Yellowstone Science

volume 14 • number 4 • fall 2006

Charles Doolittle Walcott: Forgotten Microbe Researcher

Norris Geyser Basin Fractures and Fluids

Moran and Artist Points

NPS

Looking at Past Research in a New Light

When the first exploring parties surveyed the Yellowstone region in the late nineteenth century, it was the geologic wonders—geysers, hot springs, mudpots, and fumaroles—that captured their imaginations. Because of these treasures, Congress set aside this land of "natural curiosities" as the world's first national park. Protecting these unique geothermal systems is a key mission of the National Park Service.

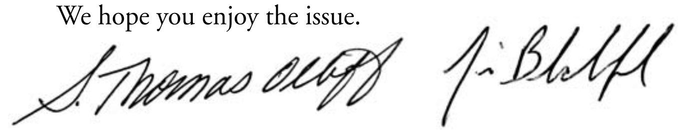
Understanding these systems is the first step in protecting them. When Hank Heasler arrived in 2002 as Yellowstone's Supervisory Geologist, one of his early tasks was to develop a scientific monitoring plan to quantify the relatively undisturbed state of Yellowstone's thermal systems and track natural changes to the systems over time. Informed by the work of earlier geothermal researchers—Don White, Patrick Muffler, Al Truesdell, Bob Fournier, Irving Friedman, Rick Hutchinson, Bob Smith, Bob Christiansen, Ken Pierce, Dan Dzurisin, Steve Custer, Nancy Hinman, and others—and co-authored with Cheryl Jaworowski and David Susong, the monitoring plan is set up to systematically gather hydrologic, geochemical, remote sensing, and geologic information to meet these goals. In this issue of *Yellowstone Science,* two articles on the Norris Geyser Basin showcase the early results of this effort, using aerial imagery to help researchers detect and monitor changes in this popular and dynamic area of the park. Cheryl Jaworowski and her co-authors report results using airborne thermal imagery to map the control of hydrothermal fluids by natural fractures. David Shean shows how historical aerial photographs can be used to identify changes in the basin's hydrothermal features.

The study of thermophiles—heat-tolerant microscopic organisms that live in the runoff channels of hot springs and geysers—has been the fastest-growing type of research in Yellowstone during the last two decades: more than 100 scientists now study microbes under 44 different research permits. The field is rich with new discoveries, cataloguing new species, mapping the function of thermophilic ecosystems, understanding how life might appear on Mars, and even searching for useful and commercially valuable information based on biological specimens.

This modern surge of microbial research dates to 1966 with Thomas Brock's discovery of *thermus aquaticus*, but Diane Smith and Ellis Yochelson's article highlights the early and essentially overlooked contributions of Charles Doolittle Walcott to the study of microbial life in Yellowstone's hot springs. His 1915 visit to the park resulted in a field diary, photographs, a report to the Smithsonian Institution, and a large collection of research specimens for the Smithsonian and universities. Although Walcott did not have the time or technology to answer some of the questions he posed, his work influenced later investigations of the park's microbial life.

Lee Whittlesey's article on Artist Point, Moran Point, artist Thomas Moran, and photographer William Henry Jackson explores how place names and geographic names can become confused over time, regardless of the fame and importance of the artists who are associated with them or the region where they lie. He also acknowledges the complexities that will guarantee continuing study into the history and geography of the places where these artists did their work.

We hope you enjoy the issue.



S. Thomas Olliff   Tami Blackford

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on the cover
Close-up of thermal pool near Great Fountain Geyser by Charles D. Walcott. *Courtesy of the Smithsonian Institution Archives.*

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Porcelain Basin in winter, Norris Geyser Basin.

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NEWS & NOTES

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Yellowstone's Summer Bison Population Estimate

Yellowstone National Park's 2006 summer bison population estimate was 3,900 animals. The estimate is based on a series of aerial surveys conducted in August. The population was estimated at 4,900 bison in summer 2005. Going into the 2006 summer season, the population had dropped to 3,400 animals. This was due to brucellosis risk management actions, hunting outside the park, traffic deaths, natural mortality, and predation.

The bison population decline did not impact the herd's reproductive capability. There were about 500 calves born this year. This is within the historical rates of the herd's annual population increase during the summer, and demonstrates the robust nature of the Yellowstone bison herd and the abundance of natural forage in the park.

The summer population estimate is used to inform adaptive management strategies under the Interagency Bison Management Plan (IBMP). Specific management actions may be modified based on expected late winter population levels as corroborated by the summer population estimate. The IBMP is a cooperative plan designed to protect Montana's brucellosis-free status while allowing for the conservation of a viable, wild bison population. Protecting Montana's brucellosis-free status requires keeping bison from mixing with cattle grazing on land outside the park.

The five cooperating agencies operating under the IBMP are the National Park Service, the U.S. Forest Service, the Animal and Plant Health Inspection Service, and the Montana Departments of Livestock, and Fish, Wildlife and Parks.

New Canyon Visitor Education Center

Yellowstone National Park opened the doors to the new Canyon Visitor Education Center on Friday, August 25, coinciding with the 90th anniversary of the creation of the National Park Service. The grand opening of this new facility marked the first major visitor center development in the park in three decades.

The visitor center's state-of-the-art, interactive exhibits will help visitors learn about and understand the geology of Yellowstone and the "supervolcano" that lies beneath it. The exhibits include a large, unique globe that rotates on a film of water, showing the location of volcanic hot spots around the world; a room-sized, fiber optic and LED animated topographic relief map of the geologic history of park; and life-size dioramas of wildlife found in Hayden Valley.

The new Canyon Visitor Education Center will serve more than 600,000 visitors per year. Of the $10.5 million used to fund the project, $8.6 million came from entrance fees collected from the 20 million people who visited the park between 1997 and 2005.

More than $1 million was donated by the Yellowstone Association. Other important contributors to the project include the Buffalo Bill Historical Center, National Aeronautics and Space Administration, National Science Foundation, and Canon U.S.A., Inc.

Errata

A photo caption on page 13 of *Yellowstone Science* 14(3) mistakenly identified the geyser behind John Varley and Richard Leakey as White Cone Geyser. The caption should have read "Varley at White Dome Geyser..." We regret the error.

YS

The new Canyon Visitor Education Center opened on August 25, 2006.

Charles Doolittle Walcott: A Forgotten Microbe Researcher in Yellowstone National Park

Diane Smith and Ellis Yochelson

Paleontologist and geologist Charles Doolittle Walcott taking notes at a pool near Great Fountain Geyser. Walcott and his wife photographed geysers and hot springs during his 1915 field season in Yellowstone. The photos in this article are reproduced from the Smithsonian report "Geological Explorations in the Rocky Mountains for 1915," by Charles D. Walcott, courtesy of the Smithsonian Institution Archives.

IN A RECENT BOOK, *Seen and Unseen: Discovering the Microbes of Yellowstone*, Kathy B. Sheehan and her co-authors introduce the work of microbiologist Thomas Brock and others who, in the late 1960s, investigated the microbial life of Yellowstone National Park. These single-celled bacteria (known as cyanobacteria) give Yellowstone's hot springs and pools their unique colors, determined in part by the temperature of the water. Brock isolated a thermophilic bacterium (*Thermus aquaticus*) that grew on slides placed in the 80°C (176°F) waters of Mushroom Pool. According to Sheehan et al., it was not until the 1980s work of biochemist Kary Mullis, who developed a method for copying DNA, that the heat-stable enzyme of Brock's microbe was identified, and the significance of Brock's discovery could be appreciated.

The knowledge that life can exist at unexpected temperature extremes like those found in Yellowstone's hot springs is a relatively new discovery in biology, one that challenges the basic assumptions of what conditions are necessary for life on Earth. Kary Mullis's breakthrough, for which he was awarded the Nobel Prize, is a prime example of how a new technology can move a field forward, reveal the past work of others (like that of Thomas Brock's) in a new light, and help us better understand the world in new ways.[1] Brock's ground-breaking work created new opportunities for investigating the rich and unique microbial life teeming within the thermal features of Yellowstone National Park, and laid the groundwork for "bio-prospecting" thermophiles in the park. And yet, long before Brock, scientists examined the same phenomena in Yellowstone. Lacking the technology to pursue their investigations, however, they were unable to reach his conclusions.

For example, as early as 1898, as documented by Alice Wondrak Biel in *Yellowstone Science* 12(3), the University of California botanist W.A. Setchell received a collecting permit for his early research in Yellowstone on thermophiles, although his work went largely unreported. Most geologists are familiar with Arnold Hague's 1899 U.S. Geological Survey stand-alone Monograph 32, Part II, the first in-depth publication to describe the geology of Yellowstone National Park. As most geologists also know, Part I, on the history of exploration and the general geology of the park, was never published. However, it turns out there was a Part III that also remained unpublished. In a 1916 letter written by Hague shortly before his death, he stated that he was editing a manuscript on "The Thermal Algae of Yellowstone National Park, with special reference to the Thermal Algae of this and other regions" as a result of Setchell's work. Clearly, although his contributions have been largely forgotten, Setchell's interest in thermal algae preceded that of Brock and the others.

W.A. Setchell's early work with thermophiles is not the only research that has gone unrecognized. In a strange twist in the history of science and Yellowstone National Park, a very well-known scientist investigated these same phenomena. And yet, the research conducted by Charles Doolittle Walcott in Yellowstone in 1915, assisted by his wife Mary Vaux Walcott and two sons, Sidney and Stuart Walcott, has been essentially overlooked as well.

The knowledge that life can exist at unexpected temperature extremes like those found in Yellowstone's hot springs is a relatively new discovery in biology, one that challenges the basic assumptions of what conditions are necessary for life on Earth.

Charles Doolittle Walcott

Charles Doolittle Walcott, a world-renowned paleontologist and geologist, is best known for his discovery of the Burgess Shale, one of the most diverse and well-preserved fossil localities in the world. He was an original member of the U.S. Geological Survey, the fourth Secretary of the Smithsonian Institution from 1907 to 1927, and President of the National Academy of Sciences from 1916 to 1922. Largely self-taught, Walcott developed his interest in geology and paleontology as a young man and was such an ambitious collector that in 1873, when he was only 23, he sold one of his collections to Harvard's leading naturalist, Louis Agassiz, and another collection in 1879 to Alexander Agassiz, Louis's son.

Walcott never lost his interest in collecting and analyzing geological formations. During his 20-year tenure at the Smithsonian, he still made time to spend many summer field seasons exploring in the West, collecting and pursuing his own research interests, which focused primarily on the study of geology and paleontology, with a particular interest in trilobites. It was on such an expedition in 1909 that Walcott discovered the Burgess Shale in Canada.

One of the earliest scientists to employ photography to document his fieldwork, Walcott visited Yellowstone briefly in both 1897 and 1898, during which he took a series of spectacular photos of the park's geysers and hot springs. It was not until the summer and early fall of 1915, however, that Walcott could return to Yellowstone to pursue in earnest his interest in the park's microscopic life, an expedition he again documented through photographs that were published the following year by the Smithsonian.

Reading through Walcott's field notes, reports, and publications from that period, one can sense his growing interest in Yellowstone and its diverse life forms. To understand Walcott's early fascination with Yellowstone's geysers and hot pools, which was in many ways ahead of its time, it helps to first understand his interest in the trace fossils known as stromatolites. Stromatolites are laminated structures commonly thought to have been formed by the activity of ancient microorganisms, especially cyanobacteria (formerly known as "blue-green algae"); however, some stromatolites possess features that are more consistent with abiotic (non-organic) precipitation. Stromatolites represent the complex interactions of microbes, sediments, and the environment—an active area of research in geology and in Yellowstone today.

Cyanobacteria can still be found in the shallow thermal waters in the park, but they particularly flourished before the rise of invertebrate animals. In the same way that cyanobacteria create the colorful biomass in Yellowstone's hot pools today, ancient bacteria formed deposits covered by thin layers of calcium carbonate in the water. The bacteria reattached to the new surface, starting the layering process anew and creating over time multi-layered rocks of fossilized bacterial mats. To picture one, think of an object about the size of a cabbage that, when cut vertically, shows a number of concentric layers.

Stromatolites occur in rock formations up to 3.5 billion years old, but are most common in the sedimentary rocks of the "Algonkian," a term used during Walcott's time to designate the rocks above the Archean and below the Paleozoic eras. Both Glacier National Park and the mountains of southeastern Montana contain excellent examples of stromatolites, leading Walcott to visit both areas. In 1914, Walcott published a paper on the stromatolites from Montana's Belt Mountains titled "Pre-Cambrian Algonkian algal flora" in which he illustrated and described 12 new species.

In that paper, Walcott wrote that the layers revealed within the rocks "[appear] to have been formed through the agency of algae closely allied to the Cyanophycaeae (Blue-green Algae)." He also noted that fellow scientist Albert Mann helped him discover "cells of the type of those of the Cyanophycaea" and that Charles A. Davis of the Bureau of Mines advised him "in relation to the recent fresh-water algae and their calcareous deposits." Although Walcott mentions these findings in passing, the combination of microorganisms and their calcium carbonate deposits had clearly piqued his curiosity about what might be discovered in the geysers and hot pools of Yellowstone National Park.

One of the questions concerning Precambrian limestone that interested Walcott and his contemporaries, a question that continues to intrigue scientists to this day, was whether stromatolites were deposited under normal marine conditions, in vast freshwater lakes, or in some environment between the two. Early in 1915, before his visit to Yellowstone, Walcott presented a paper based on his work in Montana to the National Academy of Sciences, which was later published under the title "Discovery of Algonkian Bacteria." In this paper, Walcott reported that specimens collected during his 1914 field season had been examined by Albert Mann, plant morphologist of the Department of Agriculture and Charles Resser of the National Museum. The pair, working with thin sections of the rock, discovered bacteria consisting of individual cells and what appeared to be chains of cells similar to *Micrococci*.[2] This exciting discovery still left open the question, however, of how and where these cells were formed. Believing that Precambrian stromatolites were of freshwater origin, Walcott needed an environment where he could test his hypothesis.

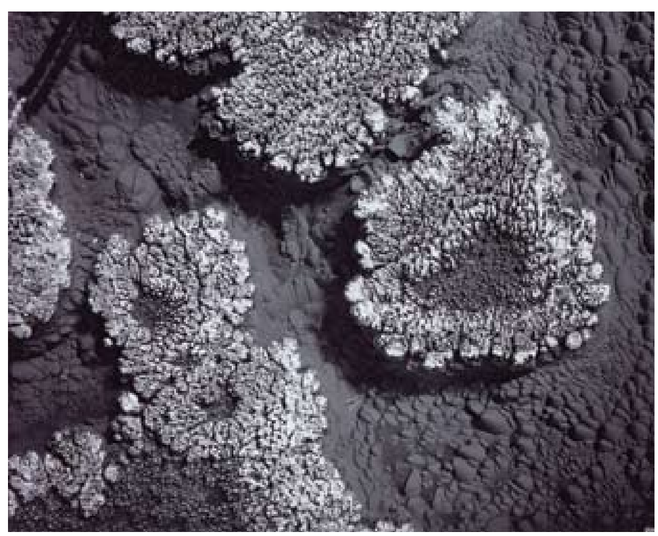
Walcott in Yellowstone

Walcott's work on the stromatolites and his unanswered questions about their formation set the stage for his 1915 field season in Yellowstone. After writing to Secretary of the Interior Franklin Lane for permission to collect material appropriate for public exhibition at the Smithsonian and for specimens to compare with rocks he had collected in the Belt Mountains, Walcott departed Washington that summer with two objectives in mind. First, he wanted to "determine if possible, the extent to which the lower forms of algae and possibly bacteria contributed, through their activities, to the deposition from the geyser and hot-spring waters of the contained carbonate of lime and silica." If so, he hypothesized, then this would provide a living example of the same kinds of biological processes that created stromatolites. Second, he wanted to secure for the Smithsonian "a series of geyser and hot-spring deposits" as well as "silicified wood from the petrified forests and certain types of volcanic rocks."[3]

His second objective was an unqualified success. With permission granted to collect for the Smithsonian Institution, Walcott left the park with approximately five tons (an amount that obviously would not be permitted today) of "siliceous and calcareous sinters in masses often of exceptional size, native sulphur, silicified wood, sundry mineral specimens and a large representation of volcanic rocks." These specimens contributed significantly to the Smithsonian's research collection, as well as to the research and education collections of the nation's universities and land grant institutions. In addition to distributing duplicate specimens to several research and teaching collections around the country, parts of Walcott's Yellowstone collection, together with specimens collected by the Geological Survey, a six-foot-square relief map, and transparencies of the park, went on public display in the alcove on the first floor of the National Museum in 1917.[4]

While in the park, Walcott took an interest in more than just the microbial life. Based on what he saw collecting around the park's geysers and hot pools, Walcott advised the Secretary of the Interior that the lack of "any one responsible for the actual care of the geysers, hot springs, paint pots, etc." was putting Yellowstone's thermal features at risk. Walcott was as worried about the damage caused by trees tumbling into a hot pool and geysers blowing out the side of a cone, allowing their mineral-bearing waters to escape, as he was by tourists defacing the formations and carrying away souvenirs of their visits. While his suggestion that the government should assist "nature in restoring the damage she has done" conflicts with current park management policies, Walcott argues eloquently in that same letter that since the government was willing to support

Close-up of a hot spring near Lone Star Geyser. One of Walcott's objectives was to document mineral deposition in and around geysers and hot springs.



In his caption for this photo, Walcott noted a "beautiful light cream-colored siliceous deposit in runoff from Artemesia Geyser."

restoration of archeological ruins in the West, that "the wonderful natural phenomena of the most extraordinary and beautiful park in the world should be equally well taken care of." And, he added, even though the "present administration of the park under Colonel Brett appears to be most efficient...he has neither authority nor money to have the work done that is mentioned above."[5] Fortunately, soon thereafter, administration of the park would be transferred to a new agency, the National Park Service, with the authority and finances to more effectively protect and preserve the park's natural features.

Mary Vaux Walcott (center, at the back of the pool) in the Lower Geyser Basin.

Walcott's lingering questions about the biological origins of stromatolites, however, remained largely unanswered. Walcott collected a number of specimens from throughout the park, including an "extensive and complete series" of hot spring deposits, and he and his wife, Mary Vaux Walcott, took a series of photographs of geysers and hot springs to document their work, which the Smithsonian published the following year. But other than detailed captions associated with the published photographs, some of which are reproduced as part of this article, Walcott's field diary and his subsequent report to the Smithsonian have little more to say about the biological origins of Precambrian stromatolites.

In a letter to an Australian colleague in 1916, Walcott wrote that his work in the park led him to conclude that much of the hot springs deposits were "made through algal and bacterial agencies" and that "the algal growth clearly controlled the form." Walcott wrote that he still believed "Cryptozoon and a number of other Paleozoic and Pre-Paleozoic forms owe their shape to algal growth," but he did not have the time nor technology to pursue this line of inquiry any further.[6]

The only other mention Walcott made of his research in Yellowstone was in a lantern-slide presentation he made to the National Academy of Sciences in 1916. But that same year, Walcott added the presidency of the Academy to his growing list of responsibilities. Between his additional administrative duties, the outbreak of World War I, and his continued research into geology and paleontology, Walcott appears to have had little time to pursue the more challenging questions of the nature and origins of microbial life in Yellowstone National Park. Given the technology available, this may have been simply a realistic allocation of his time. It would take more than 50 years for science and technology to surpass Walcott's early inquiries.

Even without sophisticated technology, both Setchell and Walcott appear to have had an understanding of the microbial life of Yellowstone's hot springs that, in retrospect, was ahead of its time. If Setchell's manuscript had been published, or if Walcott had found the time and technology needed to continue his investigations, perhaps the study of thermophile bacteria would have developed much sooner. And, they may not be the only scientists whose work impacted these early twentieth century studies in the park.

Walcott shared many Yellowstone specimens with scientists and students at colleges around the country, and researchers traveled to study in "nature's classroom." Historians of science have unique opportunities to dig deeper into Yellowstone's past and perhaps discover other significant research that directly influenced early investigations of the park's microbial life. In the meantime, however, these contributions made by Charles Doolittle Walcott and other early microbe researchers should not go unmentioned.

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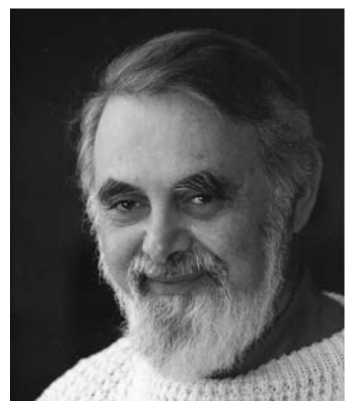
Diane Smith is a Montana writer and historian, and author of *Letters from Yellowstone*.



COURTESY ABBY YOCHELSON

Ellis Yochelson, PhD, was a Research Associate in the Department of Paleobiology, National Museum of Natural History, Smithsonian Institution, and the author of a two-volume biography of Charles Doolittle Walcott. He passed away in 2006.

Endnotes

1 Kathy B. Sheehan, *Seen and Unseen: Discovering the Microbes of Yellowstone* (Helena, MT: Falcon Press, 2005), xiii.
2 Proceedings of the National Academy of Sciences, April, 1915; 1(4):256–257.
3 Ellis. L. Yochelson, *Smithsonian Institution Secretary, Charles Doolittle Walcott* (Kent, OH: Kent State University Press, 2001).
4 "Report on the Progress and Condition of the United States National Museum for the Year Ending 1918", p. 61.
5 Charles Walcott to the Secretary of the Interior Franklin K. Lane. Letter, September 5, 1915.
6 Yochelson, *Smithsonian Institution Secretary.*

A Brief Look at Moran Point and Artist Point

and Their Association with Thomas Moran and William Henry Jackson

Lee H. Whittlesey

Lower Falls of the Yellowstone, William H. Jackson, 1871. NPS photo.

Thomas Moran, *The Grand Cañon of the Yellowstone, 1872*, U.S. Department of the Interior Museum, Washington, D.C.

ARTIST POINT AND MORAN POINT are viewpoints of the Grand Canyon of the Yellowstone River in Yellowstone National Park. Artist is perhaps more famous than Moran, but its fame rests in no small measure on the error of those who mistakenly called it Artist Point, an error that relates directly to exemplary American Romantic artist Thomas Moran. Since Mr. Moran rendered his famous painting of the canyon in 1872, the two points have shared a tangled history that connects their locations and the origins of their names with two of the American West's best known image makers. Photographer William Henry Jackson and artist Thomas Moran produced the images that made Yellowstone famous in the 1870s and romanticized it for all time to come. Those two men who would later become so famous forged their friendship in Yellowstone in 1871 and together produced the first mature artistic analysis and presentation of the Yellowstone region.[1] The later geographical and historical controversy over the two geographical points that came to be associated with their work would probably have surprised Moran and Jackson.

Moran Point on the north rim of the Grand Canyon of the Yellowstone River, long noted as inaccessible to visitors,[2] is located between Lookout Point and Grand View and is a point east of Lookout Point.[3] The point was named by members of the 1871 Hayden Survey, although no formal usage of the name has been found until 1875. Correspondence from 1938 makes it clear that park officials believed the name to have been given by one of the Hayden surveys, probably the 1871 survey.[4]

As early as 1875, some government officials knew that the name Moran Point existed and believed that it was the spot from which artist Thomas Moran made the sketches for his famous painting of the Grand Canyon of the Yellowstone with Lower Falls. General W.E. Strong wrote that "we…viewed the cañon from Moran's Point, which was named for Moran, the artist, and from which point he painted the picture now [1875] in the House of Representatives." Dr. S. Weir Mitchell proclaimed in 1879 that "half a mile down [from Lower Falls] is Moran's Rock, whence he made sketches for the picture now in the capitol."[5]

But those correct perceptions of the existence of Moran Point quickly disappeared along with knowledge of the location from which the drawings were made. Very soon thereafter, a strong belief arose that the sketches Moran made for his painting had been rendered from Artist Point on the south rim of the canyon, and because of that, Moran Point itself did not appear on maps and became lost from park officials' perception. The name Artist Point was given early in Yellowstone history, probably in 1883,[6] and probably by park photographer F. Jay Haynes.[7] The circumstances surrounding the giving of the name and the reason for it are cloudy. It is relatively certain that Haynes gave the name, as his usage of it in his 1890 guidebook is the earliest known.[8]

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Thomas Moran in 1883.

In that guidebook, Haynes embraced Artist Point as having been the spot from which Moran worked. Thus he was an early victim of the mistaken notion that the famous painting was rendered from there. Haynes perpetuated that idea in his guidebooks, and indeed his statement did not get changed in *Haynes Guide* until his son Jack changed it for the 1910 edition.[9] But one cannot escape the notion that Haynes tacitly approved of the name as referring to himself as an "artist" once he realized his own error involving Moran and corrected it in his guidebooks. Photographers in Haynes's day were commonly called artists,[10] and he was no exception. In fact, he captioned his own photograph number 2014 (YELL 663) as "Our Artist Bound for the Canyon." It depicted him with another man bound for the canyon with photographic equipment loaded on sledges.

If misinformation on the origin of the name Artist Point was still appearing in *Haynes Guide*s until 1910, it was also still occurring in the 1970s when this writer worked as interpretive information specialist for the park concessioner. So entrenched at that time was the error in the daily commentaries of park tour bus drivers and guides that the author was forced to publish a rebuttal in the Yellowstone Park Company's internal newsletter for the benefit of those bus drivers and step-on tour guides.[11] One has to believe that the error has been active in Yellowstone misbelief at numerous times since 1890.

But as early as 1900, some writers felt the need to correct the impression that Artist Point was the spot from which Moran had done his painting. Already mentioned is the example of Jack Haynes dropping the assertion from the 1910 *Haynes Guide*. Charles Taylor wrote in *Touring Alaska and the Yellowstone* (1900) that "Moran Point is the outlook from which Thomas Moran painted the sketches for his great Yellowstone picture in the National Capitol." A.M. Cleland stated in 1910 that "Artist's [*sic*] Point [is] so called because Thomas Moran is supposed to have painted the magnificent picture of the Grand Cañon of the Yellowstone which hangs in the Capitol at Washington, from that point. Mr. Moran recently stated that this idea was an erroneous one, [and] that his painting was *not* made from the south side."[12]

Still more information surfaced in 1938, when Moran's daughter sent her father's sketch with the location of Moran Point to the park. Park photographer Jack Ellis Haynes used it to write into the park place-names records the notation that Moran Point was the "point between Lookout Point and Grand View from which Moran painted the canyon. [The l]ocation was checked from information received in 1937 [*sic*—1938] from Miss Ruth Moran by Haynes, Rogers, Oberhansley, and Bauer."[13] Armed with the Mitchell, Cleland, Taylor, and Haynes sources, this writer approached Yellowstone historian Aubrey Haines in February 1978, and asked him about the conflict in location for Moran's painting. Aubrey Haines's reaction was one of astonishment that anyone could believe that the painting was made from Artist Point.[14] Not surprisingly, Haines had it right when many others in 1970s Yellowstone did not.

A look at the 1938 correspondence reveals a great deal about the location of Moran Point, who named it, and what Moran's memory was as to where it was located. In that year Ruth B. Moran sent her father's pencil sketch of the point, made about 1900, to Albright, who wrote to park superintendent Edmund Rogers about it. Albright stated that Moran "made the sketch on the brink of the lower fall of the Yellowstone and [he] marked with an 'X' Moran Point as named by one of the early Hayden surveys." Implying that the location of Moran Point was at that time uncertain to park officials, Albright continued:

> *I am sending this sketch to you, thinking that perhaps you could have one of the naturalists take it down to the brink of the fall, and do a job of identification that would once and for all fix [the location of] Moran Point. It would be a matter of great satisfaction to Miss Moran if this could be done. She is old and frail in health…Please carefully preserve the little sketch and return it to me if possible before July 1st.*[15]

Superintendent Rogers replied to Albright that Haynes, Bauer, Oberhansley, and he had gone to the canyon with the sketch and that "the question of Moran Point['s location] seems to be finally settled." Said Rogers:

> *The point indicated [by Moran in the sketch] as Moran Point is without a doubt the next promontory northeast (downstream) from Lookout Point on the north rim of the Canyon. From no other point on the north rim of the Canyon below Lookout to and including Grand View is there gained a full view of the Lower Falls. Fortunately no [other] name has been applied to this promontory and no name is in current use for it. The [William Henry] Jackson lithograph of the Lower Falls was made from Moran Point showing Lookout Point to the right.*[16]

Park photographer Jack Ellis Haynes took a photograph of Moran's sketch for posterity and reproduced it as Haynes photo number 38500. He also placed the name Moran Point in the very next (1939) edition of his guidebook *Haynes Guide Handbook of Yellowstone National Park* "now that the matter of Moran Point is finally determined definitely."[17] Haynes then instructed one of his assistants that because most of his photos showing Lower Falls and Lookout Point by chance happened to be taken from Moran Point to please "write on the negative wrappers of all [my] negatives…the words (following [my] title) 'From Moran Point'." The reason for this, explained Haynes, was that "we want to get in the habit of specifying" that these Haynes photos were taken from Moran Point.[18]

While Moran himself has left no definite statement as to the spot from whence he made his painting, five statements from others—plus the sketch by Moran sent to the park by his daughter—make the evidence convincing that the sketches for Moran's painting were performed at Moran Point. While agreeing that some portions of his painting were a bit fanciful, Moran stated that "so [generally] correct is the whole representation that every member of the expedition with which I was connected, declared, when he saw the painting, that he knew the exact spot which had been reproduced."[19] This statement from the artist himself argues strongly for the idea that he worked from one location and that others on the Hayden expedition knew that location.

That Moran knew the location of Moran Point and accepted it as a place name is also apparent from three of his later (1892) sketches: "Cliff in Yellowstone Cañon, Moran's Point," and two sketches each labeled "Moran's Point, Yellowstone Cañon." It appears that Moran descended into the canyon in order to make sketch number 898, and it does resemble present day Moran Point from below.[20]

Thus the 1938 events solved the locational problem of Moran Point for the park, and park officials of that day appear to have had no question as to whether Moran had sketched from there. In their view, he had. But the question of how the painting itself related to the actual landscape was a

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Left: View of the north rim of the canyon from the brink of the Lower Falls. *Right*: Thomas Moran's sketch made from the brink of the Lower Falls, showing Moran Point marked with an "X."

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Grand Canyon of the Yellowstone from the brink of the Lower Falls, William Henry Jackson, 1871.

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View of the Lower Falls from Lookout Point on the north rim of the canyon.

different one. Jack Haynes in 1938 believed that Moran had merely rendered "an extremely wide angle view from Moran Point" [21] in order to come up with the final painting, but that analysis seems simplistic. A recent study of Thomas Moran by Joni Louise Kinsey concludes that the 1872 painting, if not all four[22] of the canyon paintings that Moran eventually rendered, depicted a fanciful location, and that it was a made-up "compilation of a series of points of view from around the canyon."[23] This assessment seems correct, in that Moran's painting depicts a Lower Falls that is substantially farther away from the viewer than the physical viewpoint at Moran Point suggests. Indeed, as Kinsey points out, Moran admitted that he took some liberties in manipulating geographical elements within the painting. A comparison of Jackson's photos looking both upstream and downstream leads this observer to conclude, as Kinsey did, that Moran inserted some geographical elements that cannot be seen from Moran Point—such as a more distant Lower Falls—into his paintings.

As for photographer William Henry Jackson's involvement with Moran Point, he too used it as a site from which to conduct business. At least three of his photos were taken from there, although he did not note the name of the point. Jackson's photos from this point were used time and again to promote Yellowstone in early days. Constant usage has resulted in their becoming arguably the most famous of early Yellowstone photographs.[24]

Jackson's involvement with Artist Point was much less than that of Thomas Moran. He did take a few photos from the south rim of the canyon, which indicates that he traveled to that remote spot in 1871 before there was any kind of bridge over the Yellowstone River to allow access to the canyon's south rim. In fact, Hayden survey expert Dr. Marlene Merrill says that Jackson and Thomas Moran *both* went to the south rim of the canyon to make images but left no textual record of their trip. Merrill says that the two men worked together for a full day after the rest of the party left for Yellowstone Lake, so that they would have adequate time for each rim of the canyon. Jackson stated that "two very busy days were spent [at the canyon] in exploration for the best points of view."[25] His account of his time spent with Moran was published in 1936, and in it he stated that neither he nor Moran kept a diary. At the canyon, said Jackson, "Moran's enthusiasm was greater [here]…than anywhere else among Yellowstone's wonderful features."[26]

Jackson took at least seven photographs from the south rim, beginning with his numbers 82 and 1521.[27] Neither of those views was taken from Artist Point. Jackson number 82 was taken from a point west of Artist Point while number 1521 was taken from a location a good distance east of Artist Point. Five other photos of the canyon from the south rim are all relatively hard views to find in repositories. Jackson issued them as stereopticon views, probably in 1872, and marked them as taken in 1871. These are numbers 441, 446, 447, 448, and 449. Number 441 is a striking view in that it shows huge, serrated cliffs in the foreground of the photo while the canyon and Lower Falls are in the background. This view was taken from a point east of Artist Point but not as far east as Sublime Point.[28]

Moran Point and Artist Point are lessons for us in both history and geography. In history, they are examples of how

A recent study of Thomas Moran…concludes that the 1872 painting...depicted a fanciful location, and that it was a made-up "compilation of a series of points of view from around the canyon."[23] This assessment seems correct, in that Moran's painting depicts a Lower Falls that is substantially farther away from the viewer than the physical viewpoint at Moran Point suggests.

place names themselves or the reasons for them can be buffeted about through the "winds" of time—by either being misplaced and forgotten or by being misunderstood as to the reasons for their origins. In geography, they are examples of how physical points on the landscape—whether within mountains or along a canyon or nestled in a valley—can become confused over time on maps, in literature and usage, and in the minds of human beings, no matter how well known the photographers and artists are who render them or how famous the region is where they lie. The complex interplay between the images of Jackson and Moran and the geography and history of the places where they did their work guarantee that all will be fodder for continuing study by generations of researchers to come.

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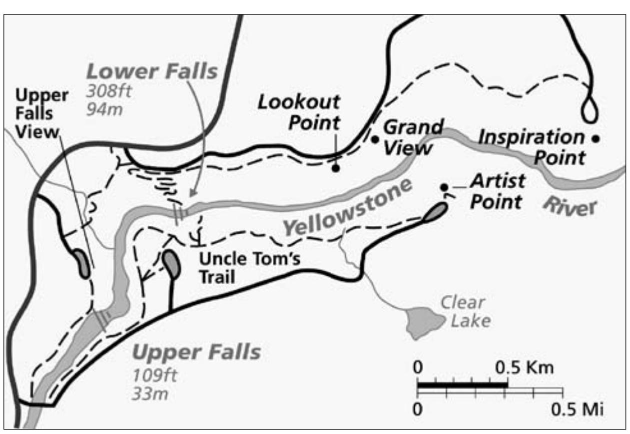


Contemporary map showing viewpoints on the north and south rims of the Grand Canyon of the Yellowstone.

Endnotes

[1] Peter B. Hales, *William Henry Jackson and the Transformation of the American Landscape* (Philadelphia: Temple University Press), 1988, p. 96.

[2] Jack Ellis Haynes, *Haynes Guide Handbook of Yellowstone National Park* (Bozeman: Haynes Studios, Inc.), 1966, p. 133. The more famous Moran Point is in the Grand Canyon National Park, Arizona. A third Moran Point is in Yosemite National Park. Moran's sketches of these other two points are reproduced in Ann Morand, *Thomas Moran the Field Sketches* (Norman and London: University of Oklahoma Press), 1996, pp. 252–253, 280–281.

[3] Moran's sketch on page 9 of this article, and the photo next to it, clearly identify Moran Point as a point east of Lookout Point as seen from the brink of the Lower Falls. For definite identification, per Jack E. Haynes, see footnote 17.

[4] Horace Albright to Edmund Rogers, May 9, 1938, and Rogers to Albright, May 27, 1938, both in NPS Place Names File 731-01, YNP Library vertical files.

[5] (General) W.E. Strong (Richard A. Bartlett, ed.), *A Trip to the Yellowstone National Park in July, August, and September, 1875* (Norman: University of Oklahoma Press), 1968, p. 57; S. Weir Mitchell, "Through the Yellowstone Park to Fort Custer," *Lippincott's Magazine* 25 (July, 1880): 700.

[6] Clyde Max Bauer, unpublished "Place Names of Yellowstone National Park," no date, about 1935, Artist Point entry. It is not known where Bauer got the information that Haynes gave the name to Artist Point in 1883, but it is likely that it was from his friend Jack Ellis Haynes (son of F. Jay Haynes) who was alive in Bauer's day and to whom he could directly talk.

[7] Detailed place names information on Moran Point and Artist Point is in Lee H. Whittlesey, *Yellowstone Place Names* (Helena: Montana Historical Society), 1988, pp. 17, 102; and Whittlesey, "Wonderland Nomenclature: A History of the Place Names of Yellowstone National Park," unpublished ms., 1988, Artist Point and Moran Point entries, YNP Library.

[8] Haynes's 1890 text read: "Almost directly opposite [Lookout Point], on the right-hand side of the canyon, is Artist's Point, so called from being the position selected by Mr. Thomas Moran from which to paint his celebrated picture, which may be seen hanging in the nation's capitol at Washington." A.B. Guptill, *Practical Guide to Yellowstone National Park* (St. Paul: F. Jay Haynes), 1890, p. 99. Guptill was Haynes's accountant and the man who wrote the text for his guidebooks, but final authority for what went into those books rested with Haynes. As late as 1902, geologist Arnold Hague traveled with Haynes to the canyon and stated that Artist Point was the place from which Moran worked. National Archives, Record Group 57, USGS Field Notebooks, box 55, Arnold Hague notebook, vol. 2, 1902, p. 12.

[9] Jack Ellis Haynes, *Haynes Official Guide Yellowstone National Park* (St. Paul: Pioneer Company and F.J. Haynes), 1910, p. 87.

[10] In fact, Haynes himself wrote to his girlfriend (later wife) Lily in 1877: "Lillie, my mind is all taken up with the 'Beautiful Art,' and [I] cannot write a letter to anybody without speaking something about Photos." Montana Historical Society, *F. Jay Haynes Photographer* (Helena: Montana Historical Society Press), 1981, p. 9. Another example refers to photographer William Henry Jackson. An 1873 writer noted that "Mr. Jackson is an *artist born* [italics added]. Neither Braun or England in the Alps ever did fuller justice to fine scenery than Mr. Jackson has done to the beauties of the great Yellowstone." [No author], "Stereoscopic Views of the West," *Philadelphia Photographer* 10 (February, 1873): 64. Yet another entry in this magazine proclaimed that Jackson's photos were "most excellent artistic studies." [No author], "United States Geological Survey of the Territories," *Philadelphia Photographer* 12 (January, 1875): 30. The magazine stated in 1876 that "it is in the hands of such…men as he [Jackson] that our art makes its rapid strides." [No author], "We Had a Pleasant Call," *Philadelphia Photographer* 13 (April, 1876): 128.

[11] [Lee H. Whittlesey], "The Artist Point Misnomer," *Commentary Newsletter* (house organ of Yellowstone Park Company) 6 (July, 1978): 9.

[12] Charles Taylor, *Touring Alaska and the Yellowstone* (Philadelphia: George W. Jacobs and Company), 1901, p. 381; No author [A.M. Cleland], *Through Wonderland* (St. Paul: Northern Pacific Railway), no date [1910], p. 62, in Rare Box RR-2A, YNP Library. While Moran, according to Cleland, gave no statement here about what spot he worked from, the fact that he said the painting was not made from the south side (south rim) *implies* that it was made from the north side (north rim). There are, after all, only two rims.

[13] Jack E. Haynes, 1938 statement, in Yellowstone Card File (now contained in drawers in Museum Curation Office, Yellowstone Heritage and Research Center, Gardiner, Montana), entry "Moran Point." At the time of this statement Jack Haynes was park photographer and honorary museum curator, Edmund Rogers was park superintendent, Frank Oberhansley was a park naturalist, and Clyde Bauer was Chief Naturalist.

[14] [Whittlesey], "The Artist Point Misnomer," *Commentary Newsletter* 6 (July, 1978): 9, mentioning Whittlesey's 1978 conversation with Aubrey L. Haines. Unfortunately Haines did not offer an opinion as to whether he thought the painting was rendered at Moran Point; he merely was certain that the painting was *not* done at Artist Point.

[15] Horace Albright to Edmund Rogers, May 9, 1938, in NPS Place Names File 731-01, YNP Library vertical files under "Place Names." Park Archivist Harold Housley says (October 3, 2005) that these files will eventually be transferred from the park library to the park archives.

[16] Edmund Rogers to Horace Albright, May 27, 1938, in NPS Place Names File 731-01, YNP Library vertical files under "Place Names." Rogers also noted that the park planned to submit this place name to the U.S. Board on Geographical Names (a check with the U.S. Board on Geographic Names reveals that this was never done) and that he was returning Thomas Moran's original sketch to Albright along with some canyon photographs that he and the others took of Moran Point. Exactly which Jackson lithograph he was referring to is not known, but it was probably one of the pictures that Jackson took from Moran Point or near it.

[17] Jack Ellis Haynes, *Haynes Guide Handbook of Yellowstone National Park* (St. Paul and Yellowstone National Park: Haynes, Inc.), 1939, pp. 124, 185. The quote is from J.E. Haynes to E.W. Hunter, May 26, 1938, in NPS Place Names file 731-01, YNP Library vertical files under "Place Names." A copy of the drawing by Thomas Moran is Haynes photo 38500, in Jack Ellis Haynes collection 1504, box 135, folder 6, "Moran Point," Montana State University, Bozeman, Montana, along with letters Haynes wrote to Superintendent Edmund Rogers on May 9, 1938, and November 17, 1938. In the latter letter, Haynes included one of his own photographs taken from east of Moran Point and showing Moran Point clearly marked with an *arrow*. Haynes's index on page 185 of his 1939 guide ("Moran Point" and "Moran's Point") makes it clear that he and park officials had previously believed that Lookout Point was the "Moran's Point" of old days.

[18] Haynes to Hunter, May 26, 1938, as cited.

[19] Moran quoted in Kinsey, *Thomas Moran*, p. 55. Moran's biographer Thurman Wilkins says that Moran "studied the views from numerous vantage points, sometimes from the canyon's rim, especially at the spot later known as Artist's [*sic*] Point." In light of the greater evidence that Moran worked for a fair amount of time at Moran Point rather than Artist Point, this must be an error. Thurman Wilkins, *Thomas Moran Artist of the Mountains* (Norman: University of Oklahoma Press), 2nd edition, 1998, p. 91.

[20] Morand, *Thomas Moran the Field Sketches*, pp. 264–267, sketches 890, 891, 898. Wilkins confirms that Moran descended into the canyon, studying its geography "sometimes from the canyon's depth." Wilkins, *Thomas Moran*, p. 91.

[21] Haynes to Hunter, May 26, 1938, as cited.

[22] Moran completed the paintings in 1872, 1893, "1893–1901," and 1908 ("Mists of the Yellowstone"). See Peter Hassrick, *Drawn to Yellowstone: Artists in America's First National Park* (Los Angeles: Autry Museum of Western Heritage; Seattle: University of Washington Press), 2002, pp. 40–41, 84–85, 86–87; and Birmingham Museum of Art, *Splendors of the American West: Thomas Moran's Art of the Grand Canyon and Yellowstone* (Seattle and London: University of Washington Press), 1990, p. 93. There are two different 1893 paintings of the canyon: one marked "Moran 1893" and one marked "1893–1901." What appears to be a fifth, although smaller, Moran painting of the canyon was reproduced in W.H. Jackson, "With Moran in the Yellowstone," *Appalachia* 82 (December, 1936), opposite p. 150. It actually is not a fifth painting but merely a differently colored version of the 1893 painting.

[23] Joni Louise Kinsey, *Thomas Moran and the Surveying of the American West* (Washington and London: Smithsonian Institution Press), 1992, p. 55. Although her overview is correct, Kinsey has made a number of other errors. Her William Henry Jackson stereograph, p. 54, was not taken from "Artist's Point" [*sic*—the correct place name is Artist Point] but rather from a point much farther east where a promontory partially blocks the falls. And her Jackson photos on page 55 are not taken from "Inspiration Point" but rather from a point farther west, because from Inspiration Point, one cannot see Lower Falls. Finally, she failed to mention Moran Point at all, a central omission considering the subject of her book.

[24] William Henry Jackson plates 20a, 20b, and 34, in [National Park Service and Arno Cammerer], *William Henry Jackson and the Hayden Yellowstone Expedition* (no place: privately printed and bound for Yellowstone National Park), no date [about 1941], vol. I, YNP Library. These are respectively: "Falls of the Yellowstone" (from Moran Point, no date, probably 1878), uncaptioned looking downstream from Moran Point (no date, probably 1878), and "Lower Falls of the Yellowstone" (from Moran Point, no date probably 1872). One authority states that Jackson's westward-looking views were his most famous. Kinsey, *Thomas Moran*, p. 55.

[25] Dr. Marlene Merrill to Lee H. Whittlesey, September 20, 2005. The Jackson quote is from Bob Blair, ed., *William Henry Jackson's The Pioneer Photographer* (Santa Fe: Museum of New Mexico Press), 2005, p. 75. Moran's biographer Thurman Wilkins states that while the main Hayden party set off southward, "Moran and Jackson remained the next *four* [italics added] days in the vicinity of the two Yellowstone falls." Wilkins, *Thomas Moran*, p. 91.

[26] W.H. Jackson, "With Moran in the Yellowstone," *Appalachia* 82 (December, 1936): 149–160. The quote is from page 155.

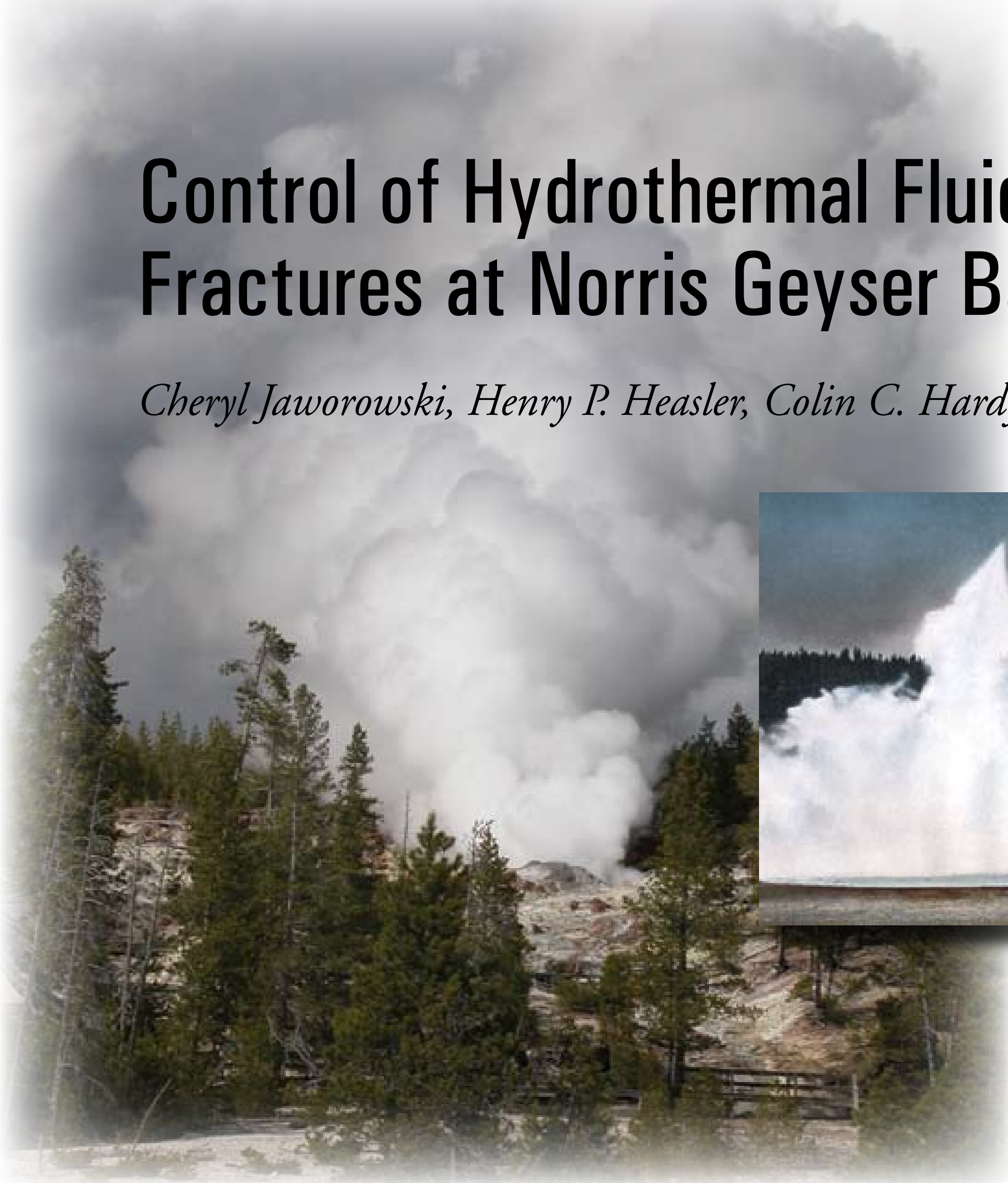
[27] William Henry Jackson photograph number 82, reproduced in Merrill, *Yellowstone and the Great West: Journals, Letters, and Images from the 1871Hayden Expedition* (Lincoln: University of Nebraska Press), 1999, p. 137. See also Jackson photo 1521 reproduced in Kinsey, *Thomas Moran*, p. 54. This is the photo used on the cover of National Park Service, *Cultural Landscapes Inventor, Artist Point, Yellowstone National Park*, 2005.

[28] These photos are pasted onto yellow cardboard mounts and are in the Bob Berry collection of Cody, Wyoming.

Control of Hydrothermal Fluids by Natural Fractures at Norris Geyser Basin

Cheryl Jaworowski, Henry P. Heasler, Colin C. Hardy, and Lloyd P. Queen

F.J. Haynes postcard of Norris Geyser Basin showing Porcelain Basin and the boardwalk descending from the Norris Museum. The hill above Porcelain Basin is made of till overlying tuff from the third catastrophic eruption of the Yellowstone volcano.



Steamboat Geyser (steam phase) during a major eruption, 2003. Fractured and hydrothermally altered Lava Creek B tuff forms the hill around Steamboat. NPS photos.

SINCE 1885, U.S. Geological Survey (USGS) maps show Norris Geyser Basin as the name of a remarkable thermal basin in northern Yellowstone National Park (Haines 1996). In his book, *Yellowstone Place Names,* Aubrey L. Haines (1996) recounts how the second superintendent of Yellowstone from 1877 to 1882, Philetus W. Norris, gave the geyser basin its name:

> *"…'Norris Geyser Plateau' made its appearance in 1879. He may not have known that the Hayden Survey had already named that thermal area Gibbon Geyser Basin on its 1878 topographic map (which was only 'in press' in 1881 and not yet available). However that may be, Norris changed the form of his usage to Norris Geyser Basin in 1881, and that form, confirmed by the United States Geological Survey in 1885, has remained in unquestioned use."*

Norris Geyser Basin is dynamic. It is noted for its acidic geysers; the highest measured subsurface temperature in the park (238°C, or 460°F, at 332 m depth within the 1960s USGS research drill hole Y-12); the world's tallest active geyser, Steamboat Geyser; and thermal disturbances. Known to occur throughout the year, thermal disturbances affect thermal features along natural fractures. During thermal disturbances, dormant features may become active, thermal waters change from clear to muddy, the pH of hydrothermal waters changes, and increased boiling changes pools to fumaroles.

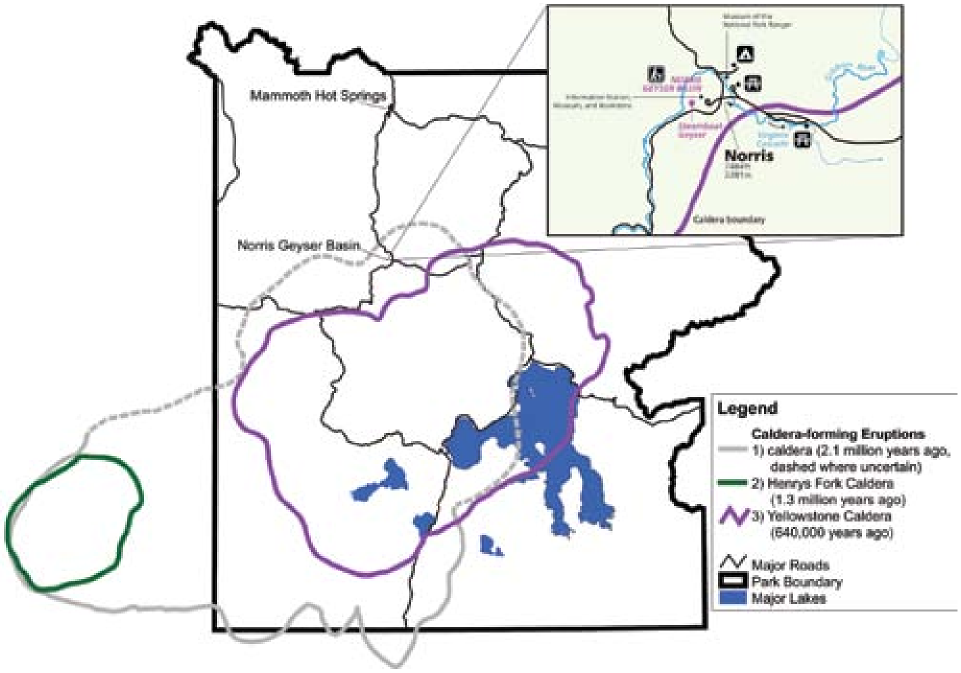


Figure 1. Map of Yellowstone National Park showing the location of Norris Geyser Basin and calderas from eruptions of the Yellowstone volcano 2.1 million, 1.3 million, and 640,000 years ago. *(The 2.1- and 1.3-million-year-old caldera boundaries were adapted from USGS Fact Sheet 2005-3024 "Steam Explosions, Earthquakes, and Volcanic Eruptions—What's in Yellowstone's Future?" and the 640,000-year-old Yellowstone caldera boundary is from Christiansen 2001.)*

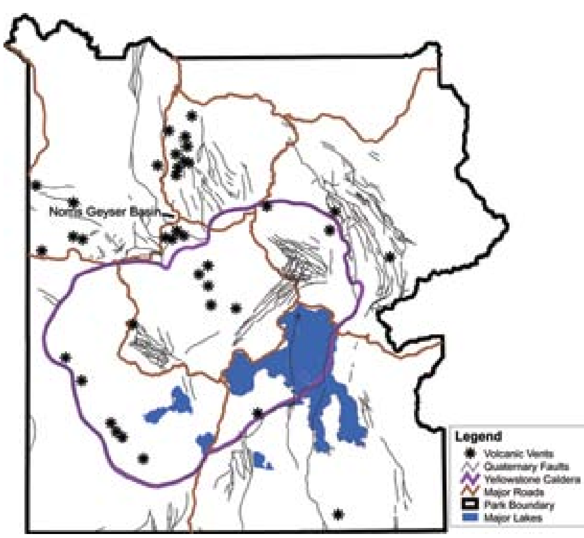


Figure 2. Map showing faults active during the last 1.6 million years, and volcanic vents (asterisks) since the eruption 640,000 years ago. North–south, northwest, northeast, and near east–west trending faults are shown. Notice the northwest trending vents of lava flows since the eruption 640,000 years ago. *(Caldera, domes, and volcanic vents from Christiansen 2001; Quaternary faults from USGS Earthquake Hazards Program, Quaternary fault and fold database for the U.S., http://earthquake.usgs.gov/regional/qfaults/).*

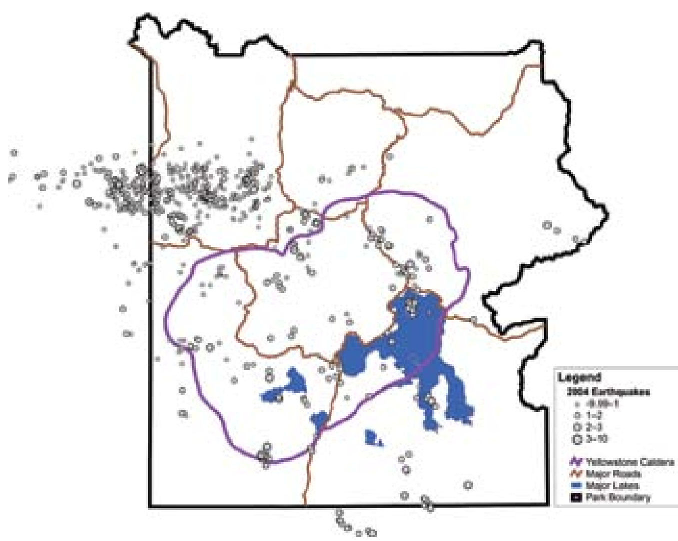


Figure 3. Map showing the location of earthquakes during 2004. Dots show the magnitudes of earthquakes. Large dots indicate earthquakes greater than magnitude 3.0. Notice the northwest trend of earthquakes within the caldera and the near east–west trends of earthquakes outside the Yellowstone caldera. *(Earthquake data from the University of Utah seismic station website, http:seis.utah.edu/catalog/ynp.shtml).*

Geographic and Geologic Setting

Norris Geyser Basin is approximately 20 miles south of Mammoth Hot Springs, between the northern rims of the 2.1-million-year-old and 640,000-year-old calderas, which formed during two of the three cataclysmic, caldera-forming eruptions of the Yellowstone volcano in the last 2.1 million years (Figure 1). Three major geologic structures intersect at the basin: (1) the boundary of the 640,000-year-old Yellowstone caldera; (2) the southern end of a north–south trending fault zone known as the Norris–Mammoth Corridor (Figure 2); and (3) an active east–west trending zone of earthquakes that extends from Norris Geyser Basin west towards Hebgen Lake in Montana (Figure 3).

Yellowstone National Park's volcanic and glacial history play a role in the hydrothermal activity visitors see at Norris Geyser Basin, where natural fractures are visible in the landscape, affect drainages, and control the flow of hydrothermal fluids. Heat is the principal driver of water through the fractured volcanic tuff (rock composed of the finer kinds of volcanic ejecta usually fused together by heat) and various glacial sediments via a system of natural fractures that relate to active faults and local geologic structures. Natural fractures can be seen at outcrops, in excavations, and in the landscape around Norris Geyser Basin. Segments of Tantalus Creek, the major creek draining the basin, follow north, northwest, and northeast trending fractures. On shaded digital elevation models or topographic maps, north and northeast trending creeks are apparent. Existing thermal features and newly formed thermal features develop along or at the intersection of natural fractures within volcanic rocks from Yellowstone's last caldera-forming eruption 640,000 years ago.

Within the park, faults that show movement since 1.6 million years ago show similar trends to the natural fractures at Norris Geyser Basin (Figure 2). Vents associated with lava flows (rhyolitic and basaltic) since the eruption 640,000 years ago also show a northwest trend similar to the natural fractures within the basin (Figure 2). In addition, east–west and northwest trends of earthquakes are apparent on maps showing seismic activity (Figure 3).

Volcanic tuff from the third major catastrophic eruption of the Yellowstone volcano, known as the Lava Creek tuff (A and B members), forms the bedrock within the geyser basin (Figure 4). Lava Creek B tuff crops out at the surface, and Lava Creek A tuff was encountered in research drill holes during the 1960s (White et al. 1988). Christiansen (1975) described the Lava Creek B tuff as a gray, brown, or pinkish-gray, ash-flow tuff that is generally densely welded except at its top and bottom.

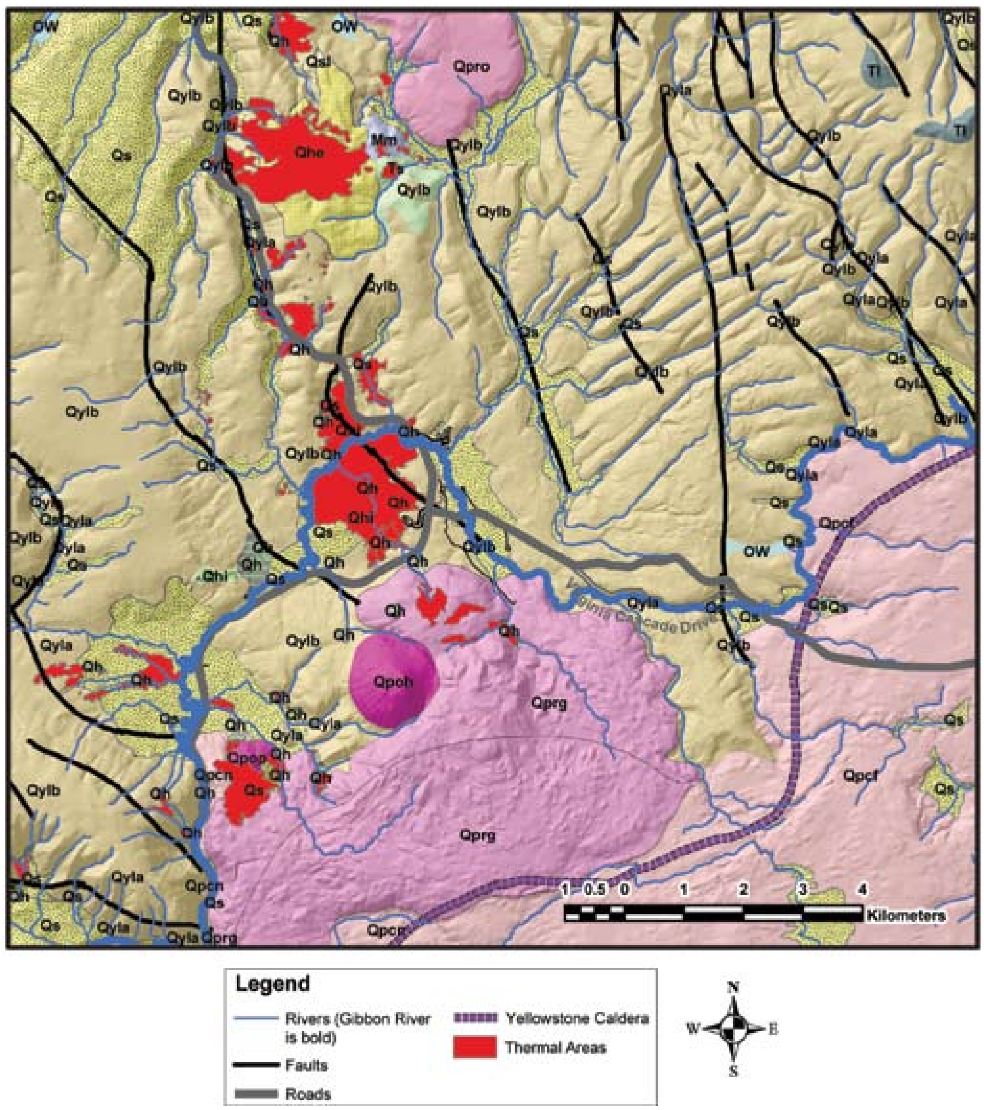


Figure 4. Bedrock geology of the greater Norris area (from Christiansen 2001) over digital elevation model, showing major north and northwest trending faults, the Lava Creek B tuff (tan colors, Qylb), hydrothermal areas (red color, Qh symbol), and rhyolitic lava flows since the eruption 640,000 years ago (pink colors: Gibbon River flow, Qprg; Solfatara flow, Qpcf; Obsidian Cliff flow, Qpro; Gibbon Hill Dome, Qpoh; and Paint Pot Hill Dome, Qpop).

Welding is a process of joining shards of volcanic glass together to form a rock that resists erosion. At Virginia Cascades to the east of Norris Geyser Basin, Christiansen (2001) describes the following characteristics of the Lava Creek B tuff from bottom (oldest rock) to top (youngest rock): (1) a basal, crystal-rich ash zone usually covered by talus; (2) a non-welded to partly welded zone with columnar jointing or fractures; (3) a moderately welded, platy-jointed zone; (4) a moderately welded zone; (5) a moderately welded and vertically fractured zone; and (6) an uppermost, densely welded zone that is weathered. The welded tuff with columnar fractures, the zone of platy-fractured tuff, and the vertically fractured tuff form fascinating outcrops along roadways and spectacular waterfalls. Fournier and others (1994) stated that the Lava Creek tuff "has little primary permeability." Therefore, a network of connected fractures is necessary to move hydrothermal fluids through this bedrock.

> …a network of connected fractures is necessary to move hydrothermal fluids through this bedrock.

Within Norris Geyser Basin, various glacial and ice-contact (sand or gravel-size sediment that has been transported and deposited by water alongside ice) sediments from the last major glaciation of the Yellowstone Plateau rest on top of the Lava Creek B tuff. Ice-contact sediments and till (an unsorted mixture of various size sediments deposited by ice) compose the topographically high landforms within Norris Geyser Basin. Till forms deposits approximately 0.5–1 m thick (White et al. 1988) on surrounding hills. Ice-contact sediments up to 100 feet thick (Richmond and Waldrop 1975) compose the Ragged Hills, which are thermal kames that formed when melting ice deposited sand and gravel within a hydrothermal area.

Volcanic flows of rhyoltic lava surround the periphery of the basin on the south and east: the 116,000-year-old Gibbon Hill Dome, 90,000-year-old Gibbon River flow, and 110,000-year-old Solfatara flow (Christiansen 2001). The 90,000-year-old Gibbon River flow is significant because it formed a dam that impounded water within Norris Geyser Basin and other low-lying areas (Richmond and Waldrop 1975; White et al. 1988). These lava flows are just a few of the rhyolitic lavas that have constructed the present landscape and filled in the Yellowstone caldera since the eruption 640,000 years ago.

Surface Hydrology

The present-day drainage of the Gibbon River and its tributaries developed as Pinedale-age ice receded (~14,000 years ago) from the area. The Gibbon River starts on the 110,000-year-old Solfatara Plateau and flows generally west along the boundary of the Solfatara rhyolite flow (Qpcf on Figure 4) and the Lava Creek B tuff (Qylb on Figure 4) until Virginia Cascades. At Virginia Cascades, the Gibbon River flows along an east–northeast trend until it reaches a broad north–northwest trending meadow at Norris Junction. From Norris Junction, the Gibbon River gently curves around Norris Geyser Basin until it enters the northeast trending Elk Meadows. The Gibbon River and its tributary, Tantalus Creek, erode various glacial, meltwater, and ice-contact sediments.

Within Norris Geyser Basin, Tantalus Creek drains the geyser basin and contributes thermal water to the Gibbon River. For the Gibbon River, instantaneous discharge measurements by D. Susong (U.S. Geological Survey) and H. Heasler (Yellowstone National Park) on July 14–15, 2004, showed the following discharge values: 43 cubic feet per second (cfs) upstream of Norris Geyser Basin; 47 cfs upstream of the Gibbon's junction with Tantalus Creek; and 54 cfs downstream of its junction with Tantalus Creek. Thermal water composes 100% of the water flowing within the Tantalus Creek drainage and into the Gibbon River. Precipitation contributes the *only* non-thermal water that flows within Tantalus Creek. On July 14–15, 2004, Tantalus Creek contributed 3.5 cfs to the flow of the Gibbon River (Susong and Heasler 2004, unpublished data). For 2005, discharge measurements of Tantalus Creek ranged from 3 to 5 cfs (USGS 2006).

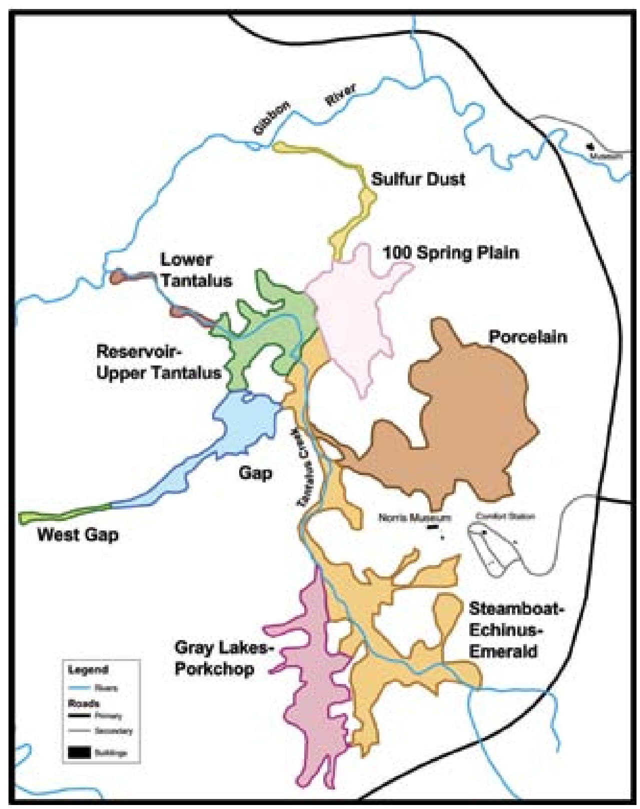


Figure 5. Map showing the hydrothermal sub-basins within Norris Geyser Basin. Using a digital orthophotograph as a base map, the surface flow of hydrothermal fluids provided the boundaries for delineation of the nine hydrothermal sub-basins.

The tributaries of Tantalus Creek form hydrothermal sub-basins of the Tantalus drainage: (1) Porcelain, (2) Steamboat-Echinus-Emerald, (3) Gray Lakes-Porkchop, (4) One Hundred Spring Plain, (5) Lower Tantalus, (6) Reservoir-Upper Tantalus, (7) Gap, (8) West Gap, and (9) Sulfur Dust (Figure 5). Thermal waters from two small areas (the Gap and Sulfur Dust sub-basins) do not flow into Tantalus Creek, but directly into the Gibbon River. This unique drainage of a geyser basin by Tantalus Creek provides an excellent geographic setting for geothermal monitoring and understanding the dynamics of a hydrothermal system.

Previous Work on Natural Fractures and Faults

Previous observations by scientists noted that natural fractures played a role in Yellowstone National Park (Christiansen 1966; Pierce 1966; Prostka 1966; Ruppel 1966; Keefer 1968; Pierce 1968; Smedes 1968) and the hydrothermal activity of Norris Geyser Basin (White et al. 1988; Fournier et al. 1994). The earliest studies of faults and fractures were initial assessments about the feasibility of airborne infrared and radar imagery for mapping Yellowstone's geology. These studies tested 3–5 micron infrared imaging scanners and active K-band radar sensors. The scientists involved in this early assessment of airborne infrared and radar imagery conducted subsequent studies on Yellowstone's volcanic rocks, glacial geology, and geology of the greater Yellowstone area. However, Ruppel's (1966) evaluation of radar imagery in the southern Gallatin Range and vicinity is most relevant to our observations of fractures in Norris Geyser Basin. Ruppel (1966) noted a system of northeast and northwest lineaments, or large lines, drawn on airborne or satellite imagery. He wondered if these lineaments represented fractures in ancient rocks.

Figure 6. Sunday Geyser in Porcelain Basin shows the intersection of major northeast and northwest trends in the Lava Creek B tuff.

Focusing on Norris Geyser Basin, White et al. (1988) observed that spring vents, tree lines, geologic features, and drainage patterns were all generally oriented to the north, northwest, and northeast. Also, White et al. (1988) noted that the well-developed network of fractures within the Lava Creek B tuff was expressed at individual thermal features such as Hurricane Vent, Valentine, Ledge, and Basin geysers. They related north trending structures to the Norris–Mammoth Corridor, and northeast trending features to the Hebgen Lake system.

Fournier et al. (1994) noted that natural fractures also played a role in the geochemistry and formation of thermal features within Norris Geyser Basin. In discussing the geochemistry of boiling pools at Porcelain Terrace, Fournier et al. (1994) state:

> *"At Porcelain Terrace these acid-sulfate pools all formed after the 1959 Hebgen Lake earthquake, when newly formed fractures allowed the hot spring water to leak sideways and flow onto ground at slightly lower elevations at the side of the terrace.… At the side of Porcelain Terrace, relatively high-chloride (550–800 mg/kg) low-sulfate (10–50 mg/kg) pH-neutral waters generally issue from a deep reservoir with an estimated temperature of 270 to 325°C…typical of thermal waters issuing along a north-trending zone at the west side of Porcelain Terrace."*

Observations of Natural Fractures at Outcrops

Natural fractures can be seen at all scales: within individual thermal features, at outcrops, within human excavations, and on airborne thermal infrared imagery. Within Porcelain Basin, Sunday Geyser (Figure 6) clearly shows that it formed at the intersection of northeast and northwest trending fractures developed within the Lava Creek B tuff. After the July–October 2003 thermal disturbance, new thermal features developed along an east–west trend approximately 40 meters east of Porkchop Geyser (Figure 7). These once steaming areas of ground are now thermal pools that developed along a network of fractures (east–west and north–south).

Figure 7. New thermal features forming along or at the intersection of natural fractures in the Back Basin near Porkchop Geyser.

East of Norris Geyser Basin, fractured Lava Creek tuff occurs in excavations and road cuts. Work on the Norris wastewater plant, water treatment plant, and the sewage line for the comfort station at Norris Geyser Basin exposed natural fractures within excavations (Figures 8, 9, and 10). These excavations exposed near-vertical natural fractures with the following trends: north to north–northeast (11–20°, 30°), northeast (50–55°), west–northwest (255°, 290°) northwest (330°), and north–northwest (345°). Sub-parallel, northeast trending (50°) fractures were the longest fractures exposed in the excavations, and they were spaced about 5–10 cm apart in zones of intense fracturing. Along fractures, hydrothermal fluids bleached the Lava Creek tuff to white, yellow-brown, or orange-brown. These hydrothermally altered zones were oriented vertically and near horizontally. Traveling east from the Norris wastewater plant, fractures crop out along the one-way drive to Virginia Cascades. The weathered and fractured Lava Creek tuff makes for a scenic drive near water flowing over a ledge of resistant rock within the Lava Creek tuff (Figure 11).

Figure 8. Natural fractures exposed during an excavation for the Norris water treatment plant, September 2003. The water level in the excavation is about (±1 foot) equal to the water level of the nearby Gibbon River.

Figure 9. Natural fractures exposed in an excavation for the Norris wastewater treatment plant, June 2004. Notice the near-vertical natural fractures, the spacing of fractures, and the hydrothermally altered fracture surfaces of the Lava Creek B tuff. Dark colors show moist zones within the outcrop.

Figure 10. Natural fractures exposed within a sewage trench connecting the water treatment plant with the comfort station at Norris Geyser Basin. The trench exposed fractured (northeast, northwest, north) and hydrothermally altered Lava Creek B tuff.

Natural Fractures Seen From Aircraft

On October 9, 2002, an aircraft-borne remote sensing system, called Spectra View® (Airborne Data Systems 2006), was deployed to acquire imagery in the mid-infrared (3–5 micron), near-infrared (0.77–0.97 microns), and three visible bandpasses (blue [0.46–0.52 microns], green [0.54–0.60 microns], red [0.64–0.70 microns]) along north–south flight lines over Norris Geyser Basin. Image data were acquired at noon and again after nightfall over a contiguous area approximately 16 km by 6.5 km. The airborne sensor system is a 5-channel, multispectral, digital remote sensing system with a geolocation protocol utilizing a global positioning system (GPS) and an inertial measurement unit (IMU) attitude detection and recording system. Yellowstone geology staff supported this effort by placing temperature loggers in six thermal pools of different temperatures along the flight path, each recording near-surface ("skin") temperatures simultaneously with the airborne acquisition. Data from these temperature loggers provided kinetic skin temperatures for calibrating the radiant temperatures associated with the airborne thermal imagery.

Colin Hardy, a fire researcher at the Missoula Fire Sciences Laboratory (USDA Forest Service, Rocky Mountain Research Station), processed and analyzed a subset of images—105 daytime and 105 nighttime images—centered along the Norris–Mammoth Corridor from Roaring Mountain to Norris Geyser Basin as part of his doctoral studies at the University of Montana (Hardy 2005). Errors in the data include geolocation, striping, and band-to-band registration between visible and thermal infrared images. The geolocation errors are due to precision and timing of the IMU/GPS georeferencing system. These errors introduce uncertainties with respect to location on the ground both within individual images and between images. In addition, the thermal infrared band exhibited a shift of 17 meters to the southeast relative to the other visible bands. Therefore, it was necessary to exploit a suite of geometric correction software tools to correct the band-to-band misregistration as well as to improve the overall georegistration of the five-band image data to a known, georegistered reference image. Viewing of the thermal infrared imagery also showed an along-track striping bias due to internal system anomalies within the 256 by 256 infrared detector array. After georegistration of the images, a prominent northwest–southeast striping was apparent in the thermal infrared nighttime imagery, particularly at low digital (brightness) numbers. Because the set of standardized software filters was unsuccessful at removing the striping, researchers developed and applied a customized, local-neighborhood (smoothing) routine. Although the striping and positional errors were significantly reduced, their presence reduce the analytical certainty of an otherwise remarkable nighttime, thermal infrared mosaic of the greater Norris area.

> The nighttime, thermal infrared mosaic of the Norris area showed an obvious pattern of major northeast and northwest trending fractures controlling the flow of hydrothermal fluids…

In addition to geometric correction of the airborne imagery, a series of radiometric calibrations were performed in order to convert the raw image data into kinetic temperature values. Intersections of image sample (pixel) locations with thermal logger (ground) locations were used to calibrate a linear model that yielded temperature values for all image pixels acquired during the overflight. (In 2005, an additional set of calibration references were deployed in order to improve the linear calibration model, especially in areas of relatively high, circa 80°C, surface kinetic temperature.) After hundreds of hours processing the imagery, a thermal infrared mosaic (geolocated within ±10 m) depicted surface kinetic temperature calibrated to ±5°C.

The calibrated, nighttime, thermal infrared mosaic of Norris Geyser Basin provides a snapshot of active thermal features within the basin and along the Norris–Mammoth Corridor. The nighttime, thermal infrared mosaic of the Norris area (Figure 12) showed an obvious pattern of major northeast and northwest trending fractures controlling the flow of hydrothermal fluids—the same pattern of fractures noted within individual thermal features, at outcrops, on maps, and in excavations. The image clearly shows dominant directions (northeast and northwest) for movement of hydrothermal fluids through the numerous fractures within the Lava Creek B tuff and overlying sediments. An interconnected network of natural fractures allows thermal waters to move vertically and horizontally through the otherwise tight subsurface rock and

Figure 11. Photograph of Lava Creek tuff along the scenic, one-way drive to Virginia Cascades. East–northeast (70°), north–northwest (352°), and northwest (330°) trending fractures aid the weathering of the Lava Creek tuff and allow plants to take hold in the cracks.

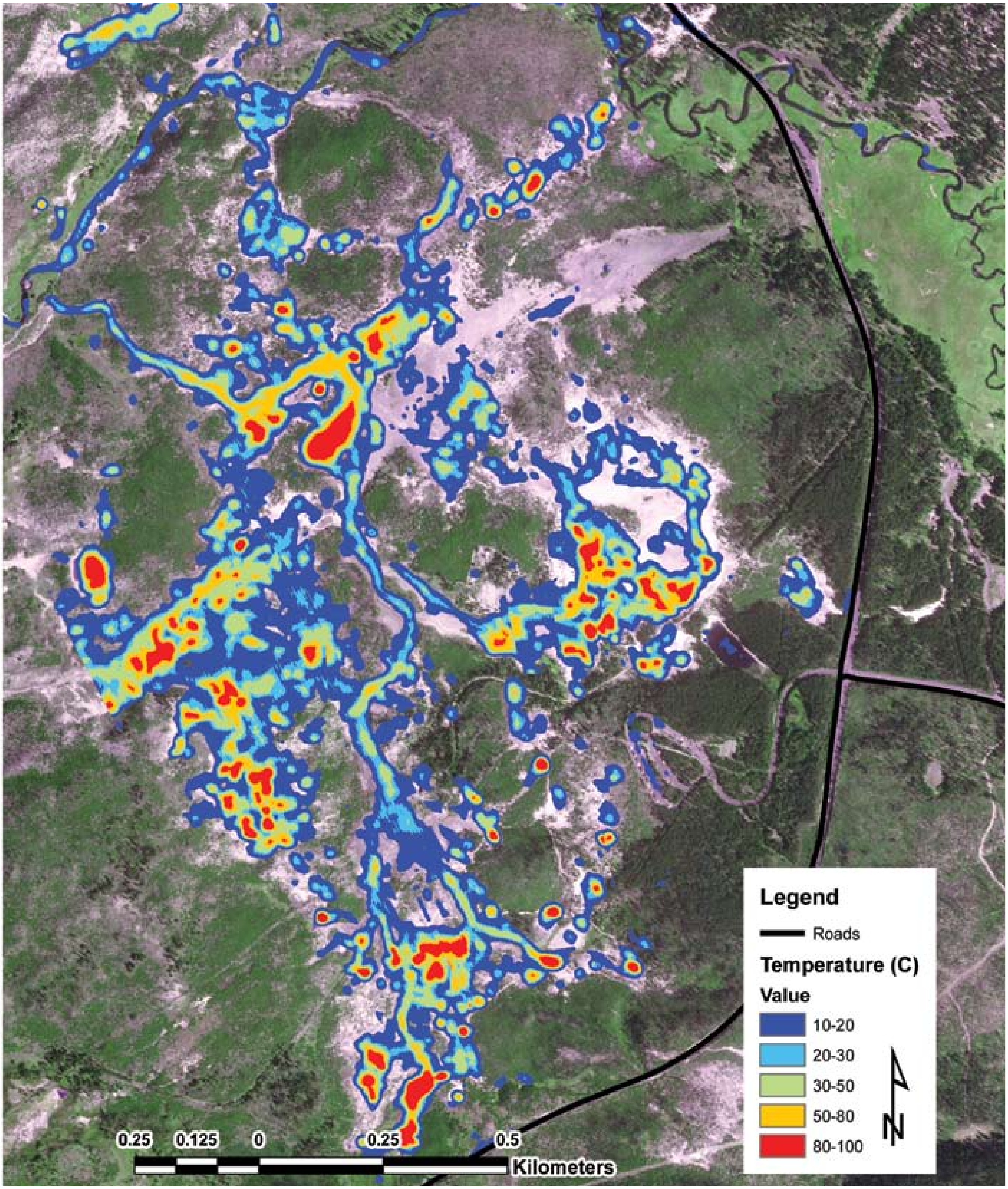


Figure 12. Calibrated, nighttime, thermal infrared image over Norris Geyser Basin, draped over a color infrared digital orthophotograph. The red (80–100°C) and orange (50–80°C) colors indicate hot thermal features. Green (30–50°C) and light blue (20–30°C) indicate areas of warm thermal waters. The river flowing from the top right of the picture around Norris Geyser Basin and toward the top left of this picture is the Gibbon River. Notice the two major trends in the orientation of active thermal features for Norris Geyser Basin: northeast and northwest. East of the Mammoth–Norris road, the Gibbon River flows in a northwest direction. West of the road, the Gibbon River generally flows around Norris Geyser Basin in a southwest direction following the other major fracture trend.

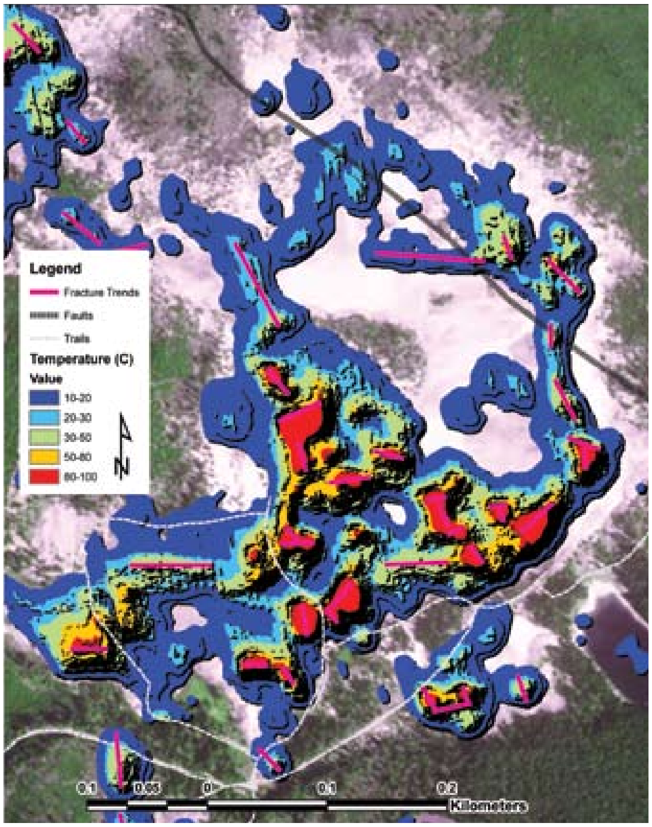


Figure 13. Nighttime, thermal infrared mosaic combined with a color infrared digital orthophotograph and a filtered image for the Porcelain sub-basin. The calibrated, thermal infrared mosaic for the Porcelain sub-basin shows that a major zone of northwest trending fractures controls the flow of hydrothermal fluids. This zone of northwest trending fractures parallels a previously mapped northwest zone of faulting.

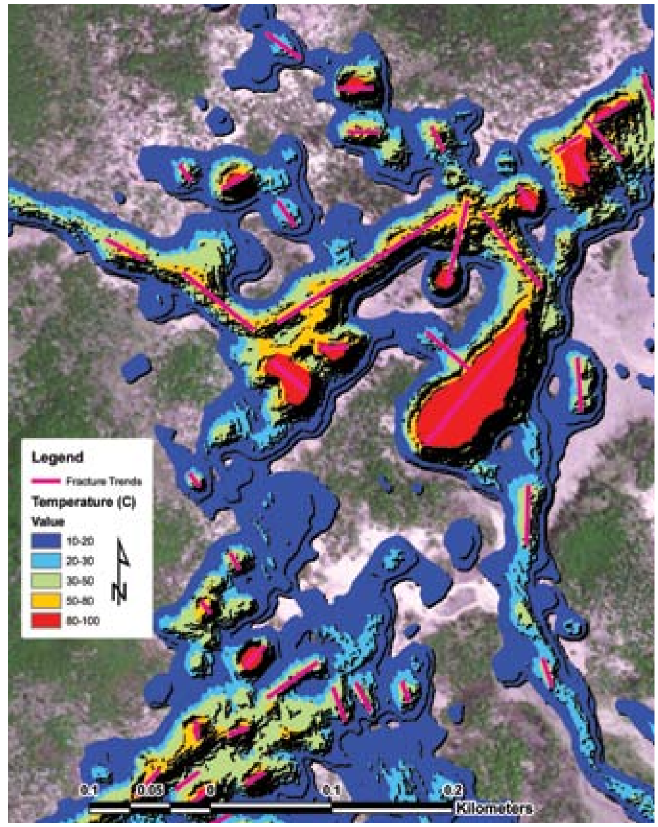


Figure 14. Nighttime, thermal infrared mosaic combined with a color infrared digital orthophotograph and a filtered image for the Reservoir-Tantalus sub-basin. Hydrothermal fluids follow northeast and northwest trending fractures. Other fracture patterns (near east–west and north–south) also control hydrothermal fluid flow. Note the circular areas of high temperature. Known hydrothermal explosion features and possible hydrothermal explosion features stand out as saturated circular pools.

overlying glacial sediments, to eventually flow onto the surface of Norris Geyser Basin.

Examination of Porcelain Basin shows east–west, northwest, and northeast trending fractures (Figure 13). A major zone of northwest trending fractures divides Porcelain Basin and controls the flow of hydrothermal fluids within this sub-basin. This zone appears to coincide with a regional zone of northwest trending faults (compare Figure 4 and Figure 13) mapped by Christiansen (2001). Northwest trends appear to terminate at northeast and east–west trending fractures.

A dominant northeast trend of hydrothermal fluid flow is apparent within the Gap and the Reservoir-Tantalus sub-basins (Figure 14). Within the Gap, numerous intersections of northeast and northwest trending fractures account for the Swiss cheese-like maze of thermal features on the thermal infrared image. This maze of intersecting fractures within cemented, ice-contact deposits contributes to the highly unstable ground within the Gap.

The Back Basin of Norris encompasses two major hydrothermal sub-basins: the Steamboat-Echinus-Emerald and the Gray Lake-Porkchop sub-basins. Both sub-basins clearly show hydrothermal fluid flow along northwest, near east–west, and north–south trending fractures. Northeast trending fractures appear less prominent than in other hydrothermal sub-basins.

In places, the amount of till and cemented, ice-contact deposits over the bedrock makes it difficult to interpret fracture trends. For example, the numerous active thermal features within One Hundred Spring Plain developed within a thick deposit of stream and ice-contact sediments overlying cemented pre-Pinedale deposits and fractured Lava Creek tuff. Within One Hundred Spring Plain, a system of northwest and northeast trending fractures localize the flow of hydrothermal fluids. Similarly, a thick deposit of cemented ice-contact sediments makes it difficult to remotely sense hydrothermal fluid flow along fractures within the Ragged Hills. However, northeast and northwest fracture trends do occur among the pockmarked surface of the Ragged Hills. East–west and north–south trending fractures are less obvious than the northeast and northwest trending fractures in these areas.

Major zones of fractures (Figure 15) are even more apparent when integrating the nighttime, thermal infrared mosaic of Norris Geyser Basin with the geologic map of White et al. (1988). The dominance of these major fracture zones varies among the hydrothermal sub-basins of Norris Geyser Basin. Major northwest and near east–west trending fractures separate One Hundred Spring Plain from Porcelain Basin. A major zone of northwest trending fractures appears to separate the Steamboat-Echinus-Emerald sub-basin from the Gray Lakes-Porkchop sub-basin. A major zone of northwest trending fractures also appears to separate the Porcelain sub-basin from the Steamboat-Echinus-Emerald sub-basin.

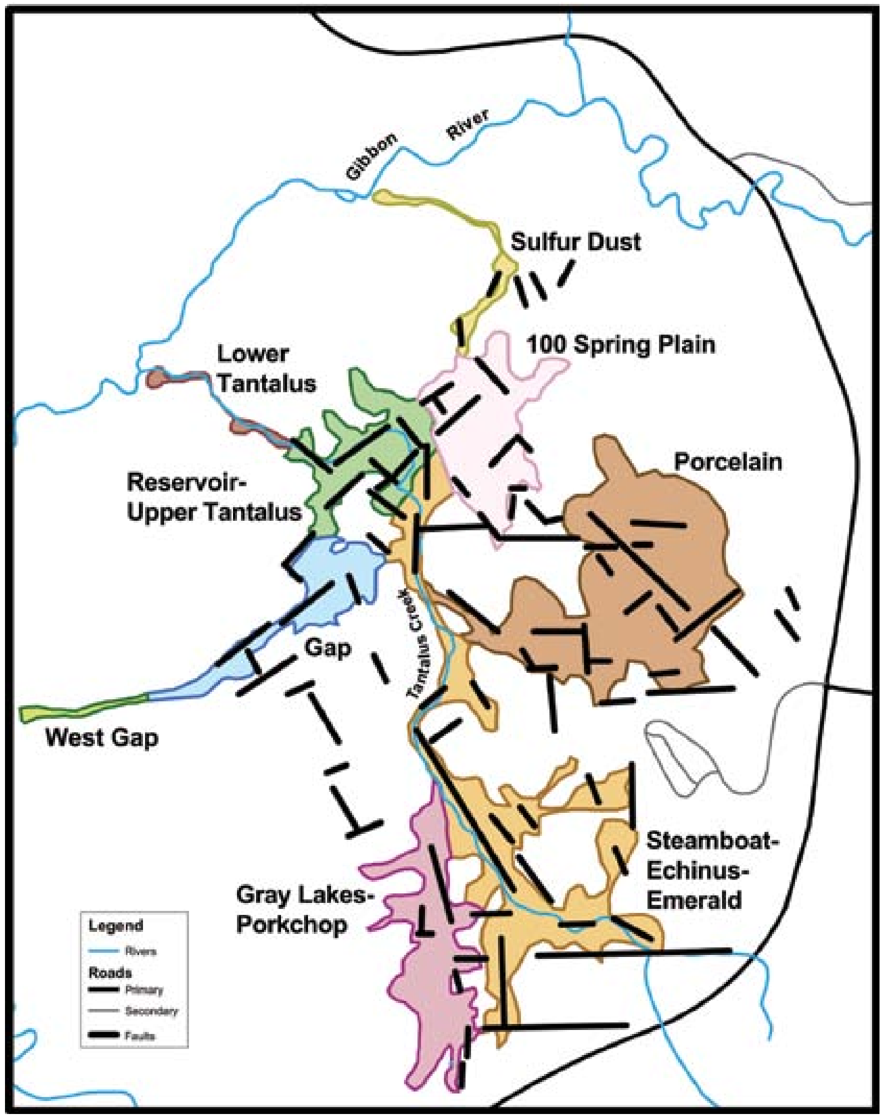


Figure 15. Map showing major fracture zones within Norris Geyser Basin. Significant variations in the dominance of the fracture trends occur among the hydrothermal sub-basins.

Summary

Natural fractures control the flow of hydrothermal fluids within Norris Geyser Basin at several scales: in individual features, at outcrops, within excavations, in sub-basins, basin-wide, and from an aircraft. Northeast, northwest, near east–west, and north trending fractures occur in all hydrothermal sub-basins within the basin. Examination of the October 2002 nighttime, thermal infrared mosaic of Norris Geyser Basin shows that two orthogonal fracture sets exist within Norris Geyser Basin: (1) north–south and east–west and (2) northeast and northwest. However, significant variations in the dominance of these fracture patterns occur among hydrothermal sub-basins. The trends of these natural fractures are similar to trends of active faults, local structures, and earthquakes.

Airborne thermal imagery has already proven its value in mapping hydrothermal fluid flow in the Norris Geyser Basin. Assessment of temperature patterns shown on these images follows a consistent train of logic related to prominent fracture zones within the geyser basin. It is important to note that the geometric and radiometric calibration of these data, while time-consuming, are a necessary prerequisite to accurate depiction of conditions in the basin at the time of image acquisition. *In situ* monitoring devices (i.e., temperature loggers) synchronized to the time of acquisition are essential to extracting a maximum amount of quality information from these remote sensor systems. Future work will extend the quality of reference data so that feature-based change detection and monitoring may be feasible.

Future Work on Norris Geyser Basin

Yellowstone National Park's geologists and researchers continue to collaborate on detecting change in Norris Geyser Basin using airborne thermal imagery. University of Montana researchers, in conjunction with the USDA Forest Service Fire Sciences Laboratory in Missoula, Montana, and Yellowstone National Park geologists directed a second remote sensing campaign over the Norris Geyser Basin in 2005 using the same sensor and aircraft described in preceding paragraphs. The objective of the 2005 thermal infrared image data acquisition was to compare it to the October 2002 thermal infrared imagery to detect changes. In October 2006, University of Montana and USDA Forest Service Fire Sciences Laboratory researchers acquired day and night thermal infrared imagery over Norris Geyser Basin and other areas of interest using a different (research grade) sensor and aircraft. This work will help to refine the fracture network controlling the fluid flow within Norris Geyser Basin and to estimate the changing flow of hydrothermal fluids.

In addition to this remote sensing effort, numerous scientists are studying the hydrothermal system within Norris Geyser Basin. U.S. Geological Survey and University of Utah researchers are studying the seismic and ground deformation within the geyser basin. Additionally, U.S. Geological Survey geochemists are investigating gas and water geochemistry in relation to hydrothermal fluid flow. University of Utah, U.S. Geological Survey, and National Park Service scientists are studying the shallow groundwater flux at Norris Geyser Basin. All of these studies and others will help us understand the very dynamic hydrothermal system that is Norris Geyser Basin.

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Norris Geyser Basin's Dynamic Hydrothermal Features

Using Historical Aerial Photographs to Detect Change

David Shean

THE SPECTACULAR hydrothermal features of Yellowstone National Park have captivated visitors and scientists alike since the late nineteenth century. While many efforts to monitor these geothermal features have been made, Yellowstone National Park implemented a scientific geothermal monitoring plan involving remote sensing during the last year. Among other efforts, the remote sensing portion of this geothermal monitoring plan calls for repeated airborne thermal surveys of high-priority hydrothermal areas in the park, including Norris, Upper, Midway, and Lower geyser basins.

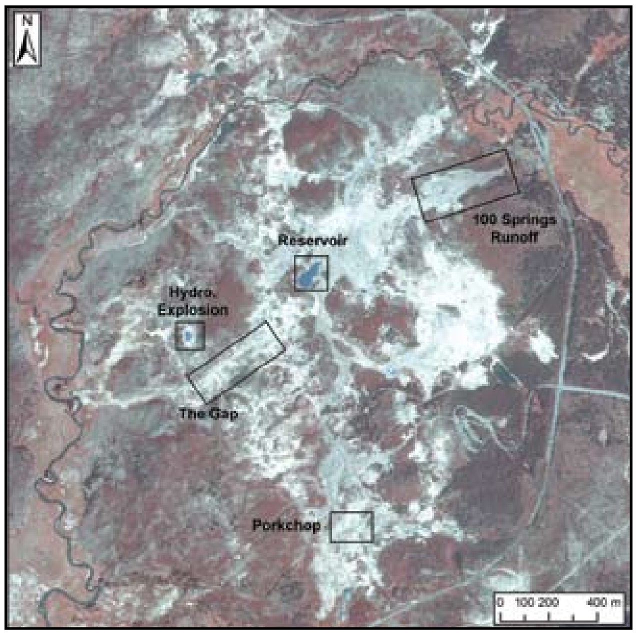

Figure 1. Context map for Norris Geyser Basin showing figure locations for preliminary change detection results over the 2001 color infrared digital orthophoto quarter quadrangle.

The Norris Geyser Basin is one of the most remarkable and dynamic geyser basins in Yellowstone. It is home to Steamboat, the world's tallest active geyser, and is renowned for its basin-wide hydrothermal disturbances. These disturbances are poorly understood, but can involve relatively rapid changes in water temperature, changes in water sediment content, renewed activity of dormant features, development of new features, and changes in eruption intervals for regular geysers.

I spent the summer of 2006 working in Yellowstone through the Geological Society of America's GeoCorps America Program. The goal of my project was to obtain high-accuracy (sub-meter) global positioning system (GPS) ground control points for several high-priority geothermal areas, and to use these points to properly georectify presently available and future airborne thermal image data. GPS points were collected for the Mammoth, Old Faithful, and Norris areas, and the thermal image data for the Norris and Old Faithful areas were rectified. I also conducted a search for historical aerial photographs and maps of the Norris Geyser Basin that could be used to detect changes in the hydrothermal features. This search involved several sources, including Yellowstone's Fire Cache map room and Planning, Compliance, and Landscape Architecture files; the Yellowstone Heritage and Research Center (HRC) archives and historic photo collection; Denver National Park Service (NPS) Technical Information Center; Yellowstone Dataset Catalog; U.S. Geological Survey (USGS) Earth Resources Observation and Science; and other resources on the web. The products of this search were scanned, orthorectified (when camera calibration reports were available), and compiled in a GIS database for analysis. In addition, a database was produced for aerial photo flightline index maps, which can be used to identify available data for future projects.

Re-rectification of Existing Color Infrared Digital Orthophotographs

In order to accurately georectify airborne thermal data for Norris, it was necessary to collect GPS ground control points using a high-accuracy (±15 cm) mobile mapping system. In addition, lines and polygons were collected to outline easily identifiable shapes or curves that would be difficult to map with just one point (e.g., trails with curves, circular hydrothermal features, or an arc of vegetation within a road pullout). These points provided sufficient detail to properly map the features after differential correction of GPS data. Due to the wide range of data (thermal, black and white, and color infrared images) used for this study, it was also necessary to have an accurate basemap to which all digital data could be registered. The best available data for re-rectification is the CIRDOQQ (color infrared digital orthophoto quarter quadrangle) image data which was flown in 2001 and is publicly available on the web. Comparisons of the CIRDOQQs with high-accuracy GPS points collected for the Mammoth, Norris, and Old Faithful areas revealed that the true horizontal accuracy is typically a few meters for the color infrared digital orhtophotographs.

Historical Maps and Aerial Photos

As part of the search for historical data on Norris Geyser Basin, several geologic maps were located, digitized, georectified, and incorporated into a geographic information system (GIS) database. These maps allowed for identification of individual features and geological units within the basin. They may also be useful for change detection, however, the accuracy of the earlier maps is questionable, and the boundaries of thermal features may only be approximate. A thorough analysis of these maps has not yet been completed.

An extensive search was completed to determine the availability of aerial photos for Norris Geyser Basin and the entire park. This search revealed that aerial photos were collected for the park from 1954 through 2002, with varying intervals between flights. They include black and white, true color, and color infrared photos. Parkwide flights were conducted in at least 1954, 1969, 1988, 1991, 1994 (DOQQ), 2001 (CIR-DOQQ), and potentially 1978 and 1998. There were many additional flights with limited coverage but higher spatial resolution (1956, 1962, 1965, 1971, 1972, 1977, etc.).

Results

Comparisons of the clipped, orthorectified aerial photographs with the re-rectified 2001 CIRDOQQ basemap show that the orthorectification process was successful. Offsets of a few meters were observed in some regions of the images, while others were almost perfectly aligned. Due to the large amount of time required for scanning and orthorectification, less than a week was dedicated to analysis of the data. Obviously, a thorough scientific analysis is necessary, but the preliminary results are promising. Even with these time limitations, several obvious changes were noted for prominent features in Norris Geyser Basin.

During the initial analysis, efforts were made to identify changes in the color, clarity, outline (shorelines), absolute location, and runoff patterns of hydrothermal features, as well as vegetation/thermal barren boundaries. A context map is shown in Figure 1, and brief discussions of the observations are presented in the captions of Figures 2–6.

There are many possible causes for the changes identified in Figures 2–6. They might be related to large earthquakes (Husen et al. 2002), ground deformation potentially related to gas or magma injection (Wicks et al. 1998; Wicks et al. 2006), changes in fluid motion at depth, hydrothermal disturbance activity, changes in precipitation input to the hydrological system, or some combination of these causes.

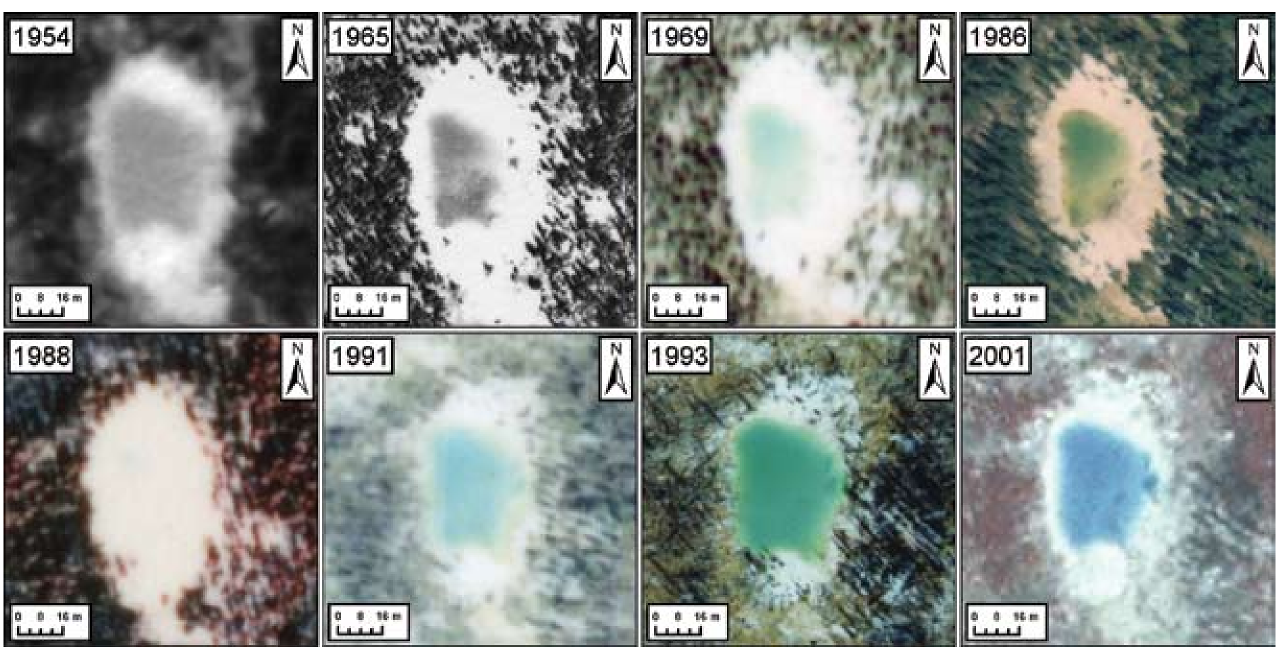

Figure 2. A relict hydrothermal explosion crater with central pool (White et al. 1988) ~200 m northwest of the Gap. Note the variations in water level, with highest apparent level in 1993.

A list of hydrothermal disturbance activity from 1926 to 1979 was obtained from the HRC library. The relevant hydrothermal disturbance dates from this list occurred on August 19, 1954 (18 days before the 1954 flight), September 25, 1965 (25 days after the 1965 flight), and September 9, 1978 (21 days before the 1978 flight). The 1978 hydrothermal disturbance may be related to the anomalous appearance of convective cells (attributed to boiling water) in the Reservoir (Figure 3). Cross-checking with ground-based observations of the Reservoir in 1978 should confirm or disprove this hypothesis. A comprehensive list of more recent hydrothermal disturbances has not yet been compiled.

In an attempt to understand some of the observed changes in the aerial photos, historical precipitation data was downloaded from the Western Regional Climate Center. Unfortunately, no data is available for the Norris area—the closest meteorological stations are located in Mammoth, Old Faithful, and West Yellowstone. Due to years with incomplete data and the large variation among these three stations, it is difficult to draw any conclusions about the influence of precipitation on individual hydrothermal features in Norris Geyser Basin. However, we do see that relatively dry periods were experienced around 1988 and 2001, when the runoff from the One Hundred Spring Plain appears to be minimal.

This technique appears to be a valuable tool for geothermal monitoring. However, it does have several limitations. It is apparent that the data type (color, black and white, color infrared) and resolution of the photographs are variable. This contributes two additional variables when attempting to isolate causes to explain any observed changes. The fact that the photos were taken at different times of the day and year also complicates interpretation. The shadows of trees and other features are of different lengths and extend in different directions for each photo. Finally, the features under study are active hydrothermal features, and thermal fog, steam plumes, and even erupting geysers can obscure the images. Despite these complications, the preliminary results presented here are promising, and many additional resources not yet investigated could provide important new data.

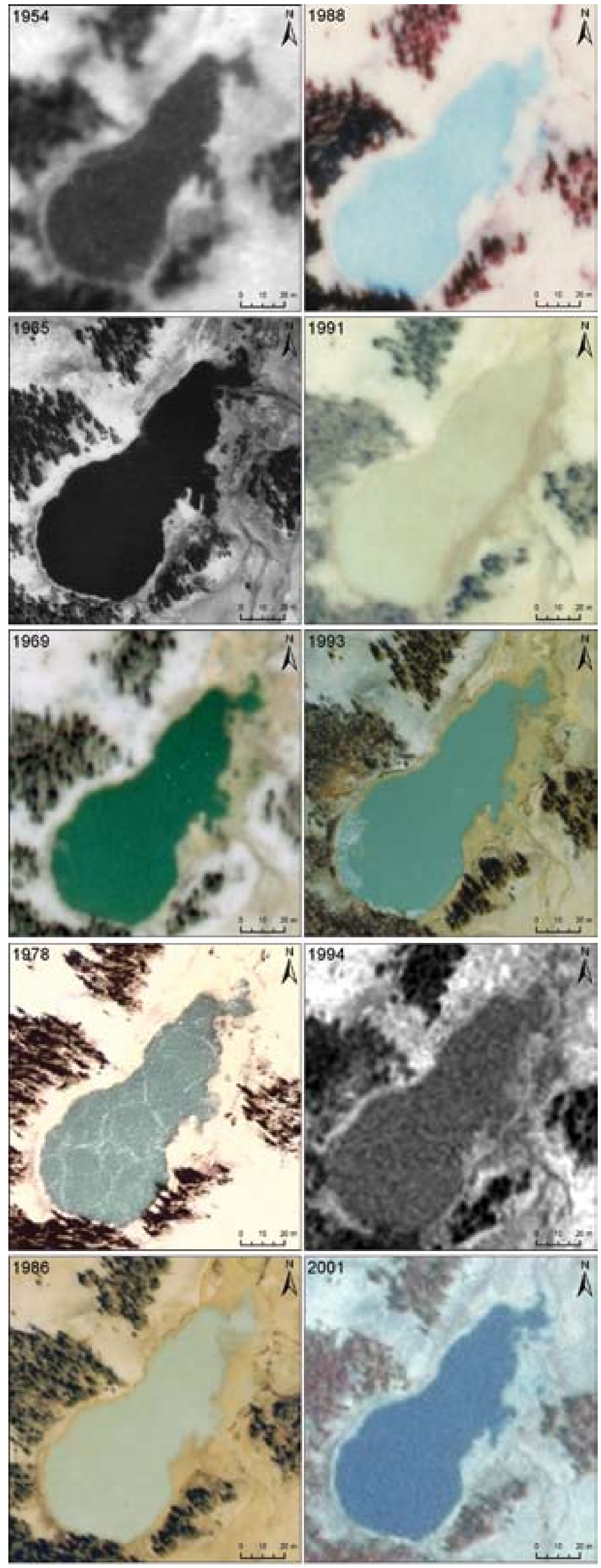

Figure 3. Aerial photos of the Reservoir. Note the remarkable stability of the borders since 1954. The 1991 photo shows a higher water level than any of the other photos, despite below-average precipitation levels during the period from 1990 to 1991. In addition, the 1978 photo shows what appear to be individual convective cells within the reservoir that are not seen in the other photos (despite similar resolution). This anomaly may be related to thermal disturbance activity that was recorded on September 9, 1978, just three weeks before the 1978 data were collected on September 30, 1978.

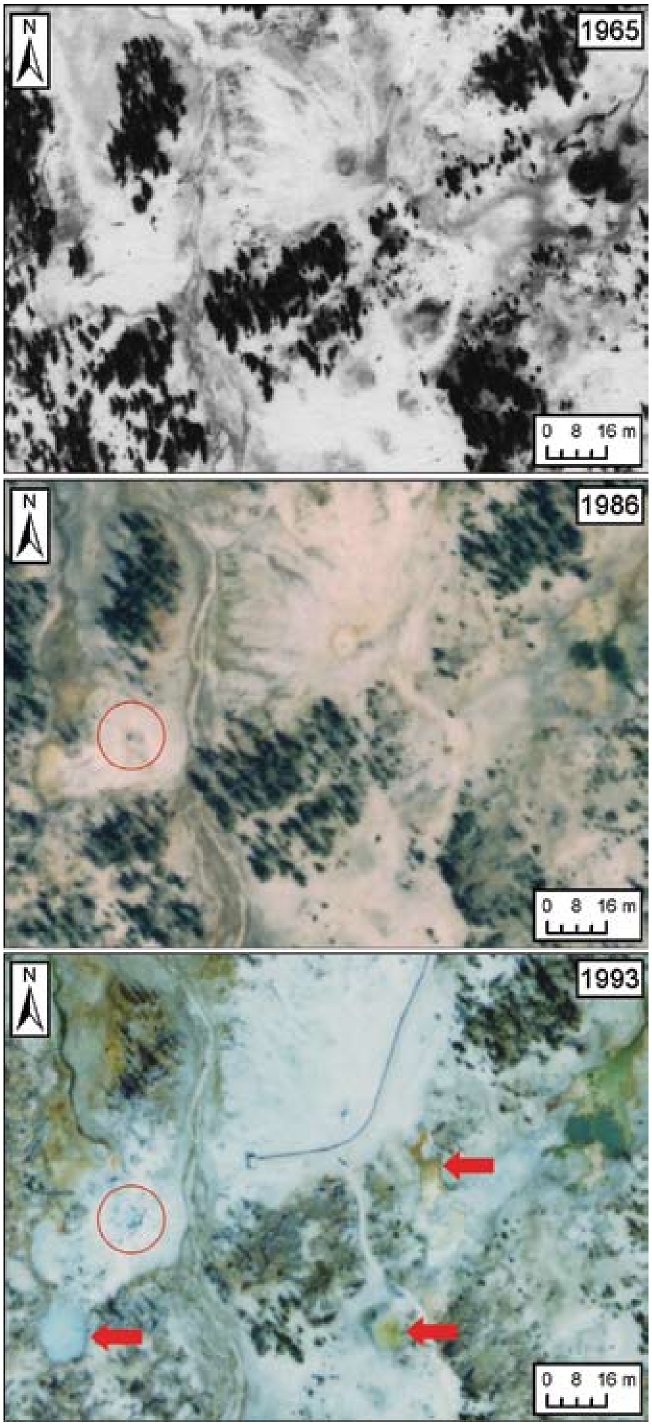

Figure 4. High-resolution aerial photos from 1965, 1989, and 1993 for the area near Porkchop Geyser. Red circles outline Porkchop, which underwent a hydrothermal explosion in 1989. Red arrows highlight new hydrothermal features observed in the 1993 photo. The large pool in the southwestern corner of the 1993 photo is not observed in 2001.

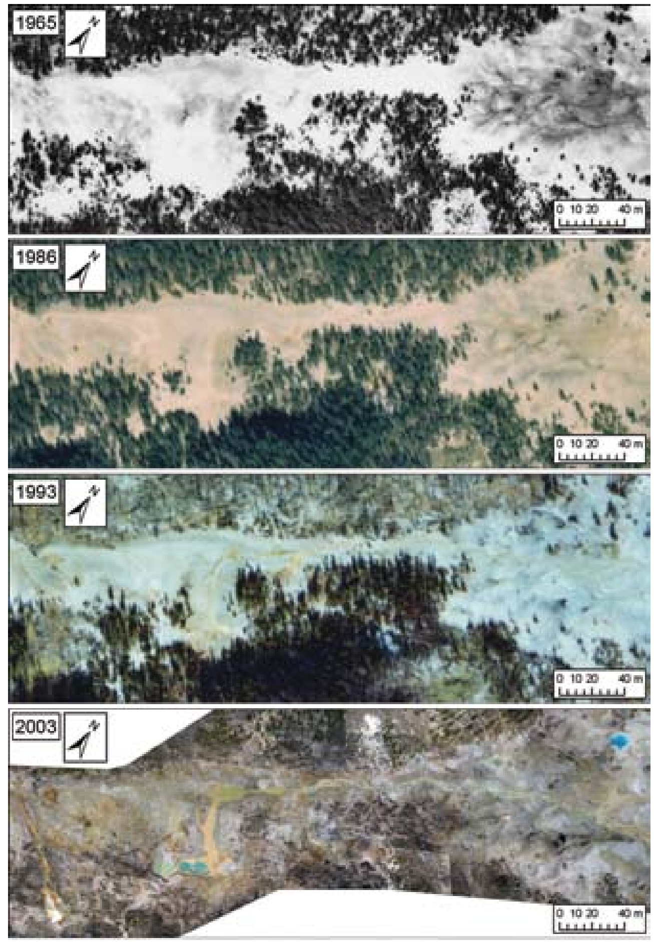

Figure 5. High-resolution aerial photos from 1965, 1986, 1993, and 2003 for the Ragged Hills area (the Gap). Note the apparent stability from 1965 to 1993, and the sudden appearance of several new hot springs between 1993–2003 (Ball et al. 2002; Planer-Friedrich et al. 2003), accompanied by notable changes in vegetation patterns.

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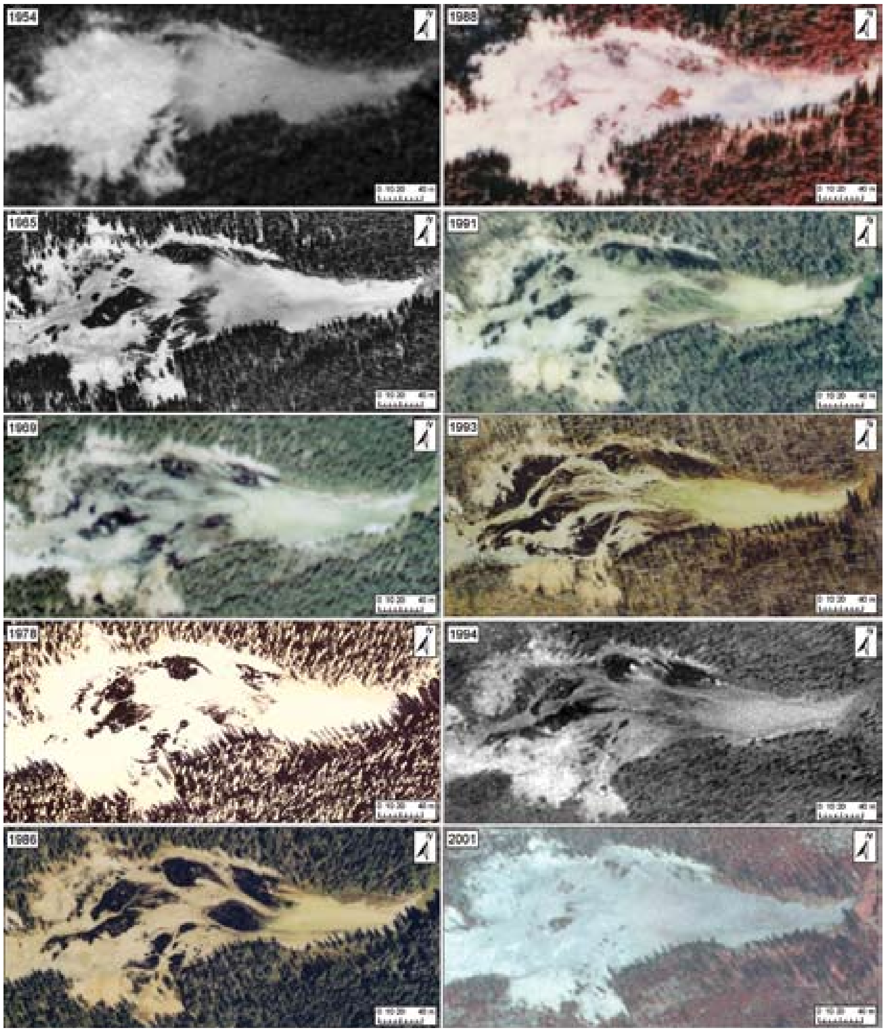

Figure 6. Aerial photos of the runoff from One Hundred Spring Plain. Note the apparent lack of bacterial/algal mats in 1988 and 2001, two years marked by below-average precipitation levels. While this apparent lack of mats may be partially related to the photo type (both of these flights are color infrared), we would expect the algal mats to be identifiable in the infrared band.

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Sapphire Pool, Biscuit Basin. Postcard by Detroit Photographic Co., ca. 1902.

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