends of projecting points seems highly improbable, and their disappearance into Lake Rotomahana seems more likely to have been caused by just the surge, initially

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We are, however, attempting to ensure that Donne's recognition by name of this feature at Waimangu is restored.

Figure 18. Geyser in Otukapuarangi Bay. R.F. Keam photograph, 9 October 2012.

Figure 19. Tourist party taking the Round Trip, Otukapuarangi Bay, before launches acquired. Mt Tarawera forms the skyline. Unidentified photographer, ca 1903.

seven or eight feet high, generated at the assumed primary (and probably only) explosion site.

The only known contemporary published mention of this event appears to have been made by geologist L.I. Grange who was the first scientist employed to undertake a major comprehensive study of the Taupo Volcanic Zone, and was at the time commencing this solo assignment for the (New Zealand) Geological Survey. In the Appendix of his resulting bulletin he wrote:

> …the Waimangu-Rotomahana area may furnish further explosions due to the cooling of the underlying basalt. A seiche at Rotomahana in December [sic] 1926 gave a feeling of uneasiness for a time (Grange 1937 p.129).

The second, and significantly larger hydrothermal explosion, occurred in June 1951 (Whaitiri 1951 diary entry), (Keam 1988 p.80):

> At approximately 4.30 p.m. on Wednesday, 13 June 1951, R.A. Whaitiri, the Waimangu guide, was in the vicinity of Gibraltar Rock, Waimangu, when he was startled by a ground shock and 'a fearful booming noise'. A huge steam column appeared over the hills in the direction of Rotomahana. Whaitiri at once investigated, rowing a dinghy on Rotomahana from the Waimangu launch jetty to the position from which he judged the explosion to have occurred. A landslide had come down in the vicinity of the steaming cliffs and vegetation was found floating on the lake whose waters in this locality were greatly discoloured. A more thorough investigation within the next day or so indicated that a surge or surges had passed over the lake, and effects on the shoreline vegetation, in places to a height of several feet above the water-line, were visible even at the Rerewhakaaitu [eastern] end of Rotomahana. The boom was heard also in Te Wairoa some 8 kilometres away but no shock was felt there. It was clear that a significant hydrothermal eruption had occurred under Rotomahana, close to where the landslide had fallen.

However, there are, we understand, events where solitary waves have been recorded as passing across the surface of Rotomahana. We know little of these occurrences and understand that they have been captured on lake level recorders. They have usually been attributed to small earthquakes. However, we believe that a different cause is more likely. Specifically, we think it probable that these can more readily be attributed to small hydrothermal eruptions occurring beneath Rotomahana. Firstly, because of the known occurrence of the 1926 and 1951 eruptions, such events can certainly happen there; secondly, the energy dissipated by a hydrothermal eruption causing a wave of given amplitude is very much less than that required to produce an earthquake sufficient to create a water wave of that amplitude. This is because energy in the eruption model is almost entirely dissipated in the water, whereas in the earthquake model energy is mainly dissipated within the solid earth with only a small fraction of it being transmitted to the water. Also it is generally to be expected that smaller energy events occur more frequently than larger energy events. It should be noted that the hydrothermal eruption model does not necessarily mean that the eruption steam bubble broke the surface of the lake. If it were small enough and the lake-bed where it occurred were deep enough the bubble could be completely condensed in the cold lake water before it reached the surface. To an observer lucky(?) enough to have been watching when the event occurred, all that would have been seen would have been an up-doming of the lake surface above the bubble followed by a dishing of the surface as the bubble collapsed – and no steam need have escaped into the atmosphere. Three lake level recorders suitably located about the lake and provided with accurate timing devices would be sufficient not only to be able to determine that an event of this nature had occurred but also possibly to distinguish it from an earthquake-generated wave. Such invisible hydrothermal eruptions are qualitatively different from normal ones, and deserve a distinctive name. Consistent with the ideas presented in an earlier paper by one of us (Keam, 2002), the choice would be to use the term 'crypto-hydrothermal eruption', and one can see that the occurrence and detection of such events could provide important information

Figure 20. Angel Wings Geyser. R.F. Keam photograph, 9 October 2012.

in U.S. situations also, such as at Yellowstone Lake, where parallels with Rotomahana exist.[13]

OBSERVATIONS OF 1981, 2010 AND 2012

From time to time over the past 60 plus years the authors have inspected, separately or together, the Rotomahana springs. Very few of these visits arose because of any concentrated effort on our part to record the activities, and mainly they were adventitious opportunities presented when we were accompanying friend(s)/family-member(s) on such trips as included the Rotomahana lake voyage. When significant changes seemed to have happened these have of course been noted.

The only more focused visits were:

(1) A three or four hour visit on 29 January 1981 by RFK in company with Simon Upton[14] and his father and brother in their private boat. Observations were concentrated on the active western shoreline of Rotomahana (Figure 11), largely on an impressive fountain type geyser (Upton Geyser, Figure 15) then active at the base of the Donne Cliffs (Figure 16), and on the main geyser in Otukapuarangi Bay (*vide infra*). However we did explore also a deep valley towards the northern end of Donne Crater where a slab of the crater wall had in much earlier times broken away from its original position and tilted

13
Small suites of lake level recorders or of acoustic pulse detectors would reveal the location and strength of the hydrothermal energy dissipated, and small suites of seismographs the location and strength of any earthquake generated, and the ratio of those two strengths, qualitatively so different, would reveal whether the event itself were an earthquake or a hidden hydrothermal eruption.

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Simon, then aged 22, was at the time embarking on a political career and was Chairman of the New Zealand Young Nationals (the youth wing of the New Zealand National Party). He was enormously helpful in the battle to preserve the Waimangu geothermal system from exploitation (and the geyser, with his permission, has been named after him in accord with honouring politicians who have particularly benefited this area). From 1981 till 2001 he was a Member of the New Zealand Parliament, and rose to ministerial rank (Health; Environment; and Research, Science and Technology portfolios) in the 1990 National Government. His interest in Waimangu began when he was a young child. In the early nineteen seventies, long before I (RFK) met him, I had by chance come across some carefully tagged but withered plantings in a normally unvisited area of Waimangu where, accompanied by his father, Simon had been attempting a botanical experiment.

(Figure 16). There is one significant fumarole/spring here in the valley floor. This particular area is almost unreachable by any approach other than boat.

(2) A three and a half hour 'sit' at the geyser (Figure 18) in Otukapuarangi Bay by the authors on 20 October 2010. The aim was personally to monitor the eruptions seeking the average period and its standard deviation. The results were that all eruptions lasted approximately one minute and their commencement times were: 10.50 a.m., 11.12 a.m., 11.32 a.m., 11.49 a.m., 12.07 p.m., 12.29 p.m., 12.45 p.m., 13.04 p.m., 13.23.5 p.m., 13.48 p.m., 14.01 p.m. Jets did not rise more than about 7 or 8 metres. The tourist boat operators pass close to the geyser for only a few minutes of each circuit on Rotomahana so that the interval between eruptions had not been ascertained, and no equipment had been available to record events instrumentally. The above record shows that during the observation time of 191 minutes, covering ten closed intervals, the average period was 19.1 minutes and the standard deviation was 3.15 minutes.

(3) It was only as recently as 9 October 2012 that the authors and Waimangu Volcanic Valley Ltd Proprietor, Harvey James, closely examined for a total time of about 90 minutes the behaviours of all the hot springs and geysers along the western shoreline of Rotomahana. All observations were made from boats. Indeed it would be quite dangerous to attempt a landing at the area most densely populated with springs (about thirty metres south of the Donne Cliffs) – it is steep, probably slippery, and has nearly boiling water constantly flowing over most of it. It had several short-period active geysers and a 'perpetual spouter'[15] at the time (See Figure 17). The information we have acquired is largely that which we obtained by photography. One of the other main tasks of this visit was to inspect the outlet of Rotomahana lake through the culvert and see Kaiwaka Hou actually flowing.

Angel Wings Geyser (Figure 20, page 51), erupted for the first time in many years in early September 2012. Its distinctive and beautiful array of three steady jets is, so far as we are aware, unique. Bradley Scott has informed us that he had seen the geyser before. Because of its appearing this time just after Rotomahana lake commenced its overflow it seems that his previous sighting must have been during the brief period of high lake level that occurred shortly after the Rotomahana culvert was installed in 1974. During our 9 October 2012 visit, Angel Wings Geyser was in eruption from 10.49.26 till after 10.50.42, and later in the day from before 12.56.17 till after 12.57.18, so an eruption was lasting about 1.5 minutes. It was not in view between these pairs of times so there could well have been one or two unobserved eruptions during that approximately 2 hour interval. Note that Angel Wings Formation (Figure 21) is distinct from Angel Wings Geyser. The formation is a pair of nearly vertical wing-like sinter sheets that have grown naturally on either side of a very active small splashing geyser six or seven metres south of Angel Wings Geyser. It is a remarkable coincidence that these two features in quite different ways have earned their similar names – note also the feather-like developments on the inside of one of the sinter wings appearing in Figure 21.

The geyser in Otukapuarangi Bay (Figure 18) was seen in eruption at 12.00.41; its next eruption was photographed between 12.07.21 and 12.08.04; and a third time it was photographed in eruption at 12.14.28. The period was thus reasonably well defined as being approximately 7 minutes, much shorter than the period of 19.1 minutes two years earlier. This quantitative result conforms with the qualitative general observations by the tourist boat operators that when a shoreline geyser is active its period shortens as the level difference between Lake Rotomahana and the geyser vent decreases, and lengthens as the difference increases. On 9 October 2012, lake level was at its highest (because it was overflowing) and the geyser vent would have been at most 0.5m higher than the lake; on 20 October 2010, the lake would have been about 1.5 to 2.0m lower.

In Fumarole Bay (Figure 16) we saw for the first time a spring in eruption (Figures 22, 23) in an area renowned (as its name implies) for the noisy and forbidding fumaroles jetting steam from vents among the rocks that have fallen from Awarua Cliffs. This spring was sending a very steady thin jet of boiling water, about 5 cm in diameter at its vent to a height of about 7 metres. It thus was behaving as a persistent spouter. A recent visit on 12 August 2014 showed that it had become a fumarole, pre-

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The commonly used term for a spring that remains in eruption indefinitely is "perpetual spouter". While evocative, it is a rather exaggerated term and we have felt that "persistent spouter" would be a more accurate description. (But see fig. 6 for S.P. Smith's surveyed approximate location.)

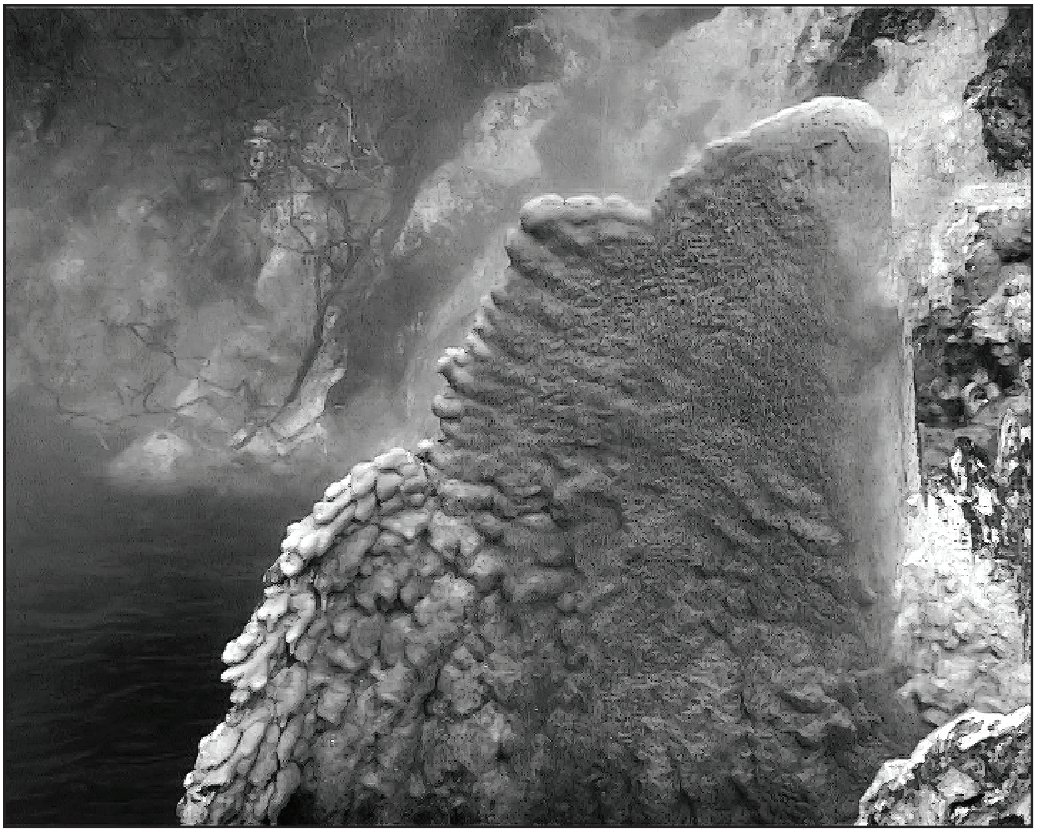

Figure 21. Angel Wings Formation. E.F. Lloyd photograph, 9 October 2012.

Figure 22. Fumarole Bay with persistently spouting spring active. R.F. Keam photograph, 9 October 2012.

Figure 23. Fumarole Bay and Awarua Cliffs. R.F. Keam photograph, 9 October 2012.

sumably reverting to a role it had previously played.

Within the approximately thirty-five years covered by this section, there have been a few specialist studies of particular aspects of the Rotomahana area, these usually being outlier segments of scientific work on the more general Waimangu/Rotomahana area. For example, Melita Keywood's thesis (1991) on geochemistry, where some details of Rotomahana features appear within her Appendices 1 and 2, and some descriptions within Appendix 3. She also mentions (p.37) unpublished work relating to many features during 1984 by D.S. Sheppard and Johnson, but access to this material has not been sought by the authors.

PRESENT-DAY MORPHOLOGY OF THE WESTERN SHORELINE OF ROTOMAHANA

There is another much smaller rhyolite dome about two-thirds the elevation of Te Hape o Toroa above Rotomahana and lying between the taller hill and the lake. Named Oruakorako, it is elongated in a north-south direction forming a narrow ridge that abuts and parallels the eastern flank of its larger neighbour. The saddle between the two is only about twenty metres lower than the ridge's summit. Nothing is yet known about the relative geological age of the two domes, which might, indeed, have been formed during the same eruption (more than 61,000 years ago).

Geologically, the rock along the western shoreline of Rotomahana for about a kilometre of its south-north extent is provided by the truncated eastern flank of Oruakorako, while further north it is provided either entirely by 1886 tephra, or by alluvium derived overwhelmingly from this tephra. Geographically, from south to north, the western shoreline of Rotomahana extends from the Haumi stream estuary in the extreme south for a distance of about 3 kilometres to the culvert where the intermittent Kaiwaka Hou begins its passage down to

Lake Tarawera. The culvert entrance conveniently defines the junction point of the western and northern shorelines of Rotomahana.

In detail, and starting from the south, one can distinguish the following western shoreline sub-divisions: First a small embayment which is the partially drowned valley at the southern end of Oruakorako separating that ridge on its east from the adjacent part of Te Hape o Toroa on its west. Next is the embayment formed by the interior walls of that part of Donne Crater that still remains above lake level – i.e. including the Donne Cliffs. Next again is a weakly embayed section whose southern part hosts onshore the most intensely active fumaroles in the whole Rotomahana/Waimangu region and to which the authors have applied the informal name 'Fumarole Bay'. North of this is a long slightly-curving sweep of shoreline producing no obvious on-shore wafts of steam; thus 'Inactive Bay'. Next is Otukapuarangi Bay. Proceeding further north again, the land at the shoreline progressively decreases in elevation, and all sign of *in situ* massive rhyolite disappears, leaving only tephra visible. Even the shoreline itself becomes indistinct at a place where a now partially-submerged alluvial delta has built out from the 'estuary' of an alluvium-floored valley. This is near the site of Black Terrace Crater.[16] Beyond this, and extending for the last one kilometre stretch to the Kaiwaka Hou culvert, exposed shore material consists exclusively of the thick tephra deposits that comprise the Rotomahana Barrier – the thick dam of tephra blocking the pre-eruption course of the old Kaiwaka stream. The shoreline itself parallels the original boundary of the 1886 Rotomahana Crater, but everywhere here it has been very slowly but progressively eroded and displaced from its original location, perhaps 10 to 20 metres, by the lapping effects of the lake's wave action.

One consistent change we have observed during the years of our familiarity with the Rotomahana western shoreline has been that along any active area almost all hot water discharges seem to occur from vents not more than about 2 to 3 metres above lake level, although steam and 'permanent' gases (CO_2, H_2S, SO_2) usually form 'steaming ground' to well above this limit. In other words the 2 to 3 metre level band through which the liquid water discharge occurs seems always to move up or down as lake level changes. Another consistent change seems to have been that geysers that have been previously active for any given lake level revive when that lake level is regained after some excursion. And, as mentioned earlier, eruption periods decrease or increase as the level difference between lake and geyser vent decreases or increases, respectively. Furthermore, with a rising lake level the cessation of a geyser's activity occurs usually when it becomes flooded ('drowned') by the lake. An echo of the behaviours occurs elsewhere at Waimangu at places where a stream runs along the foot of a very steep geothermally active slope. To be specific, around the base of Mt. Haszard, a short distance upstream from Rotomahana in the Waimangu Valley, a similar banding of water seeps and hot springs is observed, but in the absence of an adjacent lake with changing level, the geothermal water discharges remain essentially fixed in their locations. Both behaviours emphasise the essential control on the liquid water discharge elevations exerted by the water-table level inside the hills that host geothermal fluid.

ADDENDUM

Beginning nearly two hours before the first outbreak on Tarawera mountain on 10 June 1886, seismic activity of progressively increasing intensity had been noticed by residents in Ohinemutu and Te Wairoa. The earthquakes can be attributed partly to phreatic activity (explosive expansion of water) as the intruding magma encountered (cold) meteoric water occupying cavities and pore space within and beneath the mountain, and partly to the rock itself fracturing as the intrusion process opened pathways through which the magma could rise.

Nairn and Cole (1981) discovered that exposures of 1886 basalt-occupied dikes within the walls of Tarawera Rift along the mountain revealed that they were all limited--length segments geometrically aligned within a small range of values close to a 15 degrees clockwise rotation relative to the Rift direction itself. They interpreted this en echelon arrangement as being due to the intruded old mountain rock having before the eruption been in a state of tension, with the principal axes of stress and corresponding strain lying parallel to and perpendicular to what became the dike plane segments. The magmatic intrusion had thus directly released ac-

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No definite surface expression of this feature has unambiguously been recognised, so we have felt it safest not to indicate its tentative location on Figure 11.

cumulated elastic energy of deformation and this thereby had initiated and controlled the actual crater formation.

In their pioneer investigation, Nairn and Cole attributed this pre-existing deformation to movement that had occurred within a fundamental geological structure, the Tarawera Linear Vent Zone, (TLVZ). This deep-seated basement fracture zone is inferred to run for at least 28 km from beneath Southern Crater at Waimangu for the full length of the Tarawera Rift, and continuing in the same direction as far as Putauaki (Mt Edgecumbe) a dacite volcano in the Bay of Plenty district.

The pre-eruption seismic activity continued unabated during the principal magmatic ejection stage of the eruption, and both phenomena faded noticeably after about 6 a.m. on 10 June 1886.

The shock-waves comprising the seismic activity propagated outwards from their sources in the form of momentary relative displacements (strain) between adjacent elements of the rock medium they were traversing. Where the rock was already under strain, such an extra imposition could momentarily cause the vector sum of the two contributions to exceed the elastic limit of the rock and therefore cause it to fracture. The seismic activity could thus be an effective means whereby, even at a distance from any magma, fracturing within strained rock could be initiated and propagated. Within a region where pre-existing stress and strain was similar to what it had been beneath Tarawera mountain the triggered fracturing would very likely be geometrically similar. In other words, with an expectation that pre-existing stress and strain patterns had developed uniformly within the TLVZ, en echelon fracturing and crater formation elsewhere within it would very probably mimic the effects that had resulted along the Tarawera Rift's Tarawera mountain segment, even in the absence of any direct magmatic involvement. Thus crater formation could directly follow just from the existence of sufficient stored elastic energy, and the arrival of a seismic trigger. And a crater's formation event could trigger eruptions with even more energy if that formation event tapped other local energy stores such as the hydrothermal energy that had supplied the pre-1886-eruption's Rotomahana hydrothermal system.

For fuller details please see the chapter "The Tarawera eruption, Lake Rotomahana, and the origin of the Pink and White Terraces" in Keam, 2016.

APPENDIX

LAKE ROTOMAHANA PARAMETERS

Pre-1886 eruption	2003
AREA	
0.75 km^2	8.5 km^2
VOLUME	
~0.002 km^3	~0.7 km^3

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Waimangu Volcanic Valley, New Zealand, 2005

Photos by Tara Cross

Spouters within the Waimangu Geyser crater along the runoff channel of Frying Pan Lake, Dec. 19, 2005.

Small geyser next to the Angel Wings formation (see Page 52), Donne Cliffs, Lake Rotomahana, December 19, 2005. The left "wing" of the formation can be seen prominently to the left of the active geyser. Intervals were approximately 1 minute, with eruptions lasting about 30 seconds.

The Role of Near-Surface Water Movement in the Initiation of a Geyser Eruption

Jeff Cross

Abstract: Hypotheses are proposed to explain geysers that erupt in series, have sympathetic eruptions, or exchange function.

INTRODUCTION

Geysers that erupt in series, have sympathetic eruptions, or exchange function with neighboring thermal features, are fascinating. It is challenging to reconcile the frequent eruptions that occur during an eruptive series with the long periods of quiet that separate each series from the next. It is challenging to explain how a geyser can erupt following an eruption of a neighboring geyser, after an hours-long delay, but not at other times. It is challenging to explain why the flow of hot water should alternate between two thermal features, as it does when an exchange of function occurs (Marler, 1953). Benseman (1965) and White (1967), through observation and experiment at thermal areas on the North Island of New Zealand and at Steamboat Springs, Nevada, provide a basic understanding of how water flows within a geyser. With this understanding, hypotheses are proposed to explain complex patterns of geyser activity.

OBSERVATIONS BY BENSEMAN AND WHITE

The distribution, redistribution and storage of hot water at Wainui Geyser were studied by Benseman. Wainui was located at the Orakeikorako thermal area, on the North Island of New Zealand. The crater of Wainui was 4 meters (13 feet) deep and funnel-shaped, having a surface area of 60 m^2 (650 ft^2). Assuming a circular crater, this calculates to a diameter of 8.7 meters (29 feet). The vent of Wainui was flooded in 1961 when a hydroelectric dam on the Waikato River was completed, submerging much of the Orakeikorako thermal area beneath the waters of Lake Ohakuri. Because Wainui did not have protected status, it was possible to perform a series of experiments that pertain to the hydrology of geysers (Benseman 1965).

Benseman observed that the discharge rate from Wainui was highest when the overflow elevation was lowest. By building a dam across the runoff channel, Benseman raised the overflow elevation of the pool. When the overflow elevation was raised 64.8 cm (26 inches), the average interval lengthened from 932 seconds to 1505 seconds, while the average discharge rate decreased from 5.15 L/s to 3.60 L/s (1.4 to 0.9 gal/sec), as shown in Table 1. The water not discharged from Wainui was found to be discharging instead from hot springs near Wainui, between it and the Waikato River. When the dam was removed, the intervals and average discharge rates returned to their original values (Benseman 1965), *Table 1; Figs. 1-4.*

Benseman observed that raising the overflow elevation of the pool caused water to become sequestered in the hydrothermal aquifer. Lowering the overflow elevation of the pool caused water to be released into Wainui from the hydrothermal aquifer. When the dam across the runoff channel was removed, the interval of the geyser fell from 1505 seconds to values ranging from 655 to 790 seconds, before stabilizing at the 932-second value cited previously. At the same time, the discharge rate exceeded 5.15 L/s before stabilizing at 3.60 L/s. When the dam was replaced, the same phenomenon was

Overflow elevation (cm)	Flow rate (L/s)	Eruption interval (sec)
64.8	3.60	1505
0	5.15	932

Table 1: Lowering the overflow elevation of Wainui Geyser correlated with increased overflow rate and eruption frequency. Data from Benseman (1965).

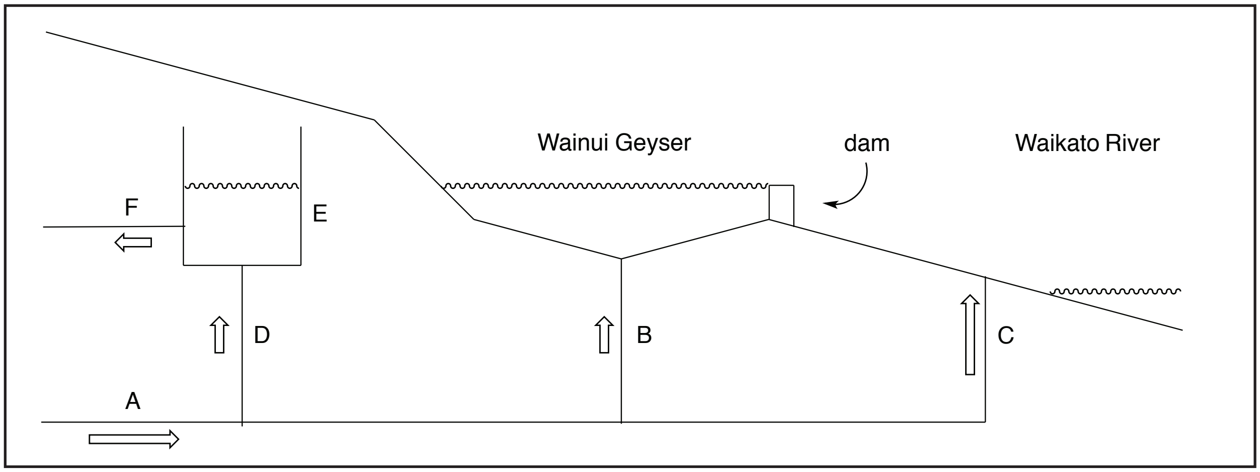

Figure 1: Diagram of Wainui Geyser, with water source (A), channel to vent of Wainui (B), channel to nearby vent (C), channel to hidden reservoir (D), hidden reservoir (E), outflow from hidden reservoir (F). Figure based on Benseman (1965).

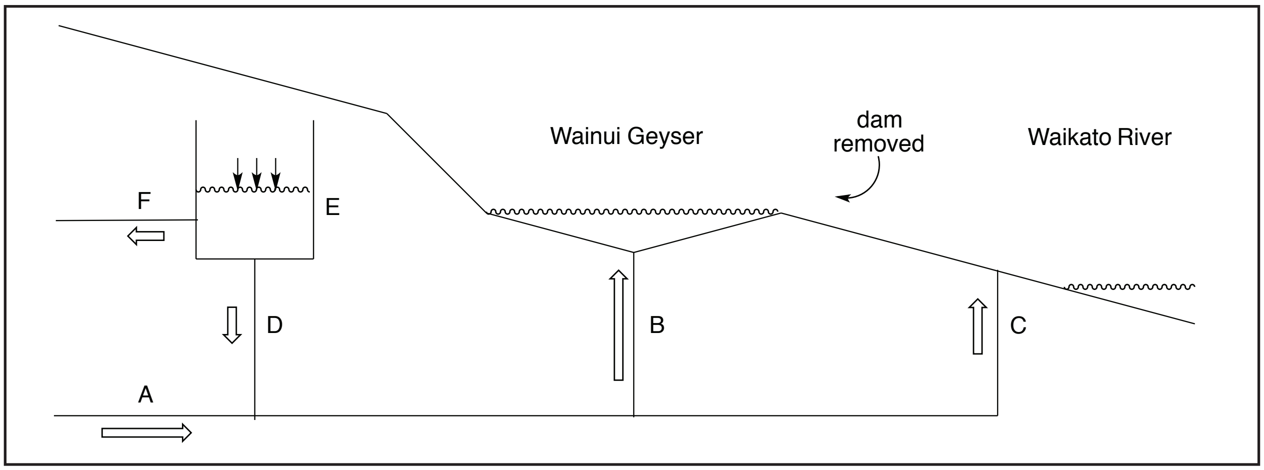

Figure 2: Wainui Geyser after the dam is removed, showing increased flow up channel (B) and an additional supply of hot water from (E) descending through channel (D), and a diminished flow through (C), all causing Wainui to erupt more frequently. Figure based on Benseman (1965).

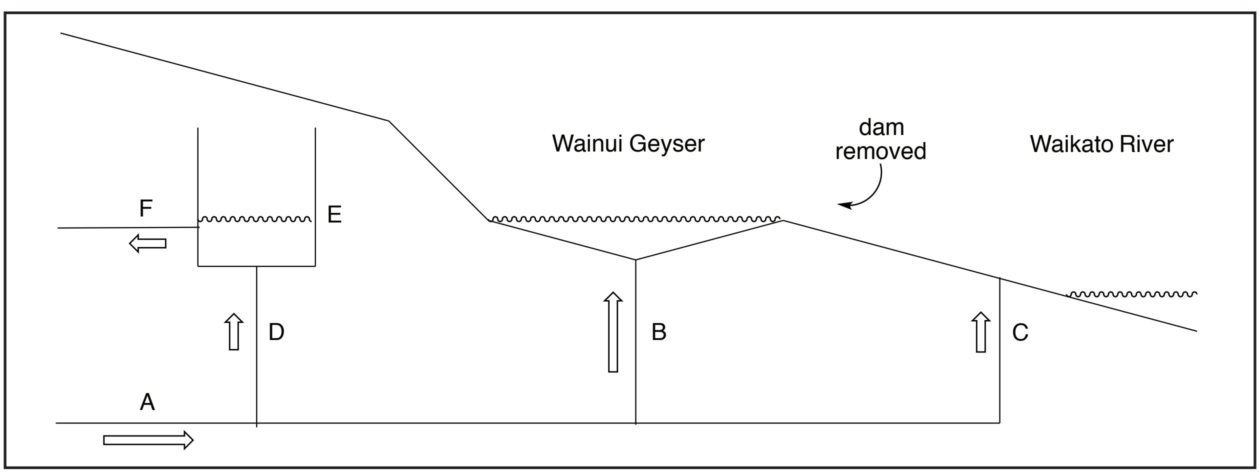

Figure 3: Wainui Geyser after reaching equilibrium, showing hidden reservoir (E) at a low, stable level, and flow up channel (B) greater than in Figure 1 but less than in Figure 2. Figure based on Benseman (1965).

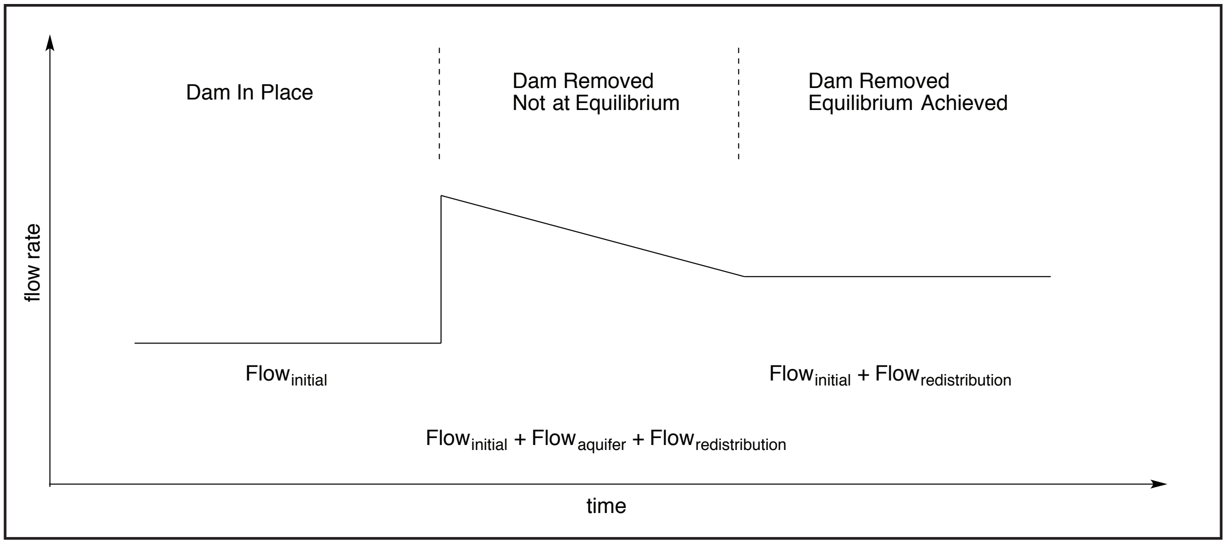

Figure 4: The flow into Wainui when the dam is in place, shortly after the dam is removed, and long after the dam is removed, with contributions to flow during each time period.

observed in reverse. The first few intervals were longer, and the average discharge rate was smaller, than the stable values (Benseman 1965).

A similar study was performed by White at an erupting well at Steamboat Springs, Nevada. The Geyser Well, as White named it, was a drilled well 43.1 feet (13.1 meters) deep and stabilized by a 6-inch (15.2 cm) diameter casing. The eruptions threw water to 60 to 75 feet (18 to 23 meters), lasted for 30 to 40 minutes, and occurred at intervals that were usually days long. Prior to an eruption, the water level remained 0.3 to 2.6 feet (0.1 to 0.8 m) below overflow (White 1967).

The Geyser Well erupted more frequently when overflow occurred prior to an eruption. During July 1949 through 1950, the Geyser Well was inactive whenever water levels were too low to allow overflow. When the water level happened to rise so that water could flow out through a corroded hole in the side of the well casing, the flow amounting to an estimated 0.05 gallon per minute (0.19 L/min), the Geyser Well erupted about once a week, as shown in Table 2. When White enlarged the hole, increasing the overflow rate to 0.25 gallon per minute (0.94 L/min), the Geyser Well erupted about once daily. When White dammed the runoff channel of nearby vent 31n, then a flowing hot spring 75 feet (23 meters) to the north, the overflow rate increased further, and the Geyser Well erupted every 8 hours. The durations decreased to 20 to 30 minutes and the height of the eruption decreased to 20 to 40 feet (6 to 12 meters). (White, 1967) *Table 2.*

Overflow (gal/min)	Eruption interval
None	inactive
0.05	7 days
0.25	1 day
>0.25, 31n dammed	8 hours

Table 2: Increased flow rate correlated with increased eruption frequency at the Geyser Well. Data from White (1967).

White reasoned that overflow facilitated heat transfer to the surface from depth, increasing the eruptive frequency. Overflow from the casing drew hotter water from depth toward the surface where, at a lower hydrostatic pressure, it could begin to boil, initiating an eruption *(Fig. 5)*. It was not due to any increase in the water temperature at depth. During the period of preliminary overflow and frequent eruptions from the Geyser Well, the temperature at the bottom of the well was only 107 to 108 °C, significantly below the 113 to 114 °C measured when eruptions were less frequent, and fully 12 °C below the boiling point of pure water at this depth within the Geyser Well (White 1967).

The observations of Benseman (1965) and White (1967) show that lowering the overflow elevation of a thermal vent, or raising the overflow elevation in a connected thermal vent, increases the rate of discharge, and that increasing the rate of discharge increases the frequency of eruption. Increased rates of discharge arise from two sources,

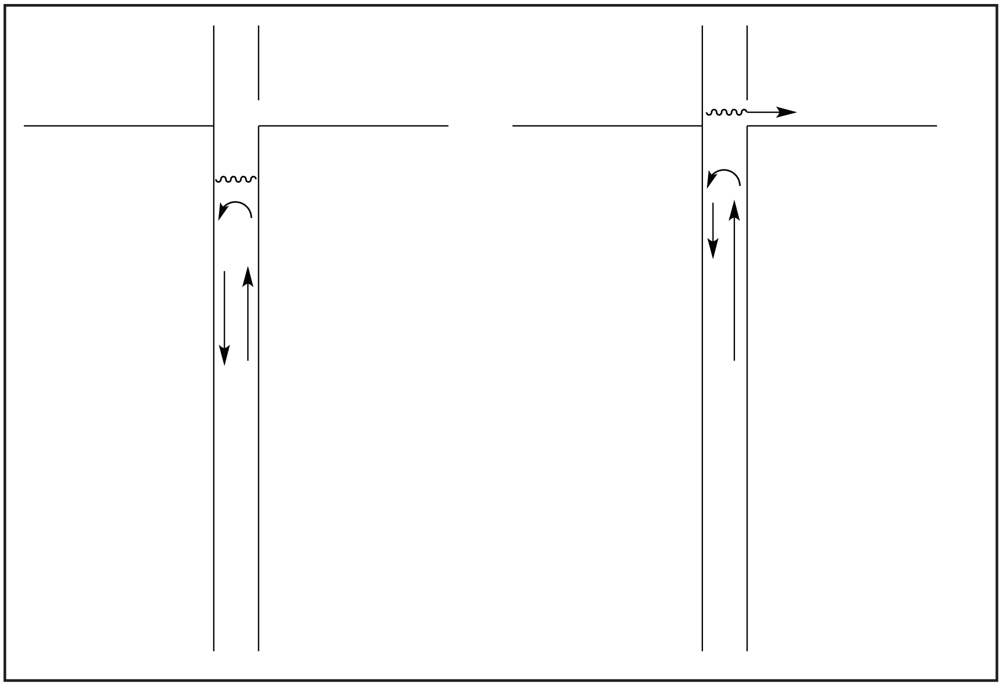

Figure 5: Circulation patterns in the Geyser Well when the water level is below overflow (left) and at overflow (right), with arrows showing increased upward circulation during times of overflow.

one permanent and one transient. Redistribution of hot water from other vents is permanent for as long as the overflow elevation is lowered. Release of water into the geyser from the aquifer surrounding the vent is transient, lasting until the source is depleted.

APPLICATION

The findings of Benseman (1965) and White (1967) can be extended to explain geysers that erupt in series, geysers that erupt only following an eruption of a connected geyser, and exchange of function. As shown above, lowering the water level in a geyser causes the frequency of eruption to increase. Although Benseman and White changed the overflow rate by building dams across a runoff channel and enlarging a hole in a well casing, the natural eruption of a geyser throws water out of the system and therefore has a similar effect, leading to complex patterns of eruption.

Consider two geysers joined below the surface by a horizontal channel. After Geyser X erupts, it is empty. Water flows from Geyser Y into Geyser X through the horizontal channel until Geyser X is full. Since part of the discharge from Geyser Y can now exit below the surface, this constitutes a lowering of the overflow elevation in Geyser Y. This increases the supply of hot water to Geyser Y, causing it to erupt one or more times while Geyser X refills. *Fig. 6, next page.*

I hypothesize that Vault Spring and Mortar Geyser erupt via this mechanism. Vault Spring drains when Giantess Geyser begins to erupt. After lying empty for about 6 hours, the water suddenly rises and Vault enters an eruptive series. Similarly, Fan and Mortar Geysers erupt together. Although Mortar surges when Fan begins to erupt, it sometimes falls completely quiet for a few minutes while Fan erupts alone, before surging into full eruption.

A geyser may act upon itself. Consider a geyser that is empty following an eruption. The flow of hot water into the geyser is increased as long as the water level is low. If the geyser erupts again before it refills completely, it empties itself a second time. The series of eruptions continues until an eruption fails to occur before the geyser is full. Once full, the supply of hot water is diminished and a longer time passes until the next series begins. *Fig. 7, next page.*

I hypothesize that Lion Geyser, Giantess Geyser and Great Fountain Geyser erupt by this mechanism. The initial eruption empties Lion, and the geyser remains empty while subsequent eruptions occur at intervals of slightly over an hour. Once it refills, many hours pass until the next series begins. Similarly, the eruptions of Giantess and Great Fountain begin with heavy surging and overflow. After a brief pause, subsequent eruptions occur.

A geyser may act upon itself to generate a series of minor eruptions that leads to a major eruption. Each minor eruption comes from a shallow reservoir, and partially empties the geyser. When the water level is low following a minor eruption, the water flow rate into the shallow reservoir from

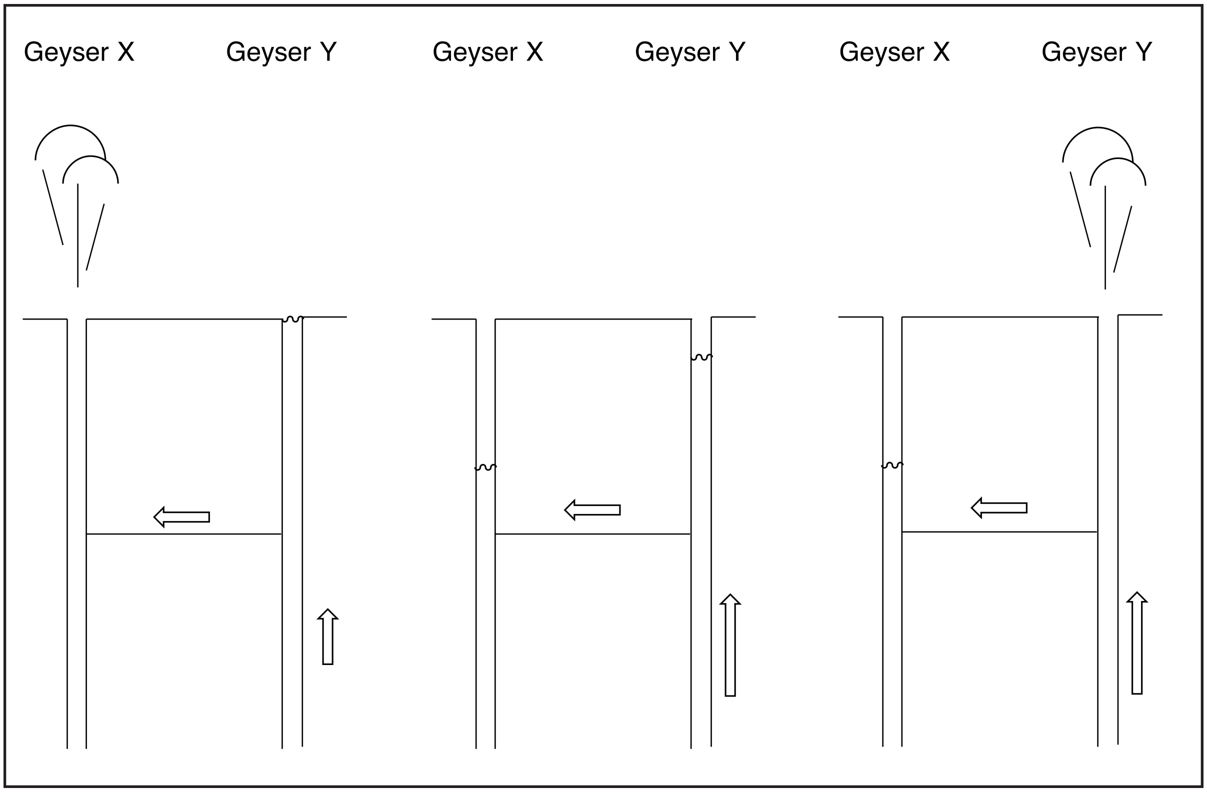

Figure 6: The eruption of Geyser X increases the flow rate into Geyser Y, causing Geyser Y to erupt.

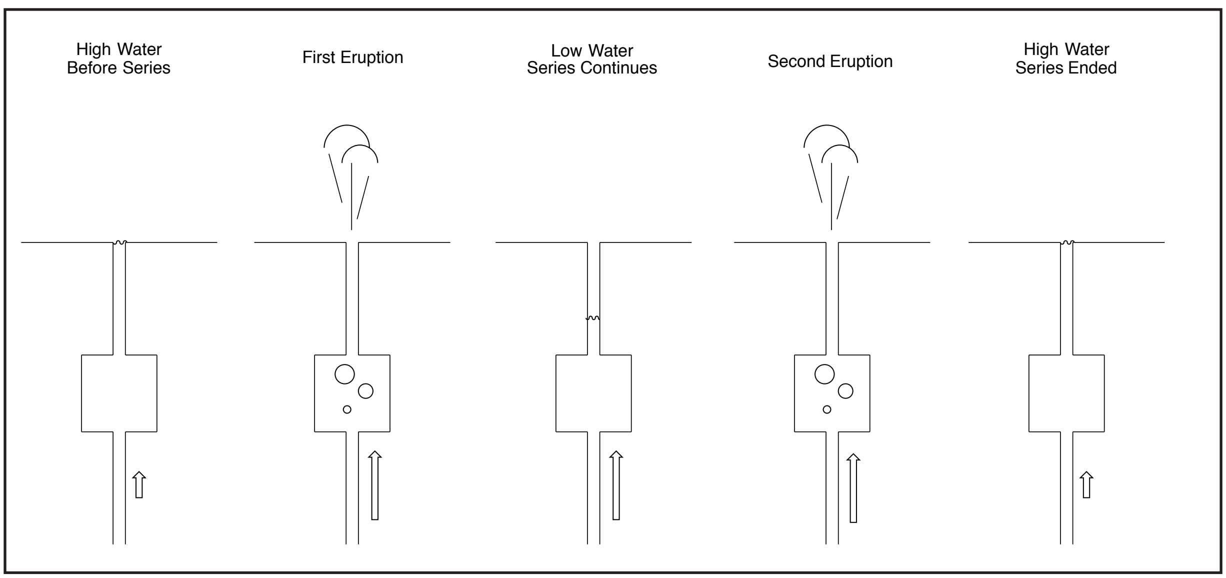

Figure 7: The eruption of the geyser empties the system, increasing the flow rate. Should a second eruption occur before the geyser refills, the process repeats until an eruption fails to occur and the geyser refills.

a deep reservoir that powers the major eruption is increased. Once the deep reservoir is hot enough, the rising water boils as it reaches shallower depths where the hydrostatic pressure is less, initiating the major eruption. *Fig. 8.*

I hypothesize that Atomizer Geyser erupts by this mechanism. At Atomizer, the major eruption begins either during a minor eruption, or immediately afterward, following a short delay. Both events are reconciled using this mechanism. The increased upward flow during and after the minor eruption allows the major eruption to begin during the minor, or immediately after.

A geyser may act upon itself to generate a series

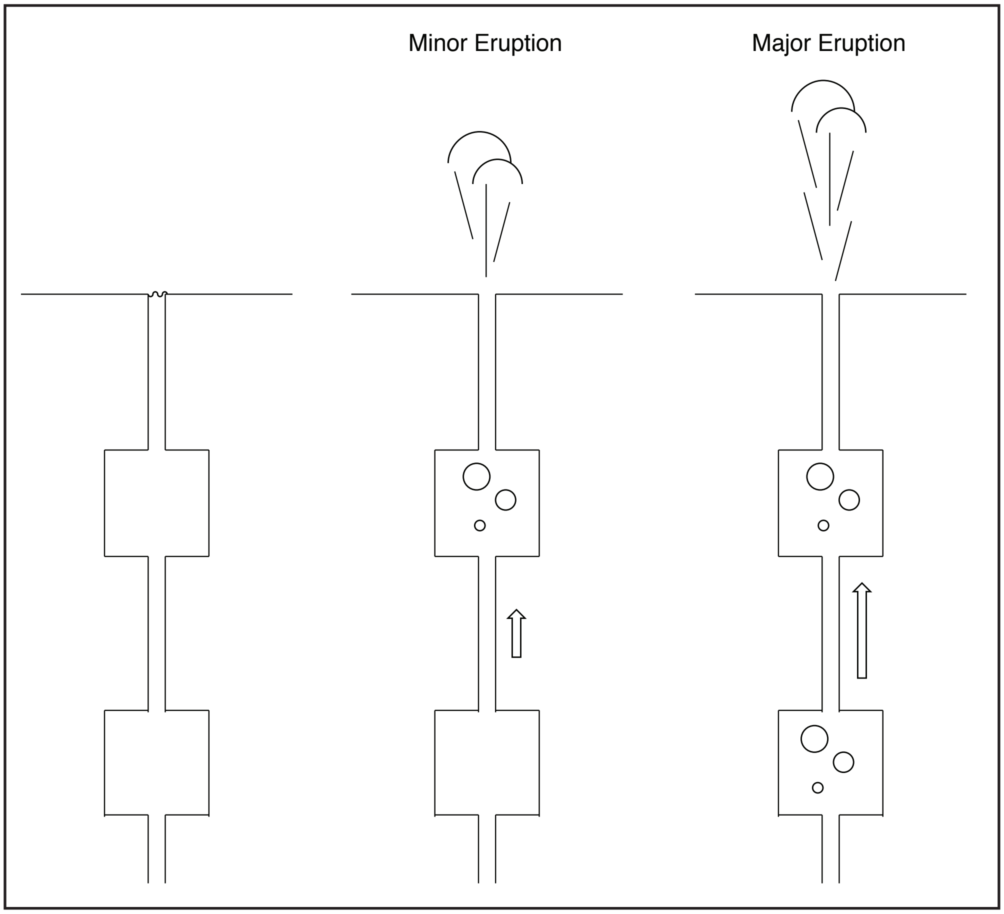

Figure 8: The minor eruption empties the upper part of the geyser, increasing the upward flow from the lower reservoir, initiating a major eruption.

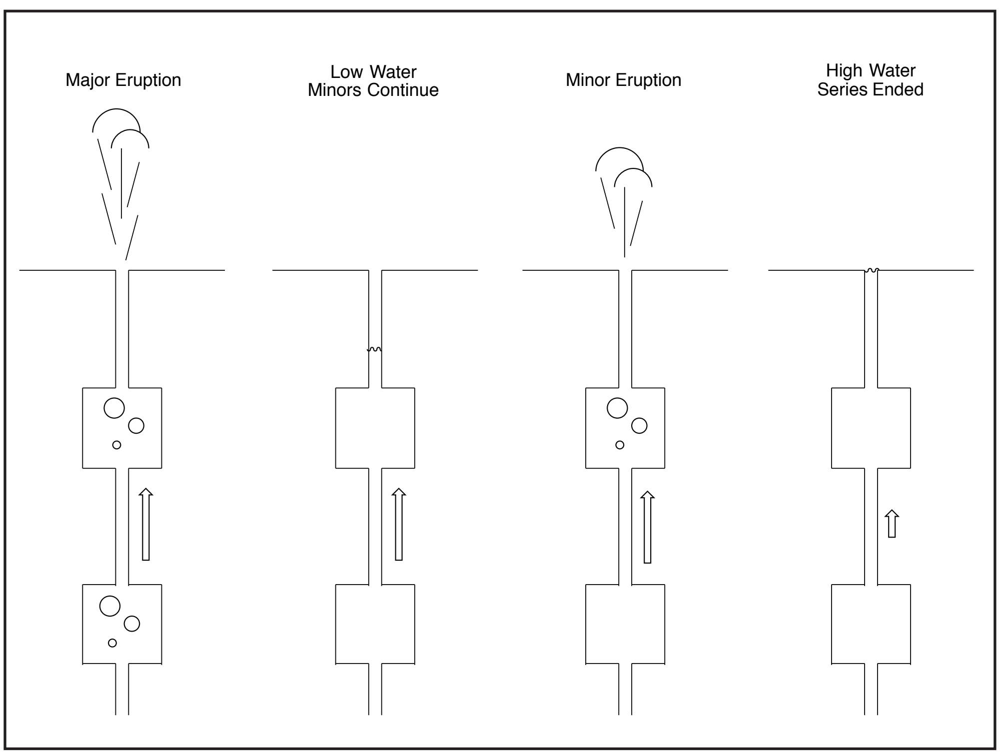

Figure 9: A major eruption empties the geyser. Afterward, the increased upward flow rate causes minor eruptions to occur while the geyser refills.

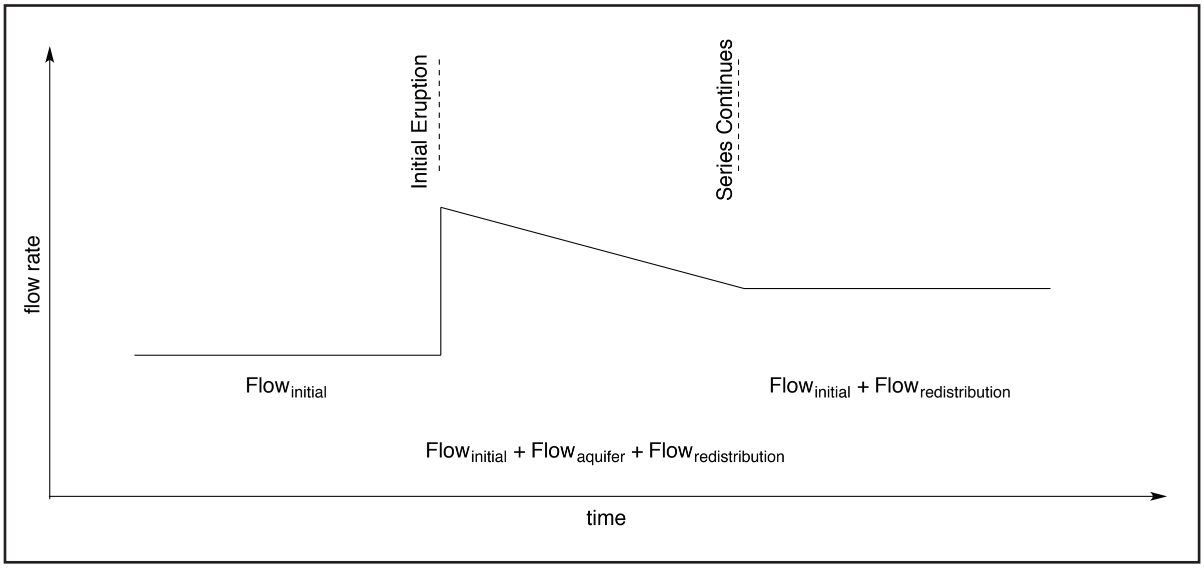

Figure 10: The flow into a geyser increases after the initial eruption. A subsequent series of eruptions occurs while water is released from the hydrothermal aquifer. The series continues.

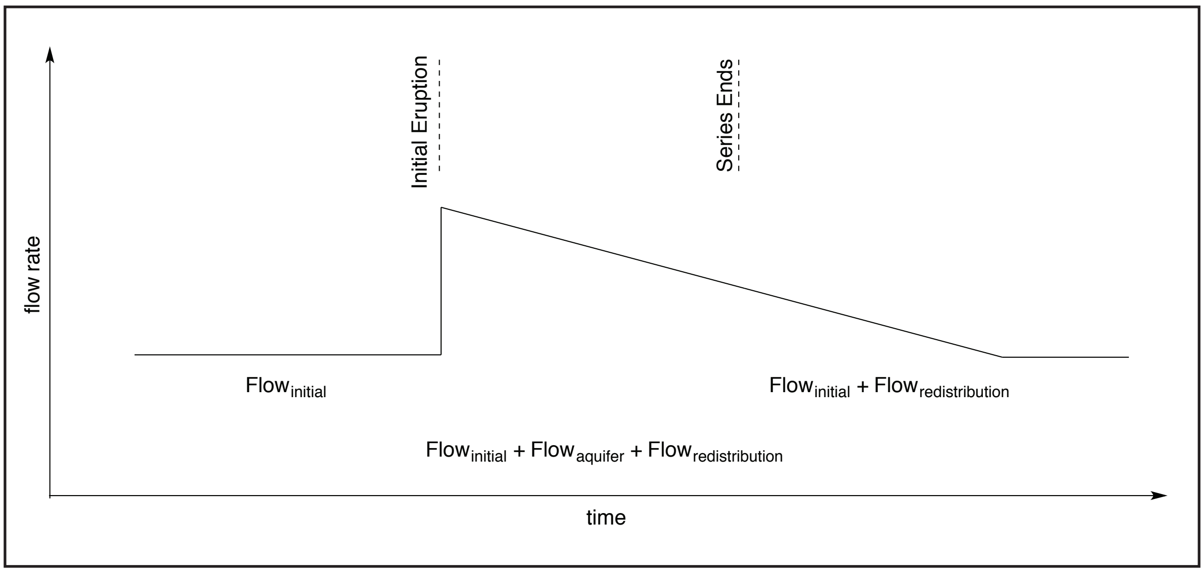

Figure 11: The flow into a geyser increases after the initial eruption. A subsequent series of eruptions occurs while water is released from the hydrothermal aquifer. The series fails to continue because the redistribution of hot water from neighboring thermal features is too small to sustain the series.

of minor eruptions that follows a major eruption. After the major eruption empties the geyser, the flow rate into the geyser is high. Although boiling does not occur in the deep reservoir that generated the major eruption because the energy is depleted there, minor eruptions are sustained within the upper parts of the geyser by high flow rates that persist until the supply of hot water is exhausted, or until the geyser refills. *Fig. 9, previous page.*

Series of eruptions and exchanges of function may be closely related phenomena. Consider a geyser that is empty following an eruption. The flow of hot water into the geyser is increased by redistribution from other vents, and by a flow of water stored in the aquifer surrounding the geyser. If the geyser can erupt only when both sources contribute, then the geyser erupts in a series that lasts only as long as the flow of water stored in the aquifer around the geyser is sustained. If the geyser can erupt in series from the increase due to redistribution alone, then the series persists indefinitely as an exchange of function, and nearby thermal vents are ebbed for

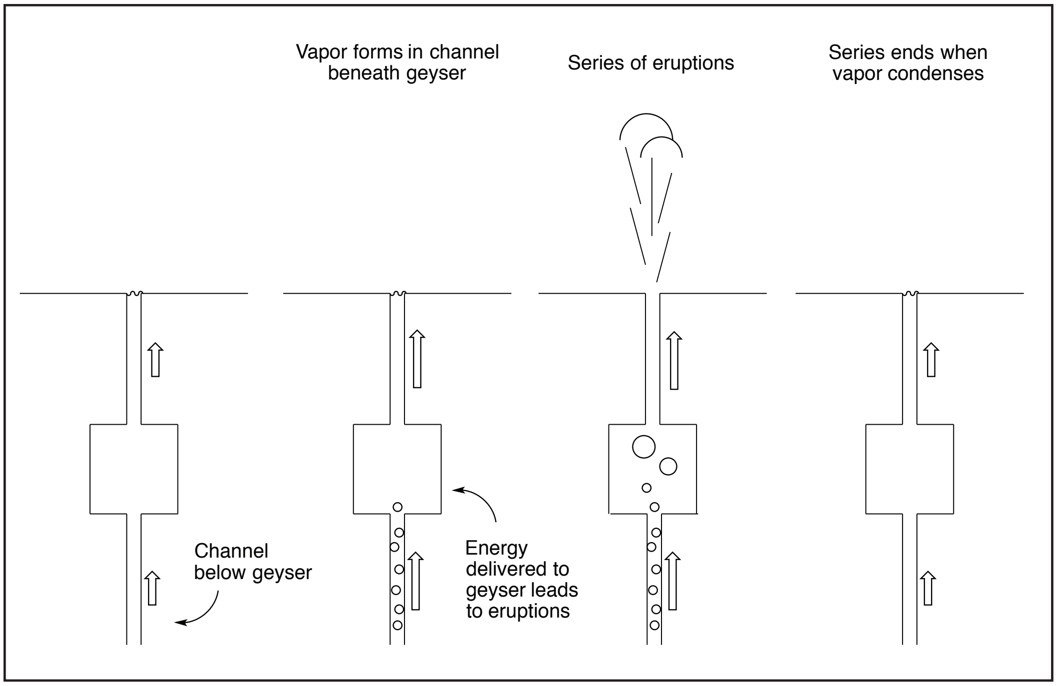

Figure 12: Boiling in a channel below the geyser increases the supply of hot water, increasing the eruptive frequency until the vapor condenses.

the duration of the active phase. *Figs. 10, 11.*

Not all geysers that erupt in series maintain low water levels during a series of eruptions. Rather, water levels are high during the series. The hypothesis of Cross and Keam (2010) can be applied to these examples. When a bubble of water vapor rises in a channel containing liquid water, the pressure below the bubble falls. When this condition develops within a geyser, the flow of hot water into the bottom of the channel increases. Hot water and vapor are delivered to points above the channel. If a geyser draws energy from these parts of the hydrothermal aquifer, eruptions occur frequently. Should the vapor condense, the supply of hot water is diminished and the series ends. Should the vapor form or condense abruptly, the change in the activity of the geyser is also abrupt. I hypothesize that this phenomenon occurred when Baby Daisy Geyser stopped erupting, with no premonitory signs, in 2004 (Taylor 2008). I hypothesize that multiple-burst eruptions of Grand Geyser occur by this mechanism. A subsequent burst may occur as long as the water level remains high within the crater after the previous burst, but becomes impossible once the crater drains. *Fig. 12.*

DISCUSSION

The hypotheses presented in this paper are based on the principles established by Benseman (1965) and White (1967) through direct observation of, and experimentation on, Wainui Geyser and the Geyser Well. Significant changes in the activity of these geysers occurred in response to small changes, of inches to feet, in the overflow elevation. Water level changes of this magnitude are routinely observed in thermal features following an eruption of that feature, or following an eruption of a neighboring geyser. It is therefore reasonable to propose the foregoing hypotheses.

Benseman (1965) and White (1967) discuss how a change in overflow elevation changes the flow within a geyser to cause an eruption, or to increase eruptive frequency. White (1967) proposed that upward motion of water within the casing of the Geyser Well allowed temperatures within the casing to reach boiling. Benseman (1965) demonstrated, more generally, that heat is carried by water, and that the activity of a geyser changes when the flow of water is altered. This is consistent with the foregoing hypotheses.

The problem of a geyser that erupts only in response to an eruption of a neighboring geyser has two possible explanations. The first explanation is that when the water level is lowered by an eruption of the neighboring geyser, it lowers the boiling point at depth, initiating an eruption. This hypothesis is unlikely. Since the water level changes are likely to be only a few inches or a few feet, the change in the boiling point is correspondingly small, requiring that the temperatures be close to boiling. A more likely hypothesis is that removal of water from the upper parts of the geyser causes the upward flow from the deeper, hotter parts of the geyser to increase. Should this movement occur through a long, narrow, vertical channel, the upward movement of the water is substantial. It is sufficient to lower the boiling point significantly. Since eruptions of neighboring geysers are frequently seen, and it is unlikely that in each example the water at depth is very close to the boiling point, this hypothesis is more permissive, and is more likely to be correct.

The hypothesis proposed to explain a geyser that acts upon itself to generate a series of minor eruptions that leads to a major eruption differs from that proposed in Cross (2010). In that model, an eruption of the lower reservoir was initiated when the minor eruption threw out water and lowered the hydrostatic head. However, if the flow rate into the lower reservoir is variable, then decreasing the hydrostatic head increases the flow rate up the channel that connects the lower reservoir to the upper reservoir. This effect is difficult to reproduce in model geysers.

Eruptions of related geysers were discussed by Cross (2008). In geyser systems that erupt from several vents at once, a progression from alternating activity from different vents to concerted activity preceded a major eruption of all the vents. This was interpreted as a progression from surficial boiling above the point at which the vents are connected to boiling below that point. This hypothesis is limited. It cannot explain how an eruption of one geyser may follow that of a neighboring geyser long after an eruption of the neighboring geyser has ended. Instead, I propose that, because the movements of hot water are altered by an eruption of the neighboring geyser, and remain altered until the neighboring geyser refills, they can cause eruptions to take place long after the neighboring geyser has finished erupting.

Exchange of function was described by Marler (1953), but it remains without explanation. The foregoing hypotheses suggest two ways that an exchange of function might occur. A series of eruptions that continues for a long period of time causes nearby features to ebb. Alternatively, persistent boiling beneath one thermal feature increases the supply of hot water to it, and decreases the supply to neighboring thermal features. The second explanation is interesting because the sudden formation or collapse of the vapor correlates with the observed abruptness of exchanges of function. Should the vapor form and condense intermittently, it correlates with the tendency of geysers to erupt at erratic intervals, especially at the beginning and end of an active phase.

CONCLUSION

Hypotheses to explain geysers that erupt in series, have sympathetic eruptions, or exchange function are proposed. These hypotheses are based on observations and experiments performed on the North Island of New Zealand and at Steamboat Springs, Nevada. They potentially explain some aspects of geyser activity for the first time, and they explain other aspects more generally than do previous hypotheses.

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Applying New Evidence to Old Data: The Case for Previously Undocumented Eruptions of Morning Geyser in 2006, 2007, and 2012

Tara Cross

Abstract: Many source materials about Yellowstone's geysers state that Morning Geyser did not erupt between its brief active phase in April 1994 and its reactivation from dormancy in June 2012. This article presents evidence for seven previously undocumented eruptions of Morning Geyser in 2006, 2007, and 2012 based on analysis of Morning's eruption patterns using electronic and visual data from October 2012 through October 2013.

Introduction

According to most published sources, Morning Geyser fell dormant after a brief active phase in April 1994 and did not erupt again until it was seen in June 2012, with the exception of a short "aborted" eruption that took place on July 6, 2006. Although there were reports of other eruptions of Morning in 2006 and 2007, T. Scott Bryan's The Geysers of Yellowstone, Fourth Edition (2008), states that these were probably large eruptions of neighboring Morning's Thief Geyser. Another report of Morning in February 2012 was assumed by geyser gazers to be Morning's Thief as well. When Morning had a full eruption that was witnessed by a geyser gazer on June 20, 2012, it was generally believed that this was the first such eruption to take place since 1994. Indeed, the Geyser Observation and Study Association (GOSA)'s bimonthly newsletter, *The Geyser Gazer Sput*, printed several articles citing an 18-year gap between full eruptions of Morning, including my own geyser summary in June 2012 (Cross 2012) and Lynn Stephens' article (2013) discussing dual eruptions of Fountain and Morning in 2012 and 2013. Local news coverage in 2012 also stated that it had been 18 years since the last activity of Morning, likely based on information from Bryan and from GOSA. In this article I will present evidence for seven previously undocumented eruptions of Morning Geyser, including confirmation of the reports from 2006, 2007, and early 2012.

A Note About Limitations of Analysis

I have used a combination of visual reports and electronic data to piece together what is known about Morning's activity in 2006, 2007, and early 2012 using information from later in 2012 and 2013 as a guide. While I have attempted to be as thorough as possible, both sources of information have limitations.

Because the Fountain Group is located in the Lower Geyser Basin, visual reports are not as readily available as they might be for the geysers near Old Faithful, even during the busier months of the year. During the winter, observations of the Fountain area tend to be limited to short visits by guided tour groups. An additional complicating factor for visual reports has been the potential for misinterpretation because of the activity of neighboring Morning's Thief Geyser, described below. This analysis shows that several reports assumed to be Morning's Thief were actually Morning, based on additional supporting evidence.

While electronic data gives a more complete picture of Fountain's activity, it cannot answer every question. Morning eruptions themselves do not appear on Fountain's logger, leaving much to inference. In addition, intense focus on the Fountain Group in 2013 revealed that Fountain's logger "missed" a few eruptions here and there, and electronic durations, while usually reliable, have not always been close to visual durations. There were also occasional periods of faulty logger data that required careful interpretation, with sometimes inconclusive results. Finally, the electronic data was not continuous, with gaps of

1.
The June 20, 2012 eruption of Morning was the first to be seen by a geyser gazer, but based on visual evidence from the Fountain Group and later information about Morning's behavior patterns, it is very likely that Morning had already erupted at least twice, on June 13 and June 18, 2012.

Morning Geyser in a solo eruption on May 24, 2013. Photo by Bill Warnock.

days or weeks making a complete analysis impossible. However, since the logger data closely matched visual data most of the time, I believe it can be very useful in confirming the activity of Fountain at the times when eruptions of Morning were reported.

Fountain-Morning Dual Eruption Activity Patterns

Since six of the seven Morning eruptions discussed in this article were dual eruptions with Fountain and the seventh was a solo following an inferred dual, my analysis relies heavily on established patterns for such events. In her article discussing the known dual eruptions of Fountain and Morning through September 2013, Stephens (2013) uses three conditions that establish a concerted (or "dual") eruption of Fountain and Morning:

1) The two geysers must both erupt at the same time.
2) These eruptions must be roughly the same size as a typical solo eruption of each geyser.
3) Both geysers must erupt for a typical length or longer.

Prior to 2012, only six historical instances of duals were known—one at the time of the 1959 Hebgen Lake Earthquake, and five during Morning's active phases in July and August of 1991. Based on visual observations in 1991, there was a clear pattern of activity when the two geysers erupted together: Fountain started to erupt, followed within a minute or two by Morning; then, after a duration in the range of 20 to 40 minutes, Morning stopped erupting while Fountain continued on. The shortest Fountain duration of these was 82 minutes, and the longest was 140 minutes (Stephens 1992a and 1992b). The duals witnessed in 2012 and 2013 continued to follow this pattern. Morning durations ranged from 18 to 33 minutes and Fountain durations ranged from 63.5 to 132 minutes, except for one very short dual during which Morning lasted only ~10 minutes and Fountain continued for only ~45 minutes.

In addition to supplying supporting visual data on dual eruptions of Fountain and Morning, the 2012-2013 active phase revealed a previously unknown behavior: a concerted eruption of Fountain, Morning, and Morning's Thief, called a "trifecta." During the four witnessed trifectas, Morning's duration was 56 to 68 minutes, Morning's Thief lasted 56 to 69 minutes, and Fountain continued on for a duration of 166 to 189 minutes. The data for duals and trifectas is summarized in Appendix A.

Based on the visual data, the following patterns have remained consistent for dual eruptions of Fountain and Morning:

1) Fountain started first, followed by Morning within two minutes.
2) Morning's eruption continued for a typical duration of 20 to 38 minutes.
3) Fountain's eruption continued after Morning finished for a much longer-than-normal duration of 60 to 140 minutes.
4) If the duration of Fountain extended past 150 minutes, it was a likely candidate for a trifecta.

Since Fountain's duration during a dual was much longer than normal, it might seem intuitive that Fountain (and also Morning) needed extra "recharge" time afterward. Although a loose relationship has been known to exist between Fountain's duration and the succeeding interval, duals in 2012 and 2013 did not seem to exhaust the system. If the next event to occur was a normal Fountain eruption, the Fountain interval was no longer than normal, and could be as short as 5 hours 37 minutes (this follow-up eruption was sometimes considerably shorter than the usual duration of 30 to 35 minutes, however). Even in the case of a trifecta, the succeeding Fountain interval was close to 9 hours in two known instances. If the next event to occur after a dual was a Morning solo eruption, the Morning interval could be as short as 4 hours 52 minutes, and the Fountain interval was then abnormally long, ranging from 12.5 to 19 hours. A summary of follow-up events after duals is provided in Appendix B.

Based on what is known about duals, then, the following things can be inferred when examining the electronic data for Fountain:

1) Fountain durations as determined by electronic logger were accurate enough to use for inferring dual eruptions with Morning.
2) Fountain durations during a dual ranged from as short as ~45 minutes to as long as 140 minutes; all dual inferences described in this article are based on Fountain durations of at least 90 minutes.
3) A relatively normal interval for Fountain following the long-duration eruption implies that it was the next event to occur after the dual.
4) An abnormally long interval for Fountain following the long-duration eruption means that it is possible Morning followed the dual with a solo eruption, a circumstance that occurred at least six times in 2012 and 2013.

A complete list of all known duals, including the six proposed in this article and four from 2012 and 2013 that Stephens (2013) did not list, is provided in Appendix A. Further description and analysis of Morning's activity from June 2012 through October 2013 calls for a separate article and is not attempted here.

Fountain and Morning Between 1994 and 2006: A Brief Overview

After a week-long active phase in early April 1994, Morning Geyser fell dormant for more than a decade. The group's activity was dominated by Fountain; its intervals generally ranged from 6 to 10 hours for the rest of the 1990s, and shortened to 3 to 8 hours in the early 2000s. Durations typically ranged from 25 to 40 minutes, roughly in proportion with intervals. While there were no indications of activity from Morning during this time, eruptions of Morning's Thief Geyser gradually became more common starting in the late 1990s. Located in a smaller crater immediately northeast of Morning's pool, Morning's Thief had been infrequently active prior to 1999, and earned its name by appearing at times when Morning seemed to have potential to erupt. This relationship did not seem to exist as Morning's Thief became active independent of Morning, however. Its eruptions occurred near the time that Fountain was expected, either shortly before or immediately after Fountain started.

By the early 2000s, boiling eruptions to less than 10 feet high had been replaced with short series of bursts that could reach 30 feet high. Over time, the size and strength of Morning's Thief's eruptions continued to grow, and by 2006 they could be more than 50 feet high. This action was impressive in its

Morning Geyser on June 21, 2012. Photo by Carol Beverly.

One of Morning Geyser's tradenark blue bubbles. May 28, 2013. Photo by Pat Snyder.

own right, to the extent that it was sometimes understandably mistaken for bursting from Morning Geyser. This resulted in numerous visitor reports of Morning eruptions that were shown to be Morning's Thief, either by examining photographic evidence or matching up a description of the eruption with the nature of Morning's Thief's behavior rather than that of Morning's.

An example of this was the report of Morning on January 5, 2006. Several park guides reported that Morning erupted along with Fountain that day, but given the timing of the eruption—near the start of a Fountain eruption—and a short duration, it seemed most likely that they had seen Morning's Thief. This was confirmed the next day by geyser gazer Mike Keller, who found "deep snow and undisturbed gravel up to the rim of Morning" (Keller 2006a) when he checked on Morning. He further stated that "the main crater of Morning did not erupt and has not since April of 1994." Though the January 5 report was a false alarm, this status was about to change.

Potential Additional Morning Eruption Dates

Based on the analysis I present here, I believe that strong evidence exists for a total of seven additional eruptions of Morning Geyser that were previously viewed with skepticism or undocumented. Six of the seven likely eruptions were dual eruptions with Fountain Geyser, which is significant because it was previously believed that only six such events had occurred prior to October 2012.

The eruptions I discuss are as follows:

1) March 2, 2006: a dual with Fountain based on electronic data.
2) March 2, 2006: a solo eruption based on visual and electronic evidence.
3) March 12, 2006: a dual with Fountain based on electronic data.
4) July 6, 2006: a dual with Fountain based on visual and electronic evidence.
5) April 18, 2007: a dual with Fountain based on electronic data.
6) May 13, 2007: a dual with Fountain based on visual and electronic evidence.
7) February 6, 2012: a dual with Fountain based on visual and electronic evidence.

Fountain Geyser Electronic Data

The electronic data used in this analysis for January 2006 through August 2011 was collected under research permit via the Geology Department at the Yellowstone Center for Resources. Analysis of the raw data was performed by Ralph Taylor and made available on the Geyser Observation and Study As-

Table 1. Electronic Log for Fountain Geyser, March 1-4, 2006

Date	Time	Duration	Interval
March 1	1858	41m	--
March 2	0622	148m	11h24m
March 3	0406	34m	21h44m
March 3	0809	25m	4h03m
March 3	1705	29m	8h56m
March 4	0104	31m	7h59m
March 4	1002	29m	8h58m
March 4	1925	29m	9h23m

Source: Taylor (2011).

sociation website, gosa.org. During the summer months of 2006 and 2007, visual observations confirmed Taylor's methods for determining Fountain's start times and durations, usually accurate within 2 minutes. Three gaps in data should be noted: February 2, 2006 to March 1, 2006; March 30, 2006 to April 21, 2006; and January 15, 2007 to March 21, 2007 (Taylor 2011). It is possible that eruptions of Morning could have taken place during these gaps.

Data from June 2007 through January 2012 did not seem to show any potential dual eruptions of Fountain and Morning based on a long Fountain duration. While it is possible that Morning could have erupted during this time period, no convincing visual or electronic evidence can be offered. Also, the following sizable gaps should be noted: January 7 to February 28, 2008, February 23 to March 1, 2009, April 15 to May 29, 2009 (Taylor 2011), and August 28 to November 22, 2011 (GeyserTimes).

The electronic data used for 2012 and 2013 was collected by the Geology Department at the Yellowstone Center for Resources and analyzed by Will Boekel and Jake Young for GeyserTimes.org. Their methods were similar to those used by Ralph Taylor, but several periods of faulty data required additional work and resulted in some estimated durations. With a few notable exceptions, this data was corroborated by visual observations during Morning's active phase. Appendix A relies heavily on this data, but this article discusses only the February 6 dual eruption in detail. A sizable break in the data occurred from April 4 to April 19, 2013 (GeyserTimes).

March 2, 2006: 0622 (approx., dual with Fountain) and 1927 (solo eruption)

The fourth edition of *The Geysers of Yellowstone* (Bryan 2008, p. 224) includes the following note: "Morning was also said to erupt on March 2, 2006, and May 13, 2007, when play 100 feet high was reported, but it is likely that those eruptions were actually extraordinarily powerful play by 'Morning's Thief.'" It is likely that this determination was made from entries in the Old Faithful Visitor Center (OFVC) logbook, where the reports are entered as Morning's Thief. However, after revisiting the reports and electronic data for March 2, I am confident that Morning in fact erupted twice that day: a dual eruption with Fountain at 0622e and a solo eruption about 13 hours later that was seen by a tour guide and two visitors.

Table 1 shows the electronic data for March 1-4, 2006. The Fountain eruption starting at 0622e on March 2 lasted 148 minutes and can therefore be interpreted as a likely dual eruption with Morning. This establishes that the solo eruption of Morning reported at 1927 on March 2 was a follow-up event to the dual. This interpretation is supported by the data in Appendix B, which shows six known instances of a Morning solo eruption following a dual eruption of Fountain and Morning in 2012 and 2013. While others may have been missed, the available data confirms the hours after a dual as a time when Morning may follow with a solo eruption.

The visual evidence for a Morning solo on March 2 is equally convincing. Xanterra snowcoach guide Russel Homen and two visitors from Livingston, Montana, were on an evening tour when they saw an eruption they described as "behind Fountain," that lasted about 25 minutes and consisted of a series of bursts that made "thumping" and "popping" sounds and reached an estimated 80 feet high and 50 feet wide (Lang 2006a, 2006b). David Goldberg spoke with Homen and confirmed that the eruption happened at about 1930 (Goldberg 2006), corroborating a logbook entry at 1927 based on a report by the visitors from Livingston that also noted that Fountain was empty and Clepsydra was in eruption until at least 10 minutes after Morning's end. While darkness and steam did limit visibility, the overall description of the eruption—the duration, the nature of the bursts, the sound, and the lack of activity by Fountain—is consistent with a solo eruption of Morning. Unfortunately, the OFVC logbook entry

Table 2. Electronic Log for Fountain Geyser, March 9-14, 2006

Date	Time	Duration	Interval
March 9	0345	27m	5h59m
March 9	0910	24m	5h25m
March 9	1454	27m	5h44m
March 9	2053	29m	5h59m
March 10	0241	32m	5h48m
March 10	0930	41m	6h49m
March 10	1911	38m	9h41m
March 11	0348	35m	8h37m
March 11	1244	34m	8h56m
March 11	2235	41m	9h51m
March 12	0901	111m	10h26m
March 13	0454	31m	19h53m
March 13	1837	32m	13h43m
March 14	0423	30m	9h46m
March 14	1314	32m	8h51m
March 14	2045	33m	7h31m

Source: Taylor (2011).

Table 3. Electronic Log for Fountain Geyser, July 4-8, 2006

Date	Time	Duration	Interval
July 4	0225	36m	6h58m
July 4	0952	32m	7h27m
July 4	1603	34m	6h11m
July 4	2240	32m	6h37m
July 5	0548	34m	7h08m
July 5	1336	32m	7h48m
July 5	2034	38m	6h58m
July 6	0549	102m	9h15m
July 6	1349	26m	8h00m
July 6	2126	30m	7h37m
July 7	0937	31m	12h11m
July 7	1906	33m	9h29m
July 8	0223	33m	7h17m
July 8	1156	33m	9h33m
July 8	2015	36m	8h19m

Source: Taylor (2011).

was amended afterward to Morning's Thief rather than Morning.

No one was able to check on Morning until Mike Keller inspected the area on March 18. However, Keller's assessment was unequivocal: he stated that "after visiting the area today is [sic] was very evident that Morning had indeed erupted in the recent past. The large snow mound that was up to its crater is gone, the sinter basin and runoff channel has been scoured clean, and vegetation in the area has been killed recently by runoff. None of this was evident when Morning was reported in mid-January" (Keller 2006c). This confirmation of the March 2 report, though entered in the OFVC logbook for March 18, 2006, unfortunately seems to have been lost in the shuffle, along with David Goldberg's (2006) description in the geyser activity summary in the April issue of The Geyser Gazer Sput and Ralph Taylor's (2006) comments on the electronic data findings in the June issue.

Whether geyser gazers simply forgot that this eruption occurred, or possibly confused it with the January 5, 2006, report that was most likely Morning's Thief, it is regrettable that the OFVC logbook entry for March 2 was not corrected and still lists the 1927 eruption report as Morning's Thief.

March 12, 2006: 0901 (approx., inferred dual with Fountain)

The Fountain data shown in Table 2 for March 9-14, 2006, reveals another dual eruption of Morning and Fountain on March 12, based on the 111-minute duration of Fountain's 0901e eruption. While no visual observations were available for March 12, it is interesting to note the interval of nearly 20 hours following the dual, which could indicate another follow-up solo eruption of Morning.

July 6, 2006: 0549 (approx., dual with Fountain)

On July 6, 2006, I was at Fountain with several other geyser gazers when water domed up in Morning's pool and it had a single burst to 30 feet followed by some boiling. This "false start" or "aborted eruption" started at 1342 but lasted only 90 seconds, and Fountain started by itself five minutes later. This event was well-publicized when it happened and does receive mention in Bryan (2008) and Stephens (2013), though it is not counted as a full eruption (nor should it, in my view, though it did start ex-

Aborted Morning Geyser eruption on July 6, 2006, at 1342. Photo by Tara Cross.

actly like the full eruptions I saw later on). However, there was still some confusion about the events of July 6.

At 0624 on July 6, Stephen Eide saw Fountain in eruption as he was driving southbound on the road and decided to watch the remainder of the eruption from up close. The eruption did not end until 0733, 69 minutes after his first observation. In retrospect, the electronic data in Table 3 shows that Eide actually saw the latter part of a dual, after Morning's eruption had ended. Fountain started at 0549e, meaning that even a 30-minute Morning would have been finished by 0624. Meanwhile, his end time of 0733 corroborates the electronic duration of 1h42m. The Geysers of Yellowstone (Bryan 2008, p. 224) gives a duration of 69 minutes for Fountain, but it should have been stated as at least 69 minutes. A dual would explain the long duration and the aborted activity of Morning at the time that Fountain would have been expected on a "normal" interval.

An event occurred during the 2012-2013 active phase of Morning that supports this interpretation. On March 8, 2013, a tour guide reported that a solo eruption of Morning was in progress at 1046 and continued for another 12 minutes. Five hours later, geyser gazer Bill Warnock was in the area when he saw a brief eruption of Morning at 1547 that consisted of a single burst to about 20 feet and some roiling for a duration of about 30 seconds. Fountain started eight minutes later at 1555, accompanied by splashes in Morning and a series of eruptions by Morning's Thief. Though the details are somewhat different, this was another instance of a short (aborted) eruption of Morning occurring at the expected time of Fountain. The subsequent start of a normal Fountain eruption was also similar.

April 18, 2007: 0934 (approx., inferred dual with Fountain)

The Fountain electronic data in Table 4 reveals another probable dual eruption with Morning at 0934e on April 18, 2007, with a duration of 149 minutes. Since Yellowstone did not open to the public until April 20, there are no visual reports for this time, but I have included it on this list because of the reliability of other long Fountain durations as a basis of inferring duals with Morning.

Table 4. Electronic Log for Fountain Geyser, April 16-20, 2007

Date	Time	Duration	Interval
April 16	0302	38m	8h12m
April 16	1221	35m	9h19m
April 16	2204	35m	9h43m
April 17	0644	36m	8h40m
April 17	1626	33m	9h42m
April 18	0016	43m	7h50m
April 18	0934	149m	9h18m
April 18	2039	27m	11h05m
April 19	1317	26m	16h38m
April 19	2210	29m	8h53m
April 20	0601	31m	7h51m
April 20	1401	30m	8h00m
April 20	2142	32m	7h41m

Source: Taylor (2011).

Table 5. Electronic Log for Fountain Geyser, May 10-15, 2007

Date	Time	Duration	Interval
May 10	0220	35m	8h24m
May 10	1036	31m	8h16m
May 10	1917	33m	8h41m
May 11	0243	36m	7h26m
May 11	1116	32m	8h33m
May 11	1949	33m	8h33m
May 12	0244	36m	6h55m
May 12	1237	31m	9h53m
May 12	2030	40m	7h53m
May 13	0937	93m	13h07m
May 13	1943	27m	10h06m
May 14	1351	31m	9h15m
May 14	2152	32m	8h01m
May 15	0633	31m	8h41m
May 15	1451	30m	8h18m
May 15	2156	33m	7h05m

Source: Taylor (2011).

May 13, 2007: 0937 (approx., inferred dual with Fountain)

A second dual eruption occurred a few weeks later. Table 5 shows that Fountain's eruption at 0937e on May 13, 2007, lasted 93 minutes. The initial eruption report came from Brad Barth, an experienced tour guide working out of West Yellowstone. He first saw Fountain in eruption from the road at 1000ie and then described bursts coming from Morning when he arrived at Fountain on the boardwalk. According to Scott Bryan's message to the geyser listserv, Barth described the eruption as "definitely from the pool of Morning and not Morning's Thief," with bursts reaching at least 80 feet high. A very important detail in this report was that Fountain was throwing rocks during the eruption, which had been seen in prior years when Morning had been active and was seen again on June 13, 2012, after what was probably the first solo eruption of Morning's 2012-2013 active phase.

The visual and electronic evidence, therefore, present a convincing case for a dual eruption of Fountain and Morning on May 13, so it is again regrettable that someone later changed this report to Morning's Thief in the OFVC logbook and added the comment "per Brad Barth originally reported as Morning."

A final note of interest about the dual eruptions of Fountain and Morning in 2006 and 2007 is that all five of them occurred after a longer-than-normal Fountain eruption lasting between 38 and 43 minutes. Though it was not reliable as an indicator, this would become a noteworthy trend during the 2012-2013 active phase as well.

February 6, 2012: 1444 ns (dual with Fountain)

After May 13, 2007, the first visual report with potential to be Morning rather than Morning's Thief came nearly five years later on February 6, 2012. Several visitors and a tour guide reported that Morning erupted along with Fountain that afternoon and provided a photo that was forwarded to the geyser listserv (Monteith 2012).. This eruption was also determined by gazers to be Morning's Thief, but the electronic data (Table 6) confirms that the Fountain at 1441e on February 6 lasted 112 minutes and was therefore likely a dual eruption with Morning. The photograph has a time stamp of 4:44 pm, which adjusted to Mountain Standard Time would be 1444 and therefore very likely within the first few minutes of the eruption.

Although the photo provided by the park visitors was taken in cold, steamy conditions with a strong wind from the north, it is clear that the burst

Table 6. Electronic Log for Fountain Geyser, February 4-8, 2012

Date	Time	Duration	Interval
February 4	0150	30m	8h03m
February 4	0932	30m	7h42m
February 4	1821	31m	8h49m
February 5	0237	31m	8h16m
February 5	1054	31m	8h17m
February 5	1953	33m	8h59m
February 6	0531	31m	9h38m
February 6	1441	112m	9h10m
February 6	2316	36m	8h35m
February 7	0548	26m	6h32m
February 7	1509	27m	9h21m
February 8	0021	28m	9h12m
February 8	0855	30m	8h34m
February 8	1755	29m	9h00m

Source: GeyserTimes.

shown in the photo is quite voluminous, with two separate spikes and a total width much greater than even the largest bursts of Morning's Thief. No water jets can be seen coming from Fountain, but the large amount of steam suggests that it was also erupting. Though a careful examination of the photo shows no snow melt on the north side of Morning in the photograph, I infer that Morning had not yet begun to overflow in that direction because the eruption had only been underway for two or three minutes. The OFVC logbook lists Fountain at 1503ie on February 6, 2012, implying that Morning may have been finished erupting by that time, approximately 22 minutes into Fountain. I was not able to track down the person making this report, but it is also possible that if the observation was made from the road, it might have been too steamy to tell if Morning was erupting or not. If Morning was already finished, a duration of 21 minutes would have been on the short end of the "normal" range for Morning durations during duals (see Appendix A).

In summary, all of the available visual and electronic evidence supports the conclusion that there was a dual eruption of Fountain and Morning on the afternoon of February 6, 2012. I have included the eruption in this analysis, rather than a more detailed discussion of Morning's 2012-2013 active phase, because Morning's solo activity likely began on June 13, 2012, more than four months later.

Conclusion

I was a fortunate witness to eight eruptions of Morning in 2012 and 2013, including three dual eruptions with Fountain and one trifecta. In October 2013, I read Stephens (2013) with interest, and found the examination of Fountain's electronic data to infer potential duals that were not seen visually to be particularly intriguing. I wondered if similar methods could be used to help explain what may have happened on July 6, 2006, when I saw an aborted eruption of Morning. The discovery of a probable dual prior to that event prompted me to investigate whether other duals had been missed, and this article is a result of that research.

The confirmation of tour guide and visitor reports of Morning that were previously thought to be Morning's Thief is an important example of how changes in geyser behavior can catch even experienced observers off guard. Those who witnessed Morning's three-week active phase in August of 1991 or its shorter active phases in May 1991 and April 1994 may have been expecting Fountain to stop erupting if Morning was active. But we knew from several historical active phases and the dual eruptions on July 4 and 5, 1991, that Morning could erupt without causing Fountain to stop. Those who knew how rare dual eruptions of Fountain and Morning have been historically were understandably skeptical that one would occur by itself without many obvious indicators or follow-up activity, but the dual reports all follow known patterns for dual eruptions that were already well documented and continued to hold true during Morning's 2012-2013 active phase. Those who knew Fountain's tendency to have longer intervals after longer durations might be surprised that a dual eruption could be followed by a normal Fountain interval—and those who saw how much energy was expended by both geysers during a dual might be surprised that Morning could follow up with a solo eruption—but these were the two most likely outcomes after a dual in 2012 and 2013.

I hope that this study will illuminate the patterns that were most helpful in interpreting Fountain's electronic data and show how later findings can help make sense out of reports that may have

Fountain Geyser, left, in a Trifecta eruption with Morning Geyser, center, and Morning's Thief, far right, on August 2, 2013. Photo by Bill Warnock.

seemed unusual at first. I was among the many geyser gazers who forgot about the confirmed Morning report on March 2, 2006, and when the electronic data was made available for 2006 and 2007 I didn't think to look at it more closely until many years later. This turned into a fascinating case study in how previous assumptions can and should be questioned when additional evidence becomes available.

In conclusion, a more detailed examination of Morning's 2012-2013 active phase is an obvious area for future study which I hope to undertake using what I have already learned. It is impossible to know when Morning might erupt next or how that activity might manifest itself, but we now have more data to help interpret its behavior when it does.

Acknowledgments

This article was possible because of the exceptional efforts of many other geyser gazers, park guides, and National Park Service staff. With thanks to all who contributed observations of Fountain and Morning, I owe special gratitude to Lynn Stephens, whose work transcribing the OFVC logbooks was important for this project and whose original analysis of dual eruptions of Fountain and Morning inspired and informed this article. Brad Barth, Maureen Edgerton, Stephen Eide, Jim Holstein, Russel Homen, Mike Keller, Karen Low, Lynn Stephens, and Bill Warnock provided visual observations that were crucial to this analysis. Thank you to the National Park Service for facilitating the electronic monitoring program and to Ralph Taylor, Will Boekel, and Jake Young for their considerable time and effort analyzing electronic data and maintaining updates on gosa.org and GeyserTimes.org. Finally, M.A. Bellingham, Jeff Cross, Maureen Edgerton, Micah Kipple, and Mara Reed provided helpful feedback that improved this article.

A Fountain Geyser/ Morning Geyser dual eruption on June 5, 2013. Photo by Bill Warnock.

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Appendix A. Observed and Inferred Dual Eruptions of Fountain and Morning Geysers

This list supplements Stephens (2013) with additional eruptions discovered in the process of researching this article.

ie – in eruption; **ns** – near start

e – electronic time

MT – Morning's Thief

*Dual dates not included in Stephens (2013)

Date	Fountain (dur)	Morning (dur)	Notes
8/17-18/1959	Triggered by Hebgen Lake Earthquake; see Stephens (2013) for details.		
7/4/1991	1440 (95m)	1442 (31m)	
7/5/1991	1343 (82m)	1345 (21m)	
8/9/1991	1923 (122m)	1924 (38.5m)	
8/28/1991	1853 (140m)	1853 (36m)	
8/29/1991	1214 (98m)	1215 (27m25s)	
3/2/2006*	0622e (148m)	inferred	Morning solo 13 hours later
3/12/2006*	0901e (111m)	inferred	
7/6/2006*	0549e (102m)	inferred	Visual confirms Fountain end time
4/18/2007*	0934e (149m)	inferred	
5/13/2007*	0937e (93m)	1000ie	Visual confirms dual
2/6/2012*	1441e (112m)	1444ns	Visual confirms dual
10/22/2012*	0002e (165m)	inferred	Possible trifecta (Note 1)
10/30/2012	0849e (130m)	0858ie (~38m)	Visual confirms dual
11/5/2012	2121e (~132m)	inferred	Logger analysis by J. Young
11/19/2012	0350e (122m)	inferred	
11/25/2012	0302e (125m)	inferred	
12/5/2012	1208e (105m)	inferred	
12/16/2012	0108e (120m)	inferred	
12/21/2012	1658e (118m)	inferred	Confirmed by snowmelt
12/25/2012	1958e (155m)	inferred	Possible trifecta; confirmed by melt
1/3/2013	2154e (228m)	inferred	Probable trifecta
1/12/2013	1638e (228m)	inferred	Probable trifecta
1/23/2013	1127e (128m)	inferred	
1/28/2013	2241e (205m)	inferred	Probable trifecta
3/6/2013*	0711e (58m)	inferred	Note 2
3/21/2013	0834e (112m)	inferred	
5/2/2013	0248e (114m)	inferred	
5/2/2013	2348e (79m)	inferred	
5/3/2013	1602 (69m)	1602 (24m)	
6/5/2013	1744 (93m)	1744 (33m)	
6/13/2013	1630 (189m)	1632 (68m)	Trifecta; MT 1631 (d=69m)
6/24/2013	1446 (94m)	1446 (32m)	

Appendix A. (Continued)

Date	Fountain (dur)	Morning (dur)	Notes
7/2/2013*	0109e (96m)	inferred	
7/7/2013	1006 (109m)	1007 (33m)	
7/16/2013	1720 (82m)	1721 (21m)	
7/22/2013	0910 (102m)	0911 (31m)	
7/23/2013	1846 (63.5m)	1846 (20m25s)	
7/28/2013	0243 (96m)	0244 (28m)	
8/2/2013	0810 (173m)	0812 (61m)	Trifecta; MT 0813 (d=60m)
8/9/2013	1634 (70m)	1635 (18m)	
8/10/2013	0952ns (~45m)	0952ns (~10m)	Note 3
8/16/2013	0728 (99m)	0728 (30m)	
8/24/2013	0959 (166m)	1000 (58m)	Trifecta; MT 1002 (d=56m)
9/3/2013	0057 (176m)	0058 (56m)	Trifecta; MT 0058 (d=56m)
10/29/2013*	0055e (101m)	inferred	

Note 1: The durations of the four observed trifectas in 2013 ranged from 166 to 189 minutes, while the longest visual duration for a dual historically was 140 minutes (August 28, 1991). While this would imply that the three electronic durations exceeding 200 minutes also represent trifectas (listed here as "probable"), the durations of 155 minutes on December 25, 2012 and 165 minutes on October 22, 2012 are less certain, especially considering the electronic durations of 148 and 149 minutes from March 2, 2006 and April 18, 2007, respectively. While it seems likely that the 155- and 165-minute durations were trifectas, I have listed them as "possible" in the absence of visual confirmation.

Note 2: Based on the Fountain logger and visual observations from March 8, a circumstantial case can be made that Fountain's 58-minute duration was likely a dual. Though this duration was shorter than Stephens' cut-off point of 60 minutes, it is not much shorter than the confirmed duration of 63.5 minutes on July 23, 2013, and longer than the estimated duration of 45 minutes on August 10, 2013 (see Note 3).

Note 3: Observer Joan Payne reported a duration of at least 45 minutes for Fountain, and James St. John confirmed it was still erupting at ~1030. However, neither observer stayed for the end of Fountain. Standard electronic logger analysis gives a duration of 24 minutes, which is considerably shorter than the visual duration. When I re-examined the logger data, it appeared that Fountain probably ended shortly after Payne left, so 45 minutes is given as an approximate duration.

Appendix B. Follow-Up Events After a Dual, 2012-2013

Data excludes possible and probable trifectas.

Date	Succeeding Ftn. Int.	Next Event	Morning Interval(s)
5/2/2013a	21h00m	Unknown (Note 1)	
10/29/2013	19h04m	Two Morning solos	~9h47m, ~4h46m
6/5/2013	18h14m	Morning solo	11h38m
12/16/2012	16h53m	Unknown	
12/5/2012	16h43m	Unknown	
10/30/2012	15h14m	Morning solo	~5h24m
11/25/2012	14h46m	Unknown	
7/16/2013	14h23m	Unknown	
7/22/2013	13h59m	Morning solo	8h50m
3/21/2013	13h58m	Unknown	
7/2/2013	13h30m	Morning solo	7h52m
7/7/2013	13h03m	Unknown	
8/16/2013	12h32m	Morning solo	4h52m
8/10/2013	11h05m	Unknown (Note 2)	
12/21/2012	9h42m	Unknown	
1/23/2013	8h57m	Unknown	
11/19/2012	8h54m	Unknown	
6/24/2013	8h42m	Unknown	
1/28/2013	8h23m	Unknown	
8/9/2013	7h34m	Unknown	
7/28/2013	7h16m	Fountain solo	
5/2/2013b	6h01m	Unknown	
7/23/2013	5h49m	Fountain solo	
5/3/2013	5h37m	Unknown	

Note 1: There were two duals on 5/2/2013, at 0248e (a) and 2348 (b). There was no intervening Fountain, but it is possible that Morning could have erupted before observers arrived about 7h40m after the start of the first dual. The only other instance I could find of two consecutive Fountain eruptions being concerted with Morning was August 28 and 29, 1991, and Morning did not erupt between those duals.

Note 2: The 8/10/2013 dual eruption was the shortest on record, with a Fountain duration of approximately 45 minutes (see Appendix A). Observers were in the area 9 hours following the dual, but it is possible that Morning could have erupted before they arrived.

About the Authors

Jeff Cross (M.S., chemistry, Colorado State University) first visited Yellowstone in 1979. His main interests are 1) the lesser known geysers of the Park's backcountry and undeveloped frontcountry thermal areas and 2) model geysers. He has contributed several articles on thse topics to The GOSA Transactions and currently serves as co-editor of that publication. He has also written articles for The Geyser Gazer Sput. After four years of teaching chemistry, including two at Whitman College in Walla Walla, Washington, he is pursuing a PhD in chemistry at the University of Utah.

Tara Cross has been studying geysers in Yellowstone since 1988. Upon receiving her B.A. in History in 2001, she worked at the Yellowstone Research Library and Archives until 2004. She completed a Master's in Library and Information Science from the University of Washington in 2007. She has been serving as co-editor of The GOSA Transactions since 2007, and from 2006 to 2014 she was a regular contributor to The Geyser Gazer Sput. She has visited thermal areas in Iceland and New Zealand but specializes in Yellowstone's geysers, including Fan and Mortar Geysers and Giant Geyser.

Stephen Michael Gryc is a classical composer whose music is performed throughout the world. He earned four degrees in music from the University of Michigan including the degree Doctor of Musical Arts. He is professor emeritus of music composition at the Hartt School of the University of Hartford. Gryc's interest in both sound and geysers led him to make digital audio recordings of Yellowstone's thermal features and other environmental sounds. His Yellowstone recordings were used in the soundtrack of the educational film "A Symphony of Fire and Water" and in the exhibits at Yellowstone's Canyon Museum. Stephen Gryc has been visiting Yellowstone National Park since 1963. He has contributed articles to The Geyser Gazer Sput and to The GOSA Transactions, Volumes VII, IX, X, XI, and X11. He is also the Sput's "Gazer News" editor.

Dr. Ron F. Keam has been interested in hot springs and geysers since the age of five. His early career was in mathematics and theoretical physics, but interests geothermal were greatly stimulated by his fellow university student, E.F. ("Ted") Lloyd. Keam later transmuted into a geophysicist. He has conducted geological and historical research in many of New Zealand's geothermal areas, favoring Waimangu above all. Now "three-quarters retired" from the Department of Physics, University of Auckland, he holds postgraduate degrees in mathematics and physics and the equivalent of a bachelor's degree in geology.

Pat Snyder fell in love with Yellowstone National Park and the geysers in the 1970s; she even photographed Ledge and Spiteful geysers erupting in August 1974. However, in the '80s, Pat became distracted by rock and roll, and spent 23 years photographing musicians before she finally returned to Yellowstone in 2001. Pat's photography skills quickly adapted from rock bands to the geyser "performers," and her pictures have been featured in the Yellowstone Association's annual calendars; on the cover of T. Scott Bryan's book, Geysers: What They Are and How They Work (2nd Edition); and in many issues of the Geyser Gazer Sput. In addition, Pat has more than 30 years of editing, writing and layout experience, most recently with Boyd Coffee Company in Portland, Oregon, where she works in the marketing department. Pat has her B.A. in English and Education from Boise State University, and her M.S.T. in English from Portland State University.

Demetri Stoumbos first visited Yellowstone as part of a family trip in 2006 and quickly got hooked on geysers. He since has worked concessions at Old Faithful for four summers between school years at Oregon State University, from which he graduated in 2015 with a Bachelor's of Science in Biochemistry & Biophysics. When not in the Park, he enjoys modelling geysers, specifically seeing how two models hooked together will affect each other.

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