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An 1871 photo by William H. Jackson of Crested Pool and Castle Geyser in the Upper Geyser Basin. The photo is part of the original album Jackson provided to the park from the US Geological Survey expedition. Jackson's photos were integral in the effort to establish Yellowstone National Park.

Using Thermal Infrared Imagery and LiDAR in Yellowstone Geyser Basins

Cheryl Jaworowski, Henry P. Heasler, Christopher M.U. Neale, and Saravanan Sivarajan

Yellowstone National Park's hydrothermal features were the main reason for the creation of the world's first national park. Over the years, many visitors, park staff, and scientists have viewed, sketched, and photographed Yellowstone's thermal features. Their protection is the primary focus of Yellowstone's peer-reviewed geothermal monitoring plan. Implementation of the monitoring plan has led to a new view of the hydrothermal systems in which a thermal area is more than the sum of its parts (thermal features, thermal deposits, altered ground, geothermal gases, thermal water, geology, and faults and fractures). It is a globally rare, composite natural resource that supports an array of recreational, economic, scientific, and cultural and natural heritage benefits.

In 2005, congress allocated funds to implement scientific monitoring of Yellowstone's hydrothermal systems. This paper highlights thermal infrared imaging results from a three-year collaborative study with the Remote Sensing Services Laboratory at Utah State University.

Yellowstone's Hydrothermal Areas

All of Yellowstone is listed as a significant thermal feature as defined by the congressionally enacted Geothermal Steam Act of 1970, amended in 1988 (*Federal Register*, vol. 52, 28795), that directs the Department of the Interior to monitor significant thermal features (*US Code* 30 § 1026, Mineral Lands and Mining). Thus, Yellowstone is required to monitor and protect its geothermal features from external threats such as those posed by geothermal development in Idaho (Island Park Known Geothermal Resource Area) and Montana (Corwin Springs Known Geothermal Resource

Area). Other potential threats to Yellowstone's geothermal systems include oil, gas, and groundwater development in Wyoming, Montana, and Idaho.

Yellowstone's earth-sourced heat (*geothermal*) can be found throughout the park. Often, visitors only see the water-sourced heat (*hydrothermal*) emanating from one of the thousands of hydrothermal features (geysers, hot springs, mudpots, and fumaroles) that make Yellowstone famous. In some places, Yellowstone's unusually high heat flow may be 60–120 meters (200–400 ft.) beneath a green, grassy meadow. Geothermal areas include both hot, dry rock and hydrothermal systems.

A key question underpinning the geology program's effort to monitor Yellowstone's heat is: *What is a thermal area?* The following working definitions may help to clarify this:

Thermal area: A contiguous geologic unit generally including one or more thermal features. Its boundary marks the maximum aerial extent of hydrothermally altered ground, thermal deposits, geothermal gas emissions, or heated ground. This is equivalent to terms such as Upper Geyser Basin, Midway Geyser Basin, Mud Volcano area, Smoke Jumper Hot Springs, or Hot Spring Basin (fig. 1A).

Thermal group: A subdivision of a thermal area that contains one or more hydrothermal features and can be isolated by physiographic, geochemical, or hydrographic parameters, though not on the basis of geologic materials (fig. 1B).

Thermal feature: A vent emitting steam or hot water, or several vents emitting steam or hot water that show an identifiable relationship. For example, Beehive Geyser has many smaller vents that erupt simultaneously to form the geyser plume.

Thermal drainage: A term referring to a physiographic/hydrologic drainage in which thermal areas are found. Examples include the Firehole, Yellowstone, or Gibbon drainages. Drainages also may be called basins, such as the Firehole Basin. Hydrologic unit parameters define a drainage.

Geology of the Upper, Midway, and Lower Geyser Basins

Yellowstone's hydrothermal areas are surface expressions of a complex system that reflects surficial sediments, bedrock geology, and faults and fractures. Numerous sediments and

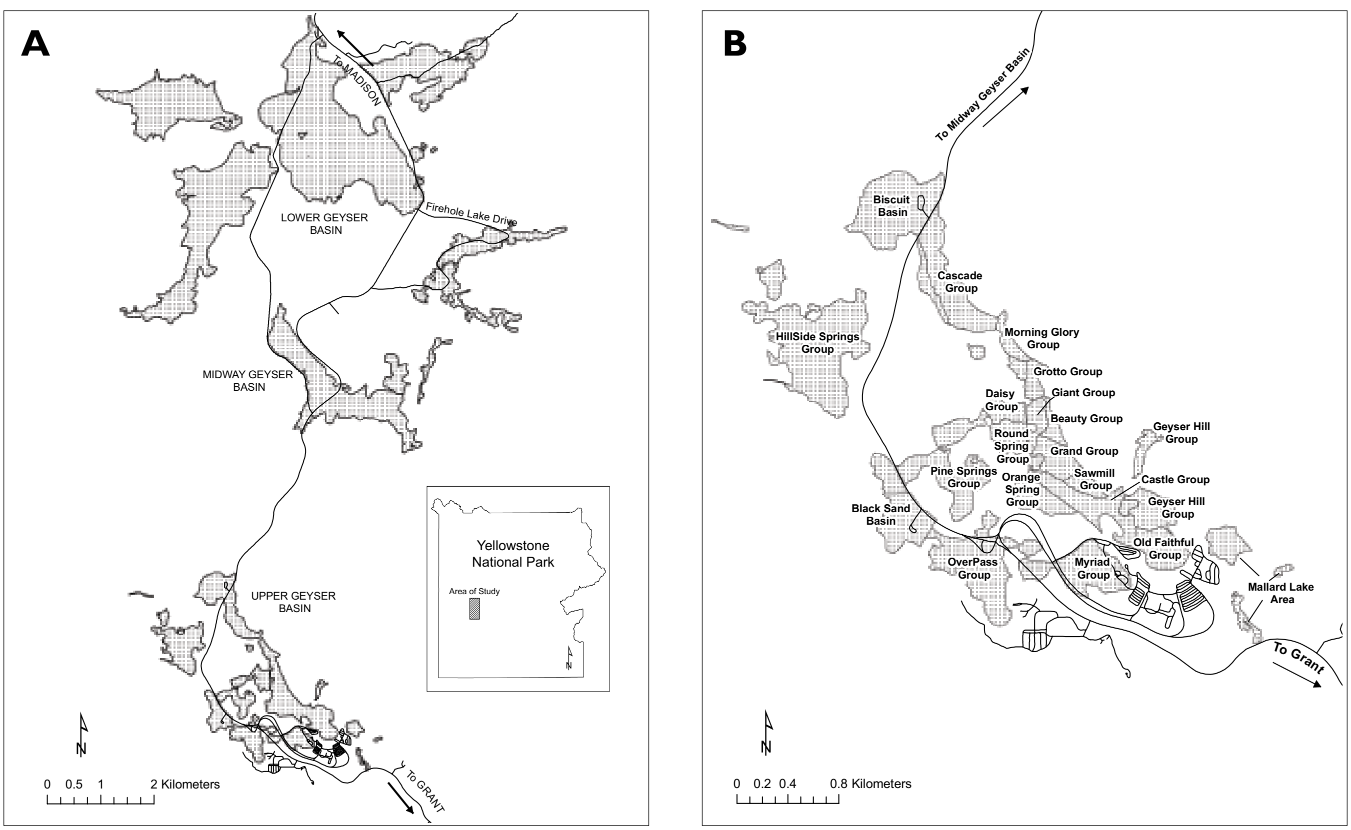


Figure 1. (*A*) Map showing the location of the Upper, Midway, and Lower geyser basins. (*B*) Map showing thermal groups of the Upper Geyser Basin. The late Rick Hutchinson, Yellowstone National Park geologist, mapped the spatial extent of these thermal areas. The Yellowstone Spatial Analysis Center converted his original mapping into a digital layer. See the NPS Data Store (http://science.nature.nps.gov/nrdata/) for a digital layer of Yellowstone's thermal groups.

Temperature and heat are two measures of Yellowstone's hydrothermal systems. Temperature is a relative measure of the "hotness" or "coldness" of an object. The temperature of a thermal spring can be measured easily but may not inform us about the hydrothermal system. In contrast, heat is a measure of energy that flows from a hot object to a cold object. Quantifying the heat from a large thermal pool at 65°C (149°F) versus a small pool at 65°C (149°F) provides important information about differences between these two hydrothermal systems. Degrees Fahrenheit (°F) or Celsius (°C) are the unit of temperature while calories or joules are the measure of heat.

episodic lava flows filled in the caldera that formed after the 640,000-year eruption of the Yellowstone Volcano (Christiansen and Blank 1974a, 1974b). Not long after this eruption, the 516,000-year-old (± 7,000 years) Biscuit Basin lava flow covered older volcanic rocks (figs. 2A and 2B). The 198,000-year-old Scaup Lake flow could represent the end of one volcanic episode (Christiansen 2001). As part of a new cycle of volcanic activity, the 153,000-year-old (± 2,000 years) Elephant Back flow and 165,000-year-old (± 4,000 years) Mallard Lake flows (Christiansen 2001; Christiansen et al. 2007) formed east of the current Upper, Midway, and Lower geyser basins. Another episode of volcanic activity involved the 112,000-year-old (± 2,000 years) Summit Lake and the 110,000-year-old (± 1,000 years) West Yellowstone lava flows (Christiansen 2001). These lava flows added new volcanic terrain along the park's western edge. Today, the Upper, Midway and Lower geyser basins occupy topographically low ground with volcanic plateaus surrounding them.

Faults and fractures have cracked rocks and allowed hydrothermal fluids to flow vertically and horizontally through the layers of rocks and sediments.

Various sediments (sand, silt, gravel, and clay) also filled in the low places and overlie the volcanic rocks. Rivers and glaciers deposited the variety of earth material, and hydrothermal fluids cemented these sediments with silica in places. The silica-rich hydrothermal deposits (sinter) form the light-colored thermal ground seen at Upper, Midway, and Lower geyser basins. In the Upper Geyser Basin, obsidian-rich, gravelly sand that is locally cemented can vary 5–150 feet (1.5–45.7 m) in thickness (Waldrop 1975). In other geyser basins, the earth materials deposited by melting glaciers are gray to brownish-gray sand and gravel.

Faults and fractures have cracked rocks and allowed hydrothermal fluids to flow vertically and horizontally through the layers of rocks and sediments. The mapped faults on the Mallard Lake resurgent dome (uplifted rock) show the expected trends of faults and fractures now hidden by sediments (fig. 2A). Northwest, north, and near east–west trends of faults and fractures probably affect the flow of hydrothermal fluids through the rocks in the Upper, Midway, and Lower geyser basins. Movement along these fractures during earthquakes may affect the hydrothermal system. Previous scientific work and observations indicate that these hydrothermal systems are affected by earthquakes (Marler 1964; Husen et al. 2004). Thus, temperature maps and LiDAR images of the Upper, Midway, and Lower geyser basins can show how subsurface faults and fractures localize the flow of hydrothermal fluids through rocks and overlying sediments.

Temperature Maps of the Upper, Midway, and Lower Geyser Basins

During September 2005, 2006, and 2007, Dr. Christopher Neale, a professor at Utah State University, and his graduate students collaborated with Yellowstone National Park geologists to acquire baseline temperature maps for the Upper, Midway, and Lower geyser basins (figs. 1A and 1B). In 2007, they used a temperature-sensing camera (a FLIR Thermocam SC640) in Utah State University's aircraft. Pilots flew over selected areas while the Remote Sensing Services Laboratory crew deployed ground-based instrumentation to document atmospheric conditions used for correction of the thermal imagery. Park geology program staff and volunteers deployed temperature loggers in select thermal pools for temperature calibration and validation of the airborne thermal imagery.

The Upper Geyser Basin is a 2.9-square-kilometer (1.1 mi^2) thermal area with numerous thermal groups and thermal features in the Firehole River drainage (fig. 1B). The September 2007 nighttime thermal infrared map of the Old Faithful area (1-m spatial resolution) shows high (40°C–70°C or 104°F–158°F), intermediate (15°C–30°C or 59°F–86°F), and low (5°C–15°C or 41°F–59°F) temperatures within the Old Faithful, Geyser Hill, and Myriad groups (fig. 3). Even the lowest temperatures on these maps show the elevated ground temperatures resulting from Yellowstone's hydrothermal system. Detailed topography from a 2008 LiDAR (light detection and ranging) sensor is the shaded, gray base for this temperature map (this LiDAR data is available at http://opentopography.org).

In the Old Faithful area, infrastructure (buildings, roadways, and water and sewer lines) obscures the natural temperature variations at the ground surface. Figure 3 shows the effects of park infrastructure directing the underground flow of heat and fluids. Low-temperatures (10°C–15°C or 50°F–59°F) around the south side of Old Faithful show the location of an abandoned sewer line. This abandoned sewer line conducts heat and steam around Old Faithful Geyser. A linear trend of elevated temperatures from an active water line parallels the road to the northeast of the Myriad Group. Ongoing field experiments and scientific investigations will provide additional information about the sources for the low temperatures on the nighttime thermal infrared maps.

In the Old Faithful area, infrastructure…obscures the natural temperature variations at the ground surface.

Park infrastructure also has adversely impacted hydrothermal features and groups in other areas. Figure 4 clearly shows the thermal signature of hot water diverted during the construction of the overpass. This area is warm enough that both lanes of the road are snow-free in the winter. This 3–5 meters (10–16 ft.) spatial resolution nighttime thermal infrared image of the Old Faithful overpass shows intermediate temperatures (15°C–30°C or 59°F–86°F) at the ground surface caused by hydrothermal fluids. The low temperatures in figure 4 (5°C–10°C or 41°F–50°F) show hydrothermally heated ground as well as vegetation and asphalt that have been heated by the sun. Similar to the overpass hydrothermal area, Black Sand Basin has a shallow

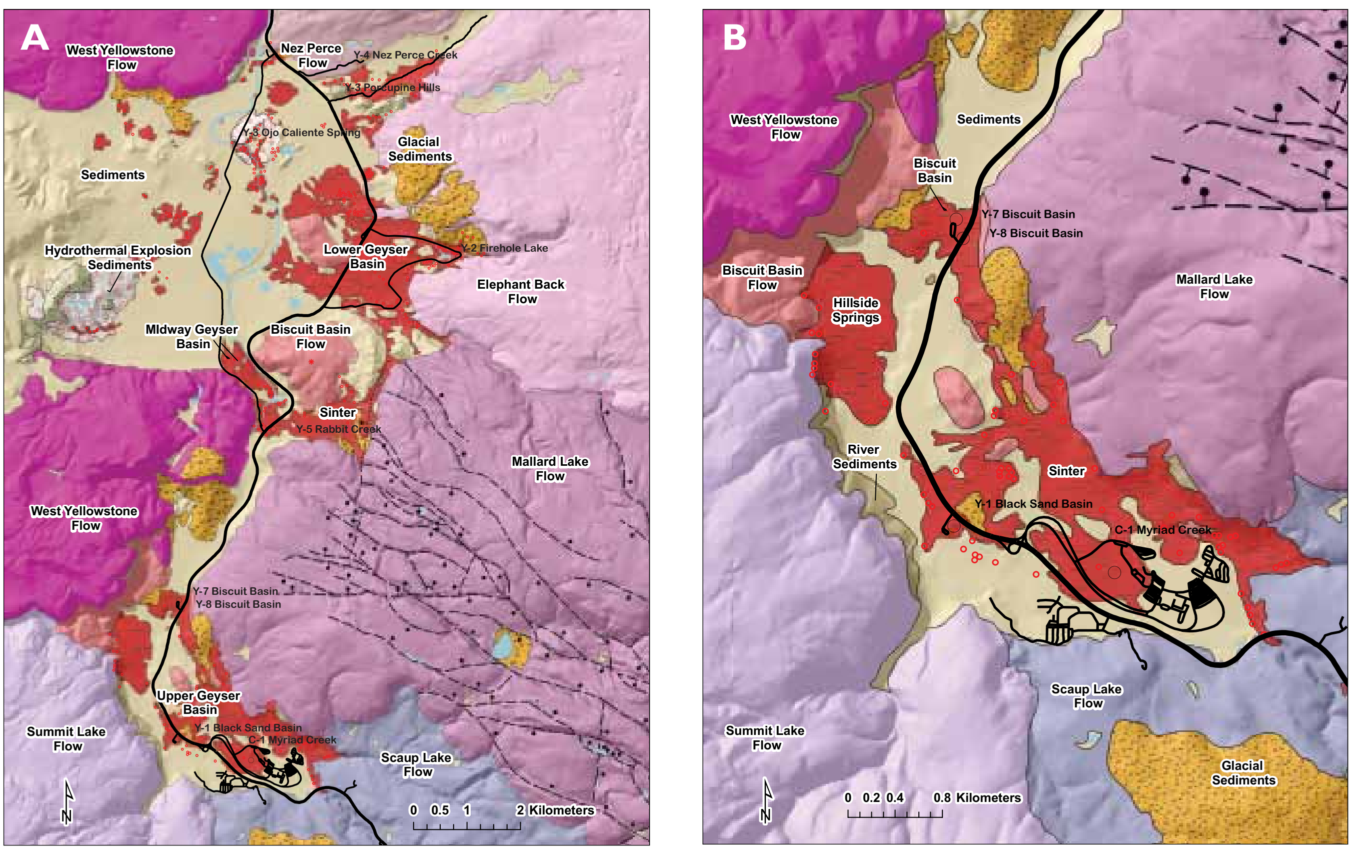


Figure 2. (*A*) Geologic map of the Upper, Midway, and Lower geyser basins over a digital elevation model. Lava flows, various sediments (glacial, hydrothermal explosion, and other) and hot spring deposits (sinter) are shown. Notice the major roads (*black solid lines*) and the faulted Mallard Lake resurgent dome (*black dashed lines*). (*B*) Geologic map of the Upper Geyser Basin over a digital elevation model. Lava flows surround the Upper Geyser Basin. The oldest lava flow, Biscuit Basin (*peach*), crops out in the river valley and along the valley sides. Younger lava flows covered the Biscuit Basin flow. Sediments deposited by ice and water occur in the river valley and on the lava flows. In places, hydrothermal water cemented the sediments and formed sinter (*red pattern*). Geologic maps are modified from Christiansen and Blank 1974 and 1974b. For a digital layer of Yellowstone's geology, see the NPS Data Store (http://science.nature.nps.gov/nrdata/).

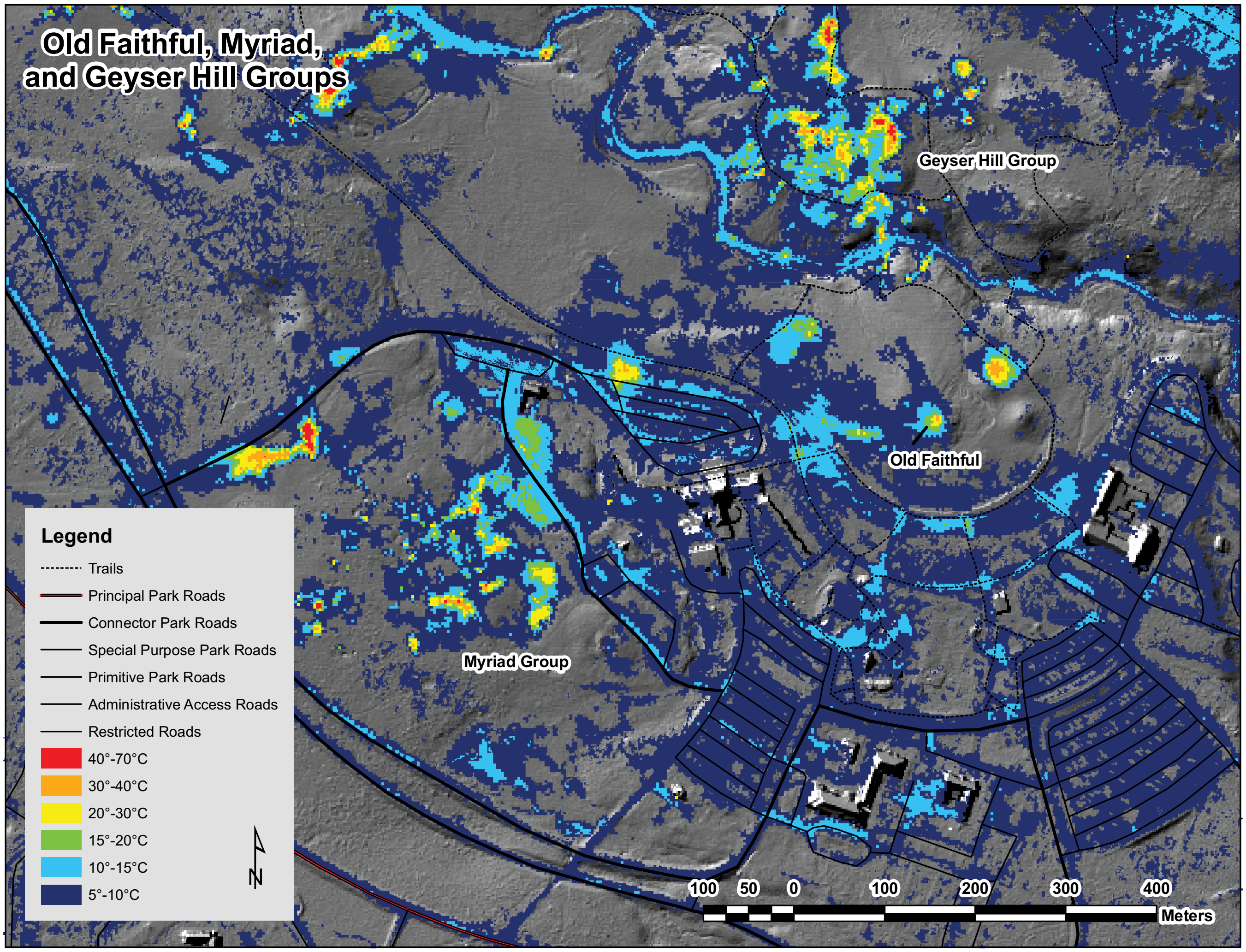


Figure 3. Map showing high (*red*), intermediate (*orange, yellow, and green*), and low (*light and dark blues*) temperatures surrounding Old Faithful Geyser, draped over a 2008 LiDAR image. Notice Old Faithful Geyser, the nearby circular area of warm ground, the Geyser Hill Group, and the Myriad Group. The arc of warm ground (10°C–15°C or 50°F–59°F) surrounding Old Faithful Geyser shows the influence of park infrastructure on the flow of heat and fluids. In contrast, the Geyser Hill Group displays the natural temperature variations (10°C–80°C or 50°F–176°F) of a hydrothermal system.

hydrothermal reservoir (Fournier et al. 1994). Thus, Black Sand Basin is a sensitive hydrothermal area that easily could be impacted by development.

Flowing north from the Old Faithful area, the Firehole River shows its hydrothermal character at 10°C–15°C (50°F–59°F) (figs. 5 and 6). At the time of the September 2007 flight, the FLIR Thermocam SC640 sensed Grotto Geyser, Radiator Geyser, Splendid Geyser, Morning Glory Pool, and other thermal features. Between Grotto Geyser and Morning Glory pools, the Firehole River flows between faulted or fractured outcrops of the Biscuit Basin lava flow and the Mallard Lake dome (fig. 5). These fractures or faults (north–northwest and east–northeast trending linear features) may fragment the hydrothermal system into subsurface blocks that move independently with earthquakes.

Not far from Biscuit Basin, the Cascade Group raises the temperature of the Firehole River (fig. 6) from a range of 10°C–15°C (50°F–59°F) to a range of 15°C–20°C (59°F–68°F). Here, the Firehole River flows between rhyolitic lava flows on the east and river terraces on the west. The LiDAR clearly shows how glaciers smoothed and cut deep glacial grooves into the hillside above the Cascade Group. It is interesting that low-temperature thermal signatures (5°C–10°C or 41°F–50°F) occur at a bedrock contact between the faulted and glaciated Mallard Lake flow and the underlying Biscuit Basin flow (fig. 6 and fig. 1A). These low ground temperatures on the east hillside may be due to vegetation, different rock types, or groundwater. Ongoing studies will help determine the causes of these low ground temperatures near the front of the Mallard Lake lava flow.

In Biscuit Basin (fig. 7), the hot thermal features (red and orange areas) near the Firehole River have been sporadically

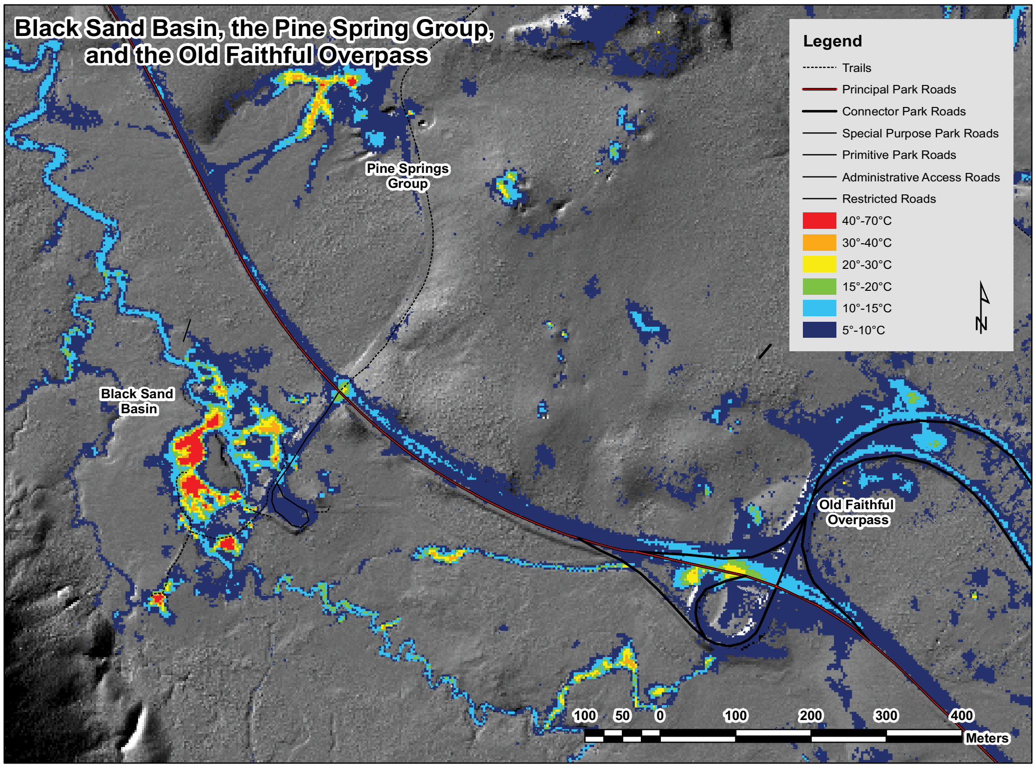


Figure 4. Map showing high (*red*), intermediate (*orange, yellow, and green*), and low (*light and dark blues*) temperatures near the Old Faithful overpass, draped over a 2008 LiDAR image. The Old Faithful overpass adversely impacted the hydrothermal system. Note the natural variation in temperatures at Black Sand Basin and the thermal character of the Little Firehole River.

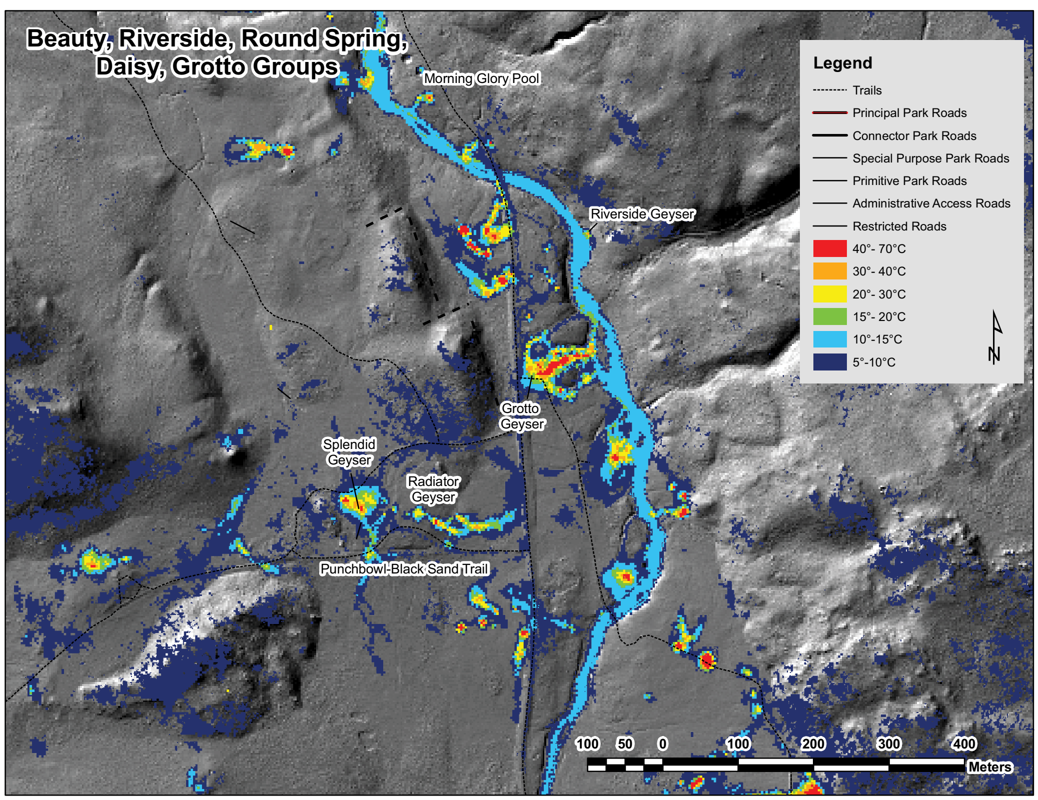
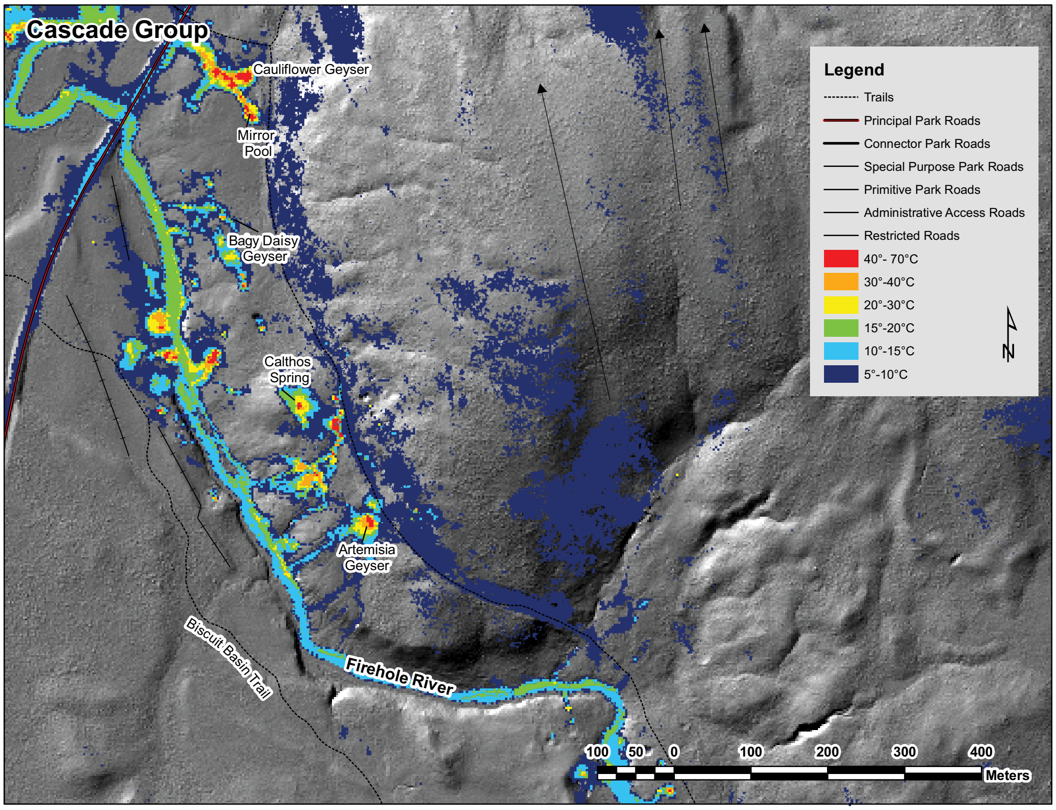


Figure 5. Map showing high (*red*), intermediate (*orange, yellow, and green*), and low (*light blue and dark blue*) temperatures along trails in the Upper Geyser Basin, draped over a 2008 LiDAR image. North–northwest and east–northeast-trending fractures (black dashed lines) may affect some thermal groups and thermal features. The old asphalt roadway, now used as a bike path, is barely visible at 5°C–10°C (41°F–50°F). The 10°C–15°C (50°F–59°F) Firehole River shows the influence of hot outflow from nearby thermal features and thermal features within the river.

Figure 6. Map showing high (*red*), intermediate (*orange, yellow, and green*), and low (*light and dark blues*) temperatures along trails in the Upper Geyser Basin, draped over a 2008 LiDAR image. Terraces (*hatched lines*) occur west of the Firehole River. Glaciers smoothed the hillside and cut deep grooves (*black arrows*) above Artemisia Geyser. The contact between the Mallard Lake and Biscuit Basin lava flows occurs near the unlabeled trail.



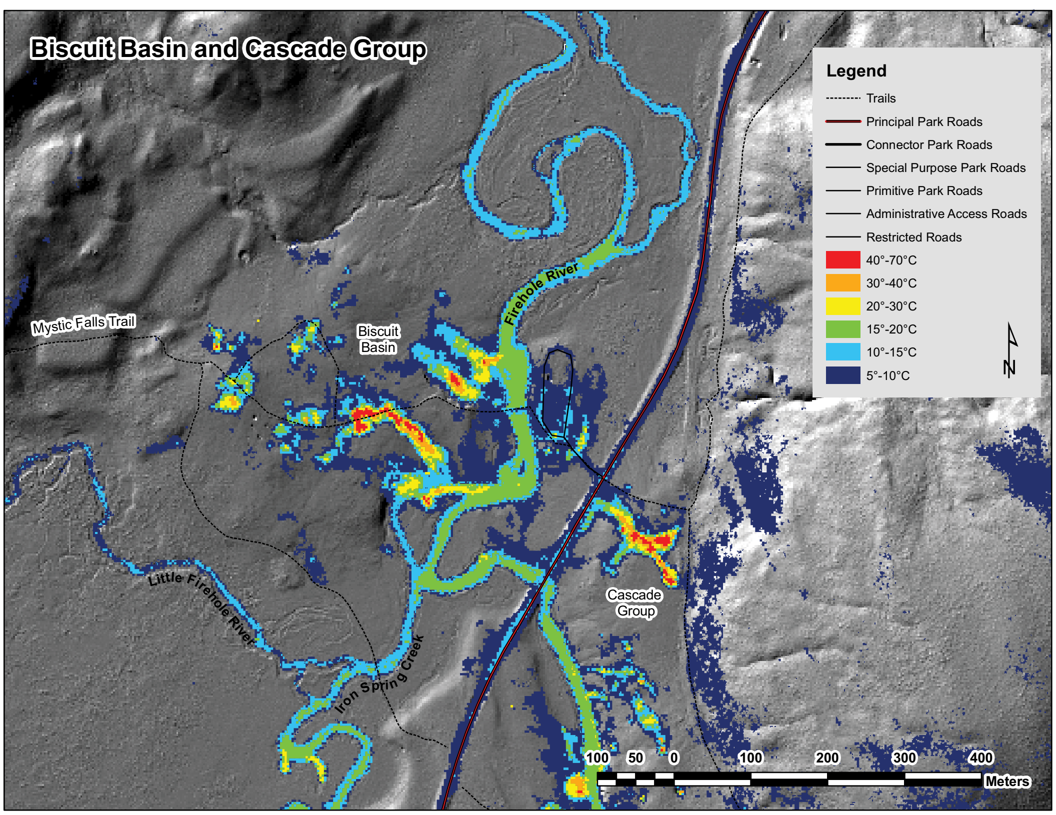


Figure 7. Map showing high (*red*), intermediate (*orange, yellow, and green*) and low (*light and dark blues*) temperatures at Biscuit Basin, draped over a 2008 LiDAR image. Beginning in 2006, the hot (40°C–80°C or 104°F–176°F) area near the Firehole River boardwalk erupts steam, water, and rock debris. Notice that only small areas of warm ground temperatures (at 5°C [41°F]) and greater are visible at the ground surface. To map the entire Biscuit Basin thermal area, elevated ground temperature, hot springs deposits, hydrothermally altered ground, and geothermal gases are necessary.

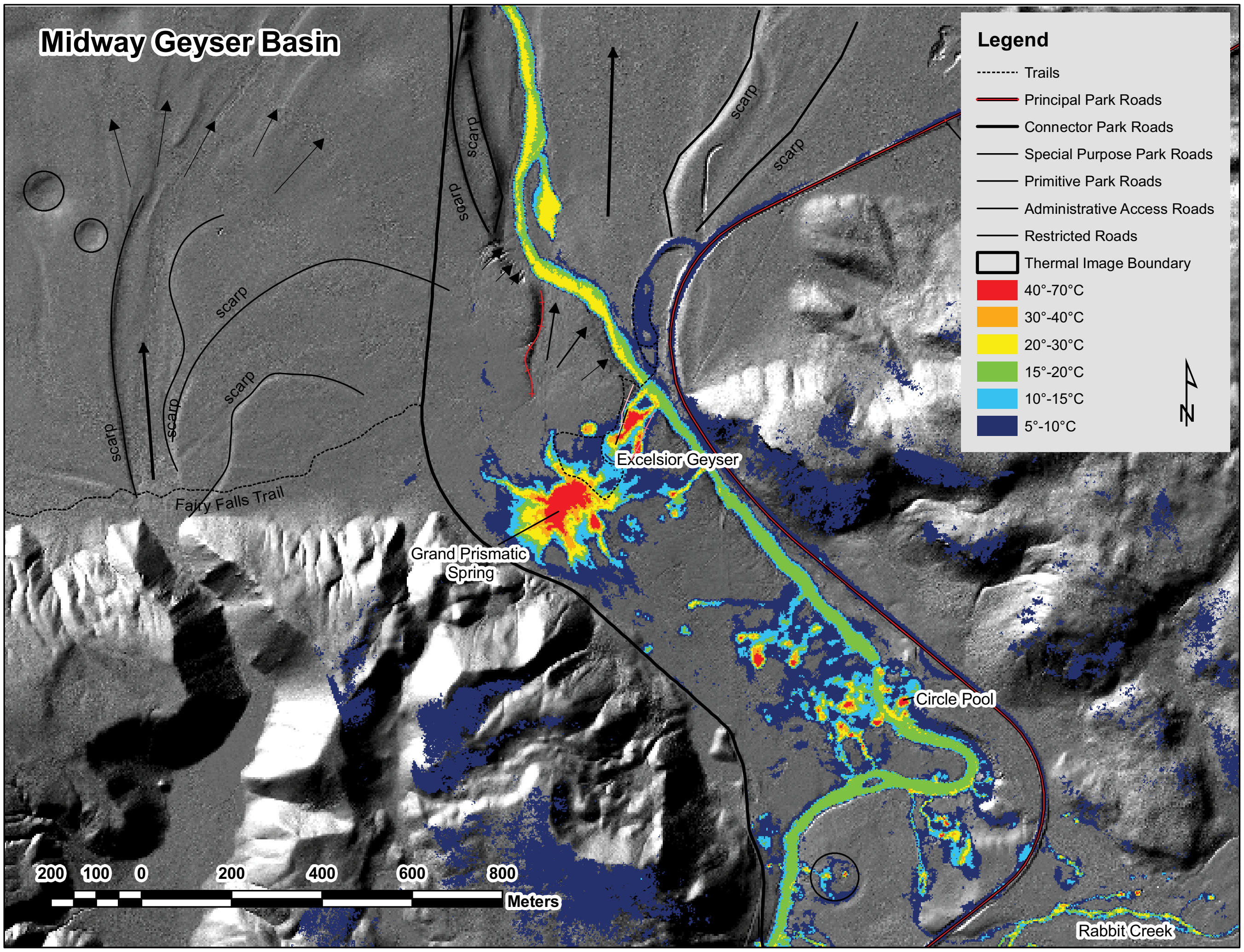


Figure 8. Map showing high (*red*), intermediate (*orange, yellow, and green*) and low (*light and dark blues*) temperatures at Midway Geyser Basin, draped over a 2008 LiDAR image. The sinuous, solid black lines near Grand Prismatic Spring indicate the boundary of the 3–5 meter nighttime thermal infrared imagery. The LiDAR allows preliminary interpretation of flood scarps (*solid black lines*), flood channels (*large arrows*), possible hydrothermal explosion features (*black circles*), and lateral debris flow deposits (*small black arrows and red hatched lines*) from Grand Prismatic Spring and Excelsior Geyser.

erupting obsidian sand, mud, and water since 2006. In July 2006 and May 2009, the authors observed these "dirty," forceful geyser eruptions, hydrothermal eruptions, or hydrothermal explosions ejecting hot water and debris both vertically and laterally. In July 2006, the laterally flowing, hydrothermal water deposited a rocky debris apron (at least 14 meters [46 ft.] wide, 11 meters [36 ft.] long, and 4.5 centimeters [1.8 in.] thick). These events provide small, modern-day analogs for the large, paleo-hydrothermal explosions in Midway and Lower geyser basins. These eruptions of obsidian sand and mud make sense when the underlying geology is considered. About 55 meters (180 ft.) of obsidian-rich sand and gravel overlie the Biscuit Basin lava flow (Fournier et al. 1994). These thermal pools that forcefully erupt are aligned along a northwest trend and may reflect subsurface fractures in the Biscuit Basin lava flow. Near the road and the Biscuit Basin parking lot, the low ground temperatures show the interaction of the low-temperature component of the hydrothermal system with the park infrastructure.

At Midway Geyser Basin (fig. 8), the Firehole River flows between the Biscuit Basin lava flow and the West Yellowstone flow (fig. 2A). Previous geologists (Muffler et al. 1982b) described and mapped the gravel and sand of the outwash plain. The 2008 LiDAR image of the area shows the terrace scarps and flood channels of the late glacial outwash plain. The Firehole River is visible as an underfit stream (too small to have eroded the valley it occupies) within a late glacial flood channel. In this reach of the river, thermal outflow increases the temperature of the Firehole River from 15°C to 30°C (59°F–86°F). The LiDAR topography also enables a preliminary interpretation of lateral debris flows (small arrows and hatched lines on fig. 8) from

An Exceptional Day at Biscuit Basin

Henry P. Heasler

On May 17, 2009, a group of scientists visited Biscuit Basin as part of a two-day Earthscope field trip. The group was standing by Wall Pool, discussing hydrothermal explosions. Just as the discussion finished at 11:17 AM, Wall Pool surged, then erupted, expelling foot-sized ejecta (figs. 1 and 2). There was a sensation of heat associated with the eruption, which lasted for an estimated 10 to 15 seconds.

Was the May 17 event a hydrothermal explosion or a geyser eruption? A hydrothermal explosion is caused by a depressurization of a column of boiling water, much like the forces that cause a geyser eruption. The difference between a small hydrothermal explosion and a geyser eruption is that a hydrothermal explosion results in the fragmentation and ejection of overlying strata. Rocks are expelled, either creating a new depression or enlarging an existing vent. The expelled rocks form a debris pattern of ejecta around the explosion.

The Wall Pool event, however, had characteristics of both a hydrothermal explosion and a geyser eruption. Debris were ejected and formed a pattern around the pool (fig. 3). The current turbidity of the pool's water makes it difficult to determine if there was any change in the vent. Sometimes the pool erupts many times in a season, much like geysers. Dick Powell and Ralph Taylor, park volunteers, documented nine eruptions of the pool between June 29 and September 21, 2009. Thus, the eruption of Wall Pool can be considered on a continuum between a geyser eruption and a hydrothermal explosion. Perhaps the best term to use is an unusually forceful geyser eruption.

The name of the feature erupting also is unclear. US Geological Survey maps of the area from 1974 clearly label Black Opal Pool and Wall Pool. However, other investigations indicate that the area of the eruption may be named Black Diamond Pool.

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Figure 1. Beginning of the hydrothermal explosion/forceful eruption in Wall Pool on May 17, 2009, looking north northwest.

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Figure 2. Continuation of the hydrothermal explosion/forceful eruption in Wall Pool. Note the debris being ejected by the explosion/eruption.

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Figure 3. A park geologist and volunteer analyze ejected debris after a 2006 explosion/eruption of Wall Pool.

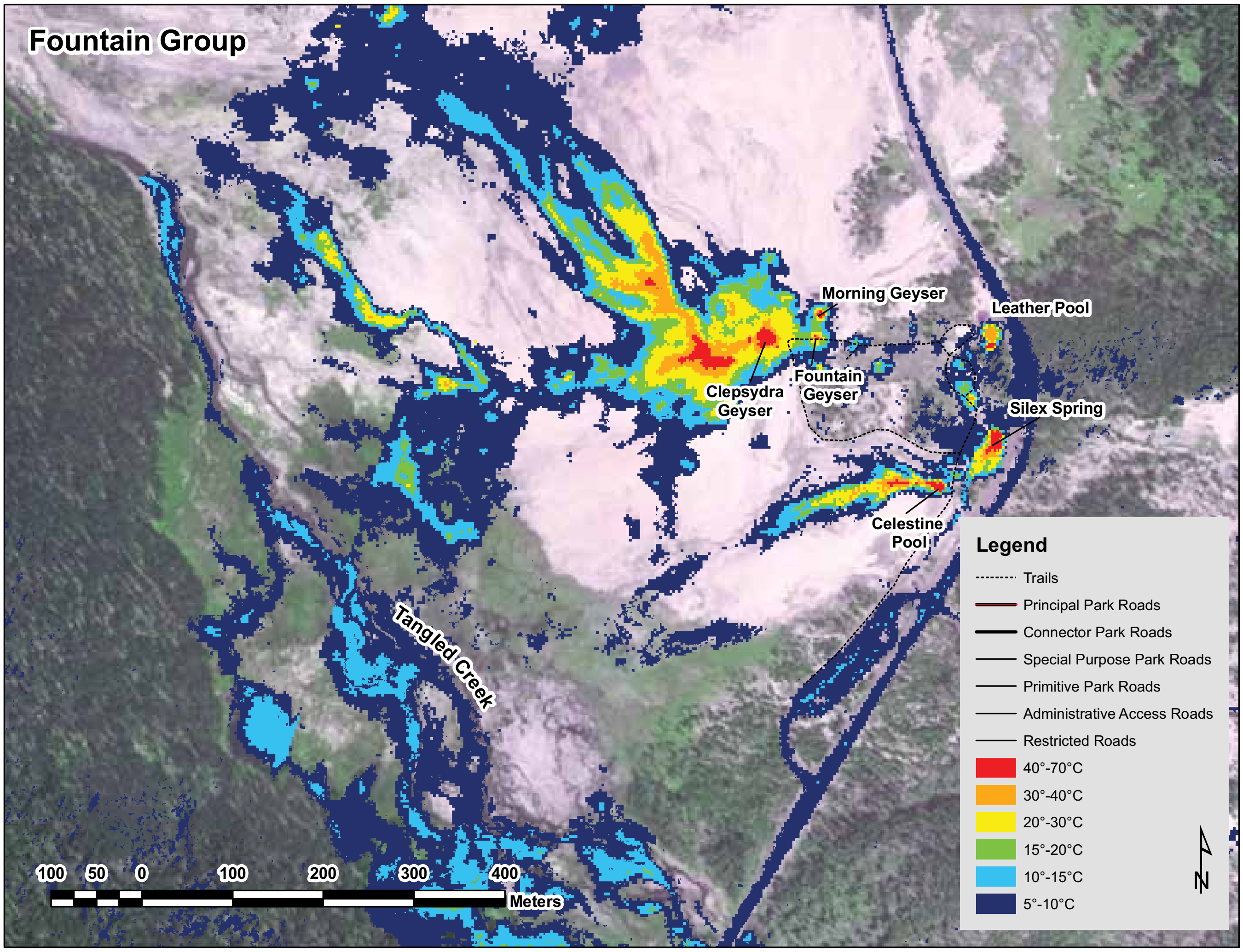

Figure 9. Map showing high (*red*), intermediate (*orange, yellow, and green*) and low (*light blue and dark blue*) temperatures of the Fountain Group, draped over a color infrared image. Notice the thermal outflows from Clepsydra Geyser, Celestine Pool, and Silex Spring. Fountain Geyser, Morning Geyser, and Leather Pool are hot to intermediate thermal spots. Tangled Creek (*lower left*) also shows an influence from hydrothermal features. The main road crosses the vegetated Elephant Back lava flow.

hydrothermal explosions at Grand Prismatic Spring and Excelsior Geyser. On the LiDAR, these lateral debris flow deposits appear to cross-cut the scarps of the late glacial flood terraces. Thus, the hydrothermal explosion events appear to be younger geologic events than late glacial floods. Other potential hydrothermal explosion craters are circular depressions in the late glacial sediments. Field investigations may confirm these initial interpretations of the 2008 LiDAR imagery at Midway Geyser Basin.

A tributary to the Firehole River, Tangled Creek flows by the Fountain Group at Fountain Flats (fig. 9). Hydrothermal features raise the temperature of Tangled Creek to 10°C–15°C (50°F–59°F). A ground surface temperature above 10°C (50°F) is a clear hydrothermal signature. Within the Fountain Group, the highest temperatures (30°C–70°C or 86°F–158°F) come from Clepsydra Geyser, Silex Spring, and Celestine Pool. Figure 9 shows that only some areas of the white sinter emit high surface ground temperatures detectable by airborne thermal infrared sensors.

At Pocket Basin (fig. 10), the presence of thermal features, heated ground, hot springs deposits, and chemically altered ground shows why the definition of a hydrothermal area is inclusive. In the Lower Geyser Basin, the LiDAR and thermal infrared imagery shows the Firehole River cutting through Pocket Basin's debris apron. Muffler et al. (1982a) described the apron as "unconsolidated breccias… with blocks of tough cemented yellow-stained sandstone, siltstone and conglomerate…." The LiDAR imagery shows radial flow lines (fig. 8) in this debris apron that could be associated with a lateral wave from the hydrothermal explosion at Pocket Basin. Here, the entire Firehole River has temperatures greater than 15°C (59°F), indicating that it is part of the hydrothermal system.

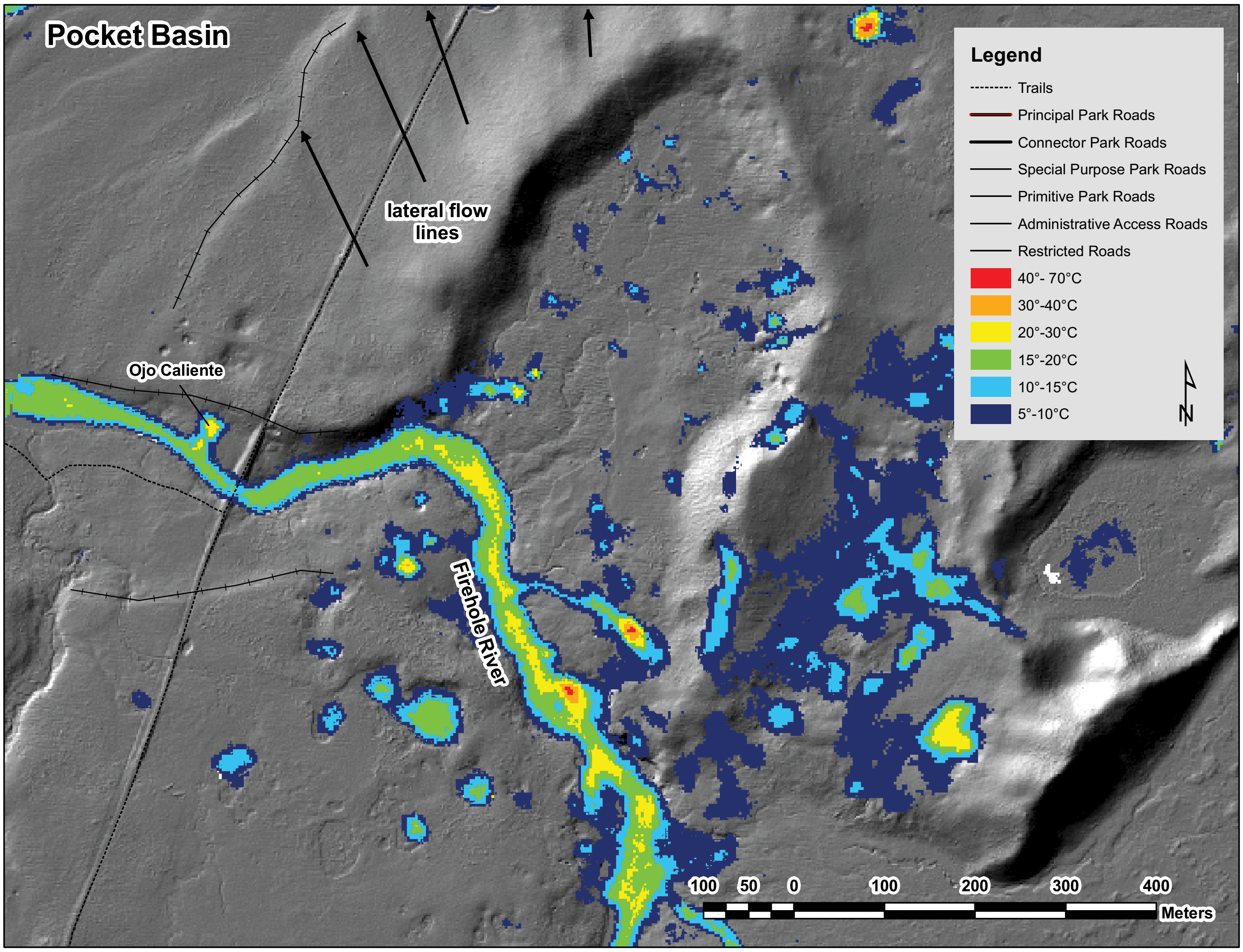

Figure 10. Map showing high (*red*), intermediate (*orange, yellow, and green*), and low (*light and dark blues*) temperatures at Pocket Basin, draped over a 2008 LiDAR image. Notice the lateral debris flow lines (*arrows*) in the debris apron and scarps (*black hatched lines*).

Discussion

In the late 1800s Nathaniel Langford, first superintendent of Yellowstone National Park, investigated one of Jim Bridger's stories about the Firehole River. According to Chittenden (1895), Langford described

> *…the stream as flowing over the smooth surface of a rock, and reasoned that, as two sticks rubbed together produced heat by friction, so the water rubbing over the rock became hot… Mr Langford found a partial confirmation of the fact, but not of the theory, in fording the Firehole River in 1870. He passed over the smooth deposit of an active hot spring in the bed of the stream, and found that the stream bottom and the water in contact with it were hot.*

Today, the thermal infrared maps of the Upper, Midway, and Lower geyser basins show that the Firehole River is an integral part of the hydrothermal system. Although people still feel the warmth of the Firehole River and its thermal springs, current-day visitors and scientists can understand that the heat beneath our feet ultimately comes from Yellowstone's active volcano, not from the friction of the water flowing over the riverbed.

Summary

The airborne thermal infrared images presented in this report show the vast size and interconnectedness of thermal areas. The figures and geologic discussions emphasize that thermal areas are much more than isolated thermal features or groups of thermal features. The entire Upper Geyser Basin is clearly one large contiguous geologic unit defined by altered hydrothermally altered ground, thermal deposits, heated ground, and geothermal gases. Thus, the entire Upper Geyser Basin is a thermal area. The perspective that thermal areas are more


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Old Faithful Geyser erupting as seen from Castle Geyser in 1952.

than just the thermal vents in an area is a critical realization necessary for the protection of Yellowstone's unique hydrothermal resources.

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Acknowledgements

Many people contributed to the success of this collaborative research. Former Utah State University graduate students, Deepak Lal and Osama Akashesh, participated in the image acquisitions and image processing during 2005 and 2006. Dr Bayanai Cardenas, professor at the University of Texas, provided a FLIR Thermocam SC640 in 2007. Geology program volunteers Ralph Taylor, Dick Powell, and Karin Horrigan placed temperature loggers in thermal features before the anticipated flights. Conversations with park botanist, Jennifer Whipple, aided our understanding of vegetation in the thermal areas. Yellowstone National Park law enforcement rangers at Old Faithful allowed the temporary deployment of a station for calibrating airborne imagery. The Research Office at the Yellowstone Center for Resources reviewed and permitted this project. The Fire Cache approved the flight plans and contacted the pilots while they gathered imagery. Dr. Bob Smith of the University of Utah advocated for funding the GeoEarthScope airborne LiDAR group. In addition, David Phillips and his team (UNAVCO) and Christopher Crosby's team (University of California, San Diego) acquired and processed the 2008 LiDAR imagery. The Technical Oversight Committee of the Water Rights Compact between Montana and the United States also provided critical external support for this effort. Finally, Yellowstone National Park's geothermal monitoring plan would not have been possible without the late Irving Friedman. His passion for Yellowstone and belief in protecting its hydrothermal features resulted in the funding of the park's geothermal monitoring plan.


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