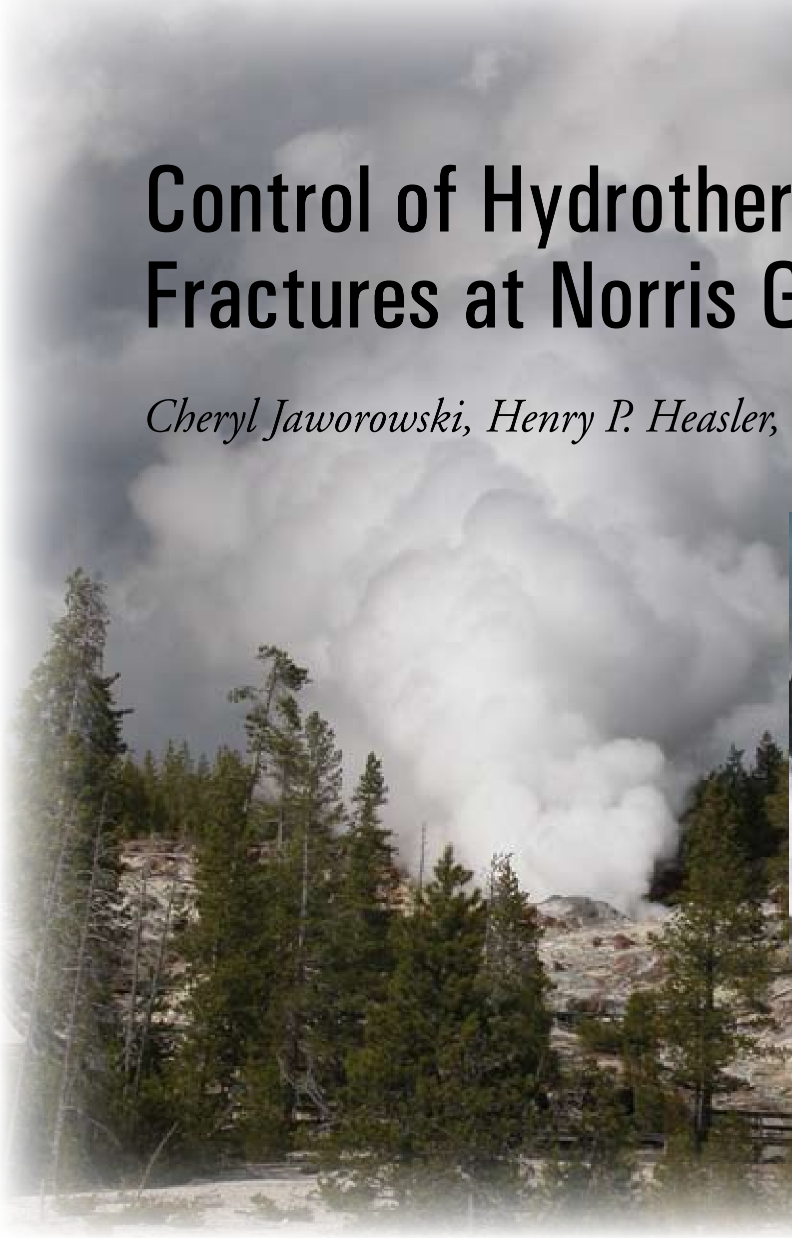
Control of Hydrothermal Fluids by Natural Fractures at Norris Geyser Basin

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.

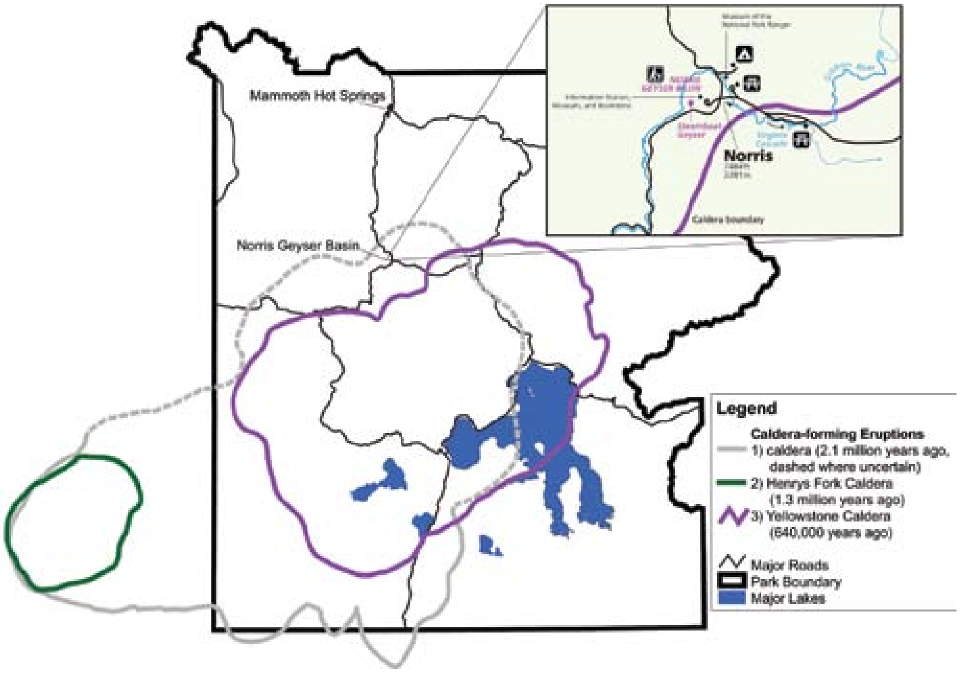


Figure 1. Map of Yellowstone National Park showing the location of Norris Geyser Basin and calderas from eruptions of the Yellowstone volcano 2.1 million, 1.3 million, and 640,000 years ago. *(The 2.1- and 1.3-million-year-old caldera boundaries were adapted from USGS Fact Sheet 2005-3024 "Steam Explosions,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

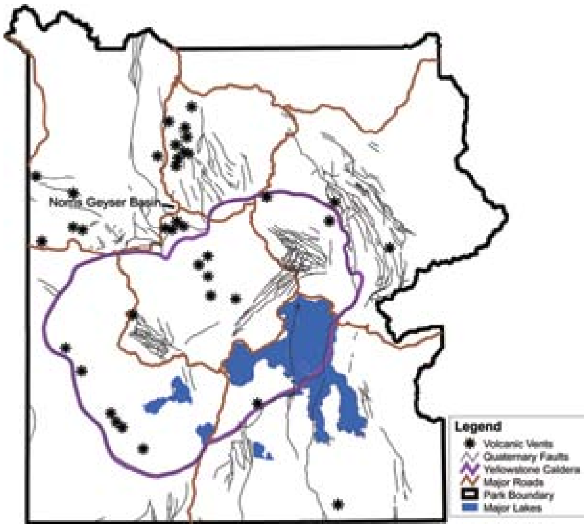


Figure 2. Map showing faults active during the last 1.6 million years, and volcanic vents (asterisks) since the eruption 640,000 years ago. North–south, northwest, northeast, and near east–west trending faults are shown. Notice the northwest trending vents of lava flows since the eruption 640,000 years 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/).*

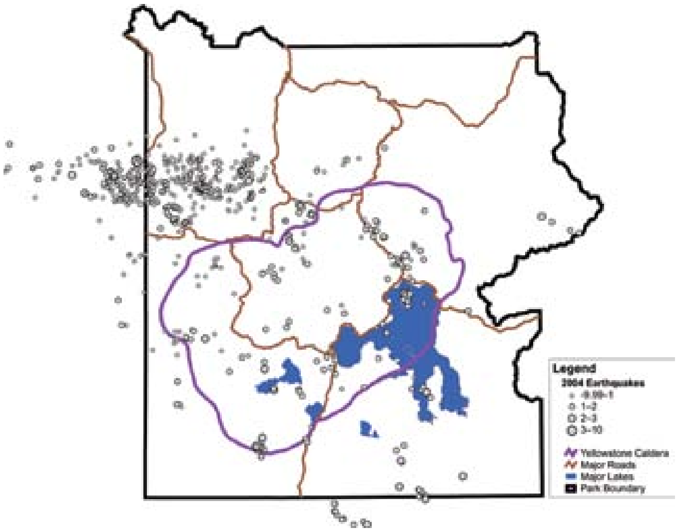


Figure 3. Map showing the location of earthquakes during 2004. Dots show the magnitudes of earthquakes. Large dots indicate earthquakes greater than magnitude 3.0. Notice the northwest trend of earthquakes within the caldera and the near east–west trends of earthquakes outside the Yellowstone caldera. *(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.

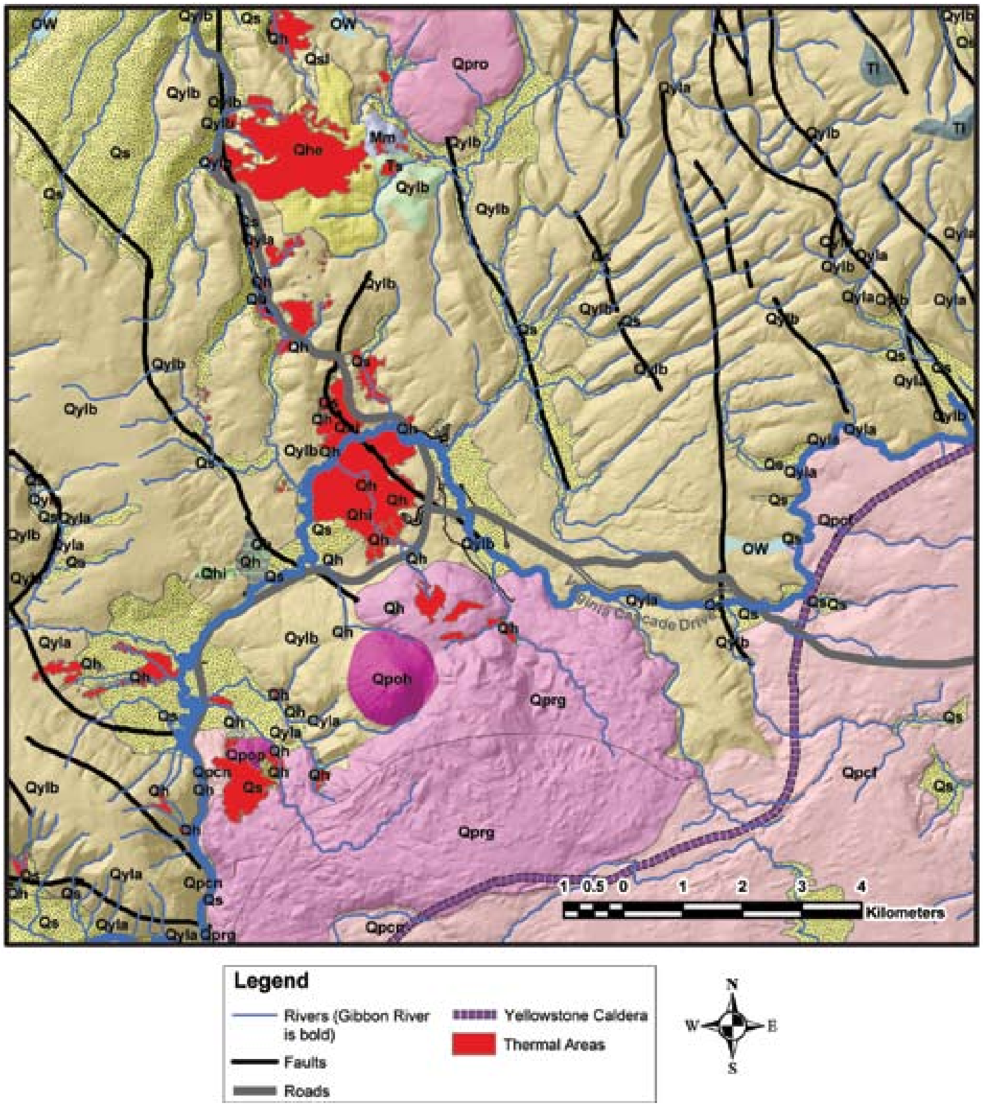


Figure 4. Bedrock geology of the greater Norris area (from Christiansen 2001) over digital elevation model, showing major north and northwest trending faults, the Lava Creek B tuff (tan colors, Qylb), hydrothermal areas (red color, Qh symbol), and rhyolitic lava flows since the eruption 640,000 years 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).

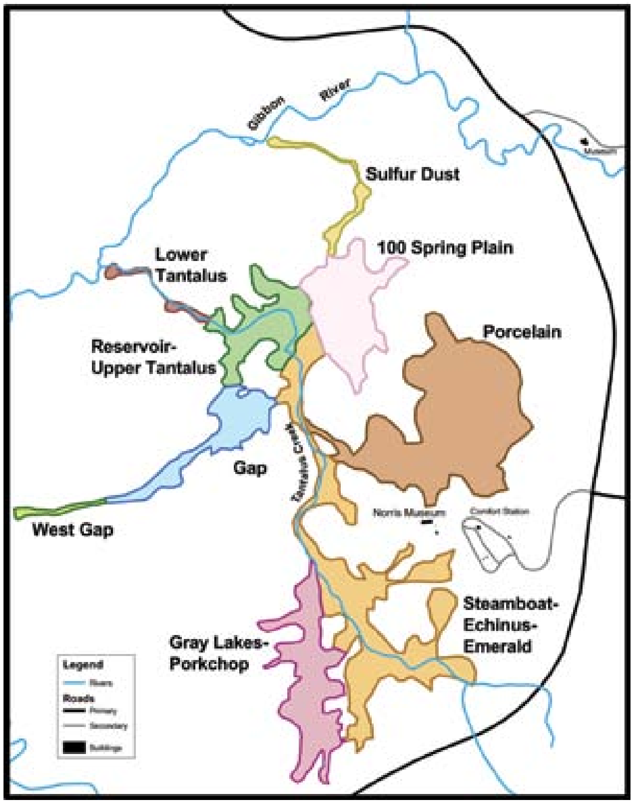


Figure 5. Map showing the hydrothermal sub-basins within Norris Geyser Basin. Using a digital orthophotograph as a base map, the surface flow of hydrothermal fluids provided the boundaries for delineation of the nine hydrothermal sub-basins.

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).

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

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.

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.

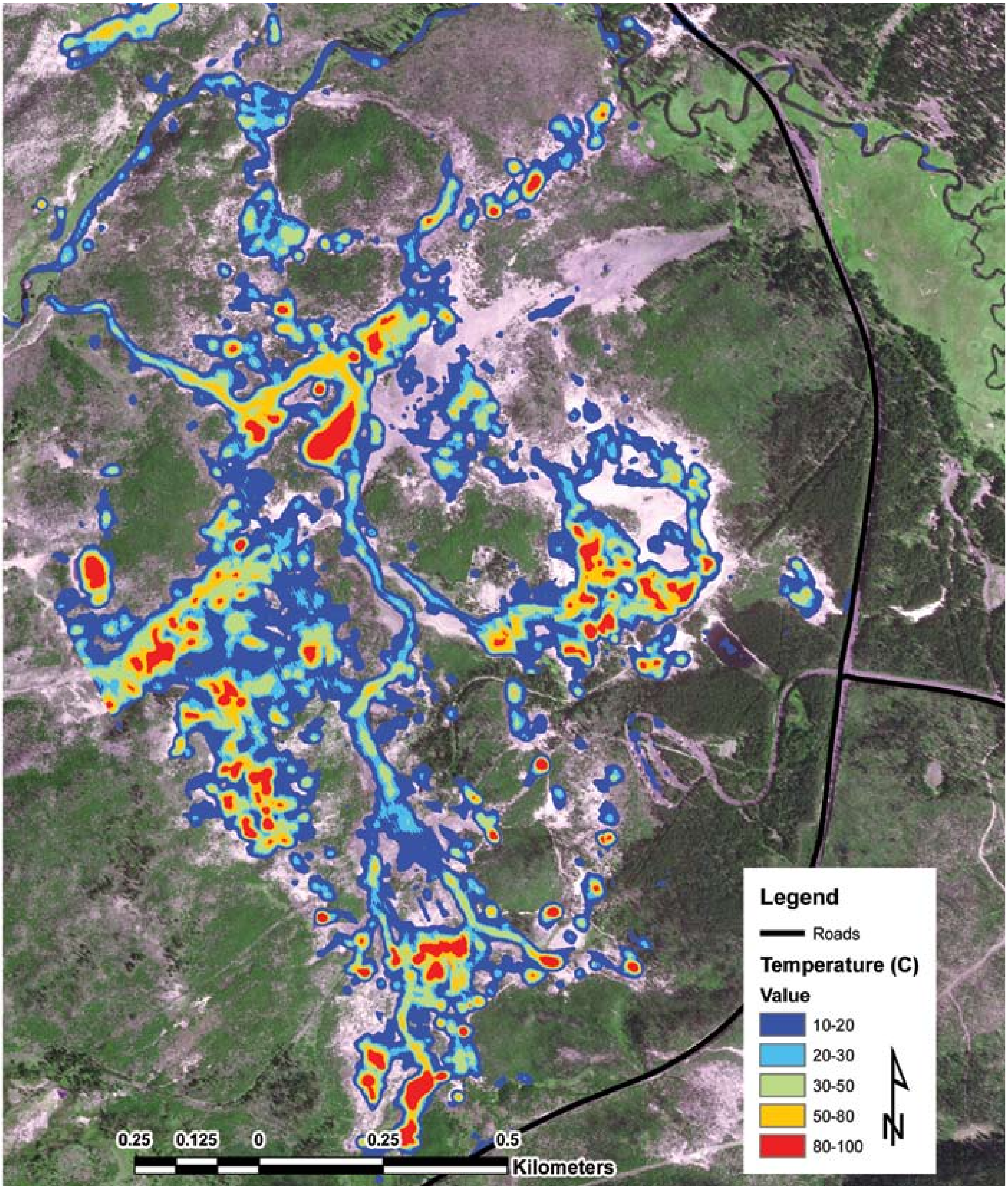


Figure 12. Calibrated, nighttime, thermal infrared image over Norris Geyser Basin, draped over a color infrared digital orthophotograph. The red (80–100°C) and orange (50–80°C) colors indicate hot thermal features. Green (30–50°C) and light blue (20–30°C) indicate areas of warm thermal waters. The river 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.

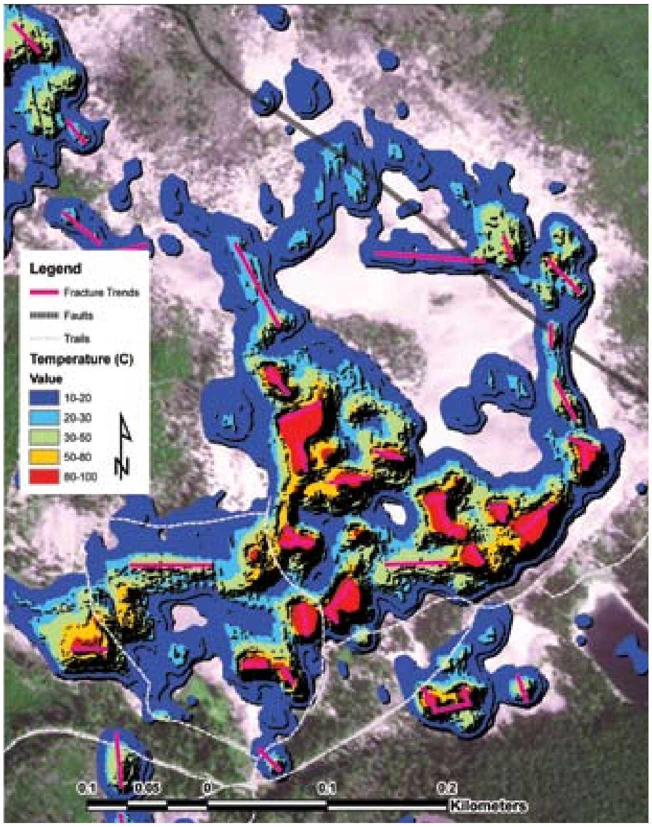


Figure 13. Nighttime, thermal infrared mosaic combined with a color infrared digital orthophotograph and a filtered image for the Porcelain sub-basin. The calibrated, thermal infrared mosaic for the Porcelain sub-basin shows that a major zone of northwest trending fractures controls the flow of hydrothermal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

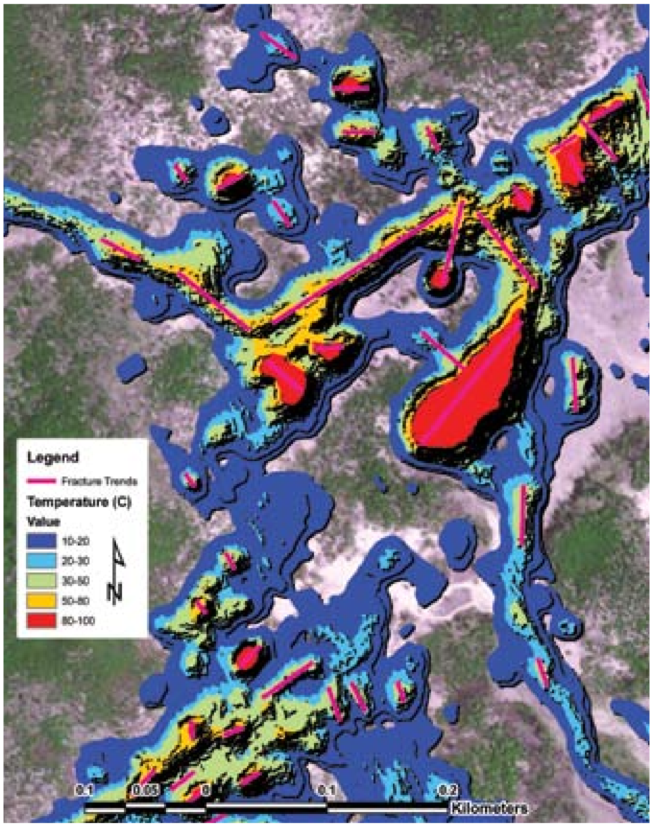


Figure 14. Nighttime, thermal infrared mosaic combined with a color infrared digital orthophotograph and a filtered image for the Reservoir-Tantalus sub-basin. Hydrothermal fluids follow northeast and northwest trending fractures. Other fracture patterns (near east–west and north–south) also control 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.

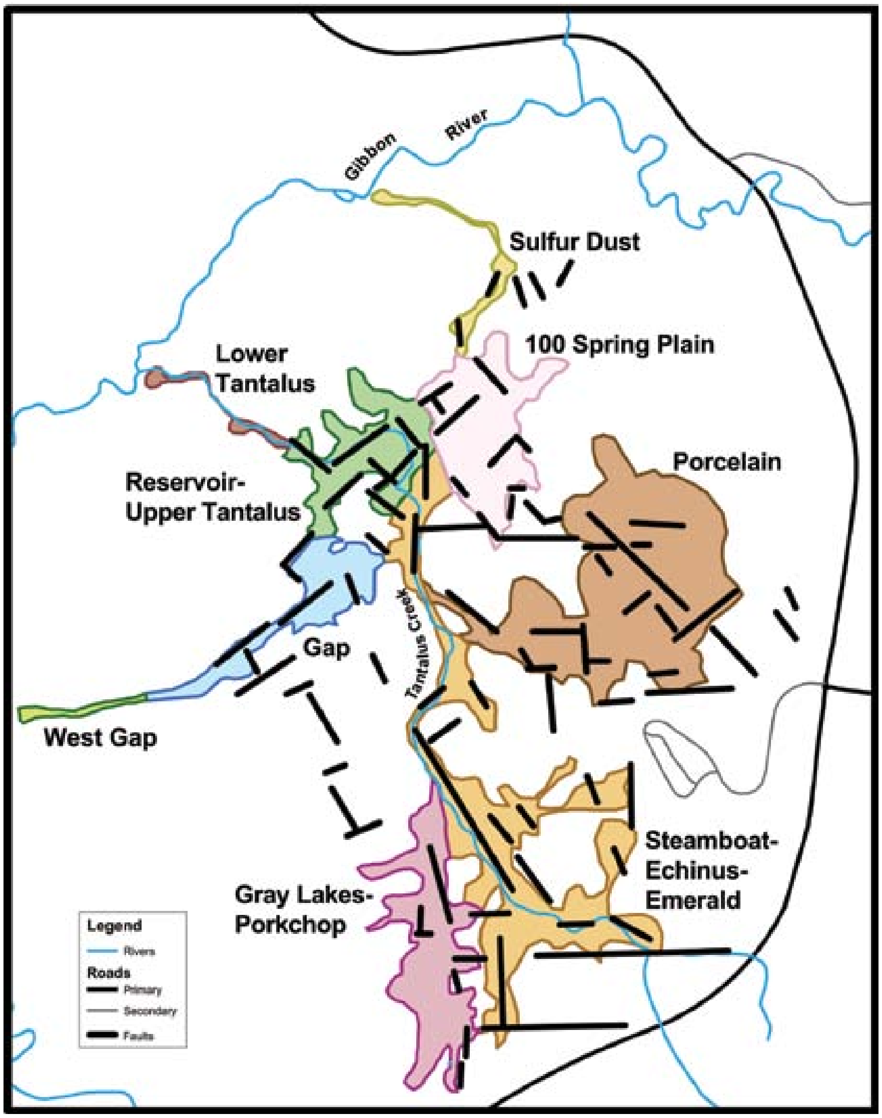


Figure 15. Map showing major fracture zones within Norris Geyser Basin. Significant variations in the dominance of the fracture trends occur among the hydrothermal sub-basins.

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.

Cheryl Jaworowski is a geologist at Yellowstone National Park. She earned her doctorate in geology from the University of Wyoming and specializes in Quaternary geology and applying remote sensing to geologic mapping. **Hank Heasler**, Park Geologist for Yellowstone National Park, specializes in terrestrial heat transport. Dr. Heasler's studies have included low-temperature geothermal systems, heat flow of the Rocky Mountain region, maturation of hydrocarbons, and changes in climate as indicated by ground temperatures. He received his PhD from the University of Wyoming. **Colin C. Hardy** is Project Leader of the Fire Behavior Research Work Unit, Rocky Mountain Research Station, U.S. Forest Service, at the Missoula Fire Sciences Laboratory in Missoula, Montana. His doctoral work at the University of Montana focused on thermal infrared remote sensing of wildland fires, using Yellowstone's geothermal features as an experimental test bed. **Dr. Lloyd P. Queen** is Professor of Remote Sensing in the Department of Forest Management at the University of Montana. Since May 2000 he has served as the Director of the National Center for Landscape Fire Analysis in the College of Forestry and Conservation at UM. He received his PhD from the University of Nebraska.

References

Airborne Data Systems. 2006. Airborne Data Systems [Homepage of Airborne Data Systems], online. Available: <http://www.airbornedatasystems.com> [Oct. 2006].

Christiansen, R. L. 2001. The Quaternary and Pliocene Yellowstone Plateau volcanic field of Wyoming, Idaho, and Montana: U.S. Geological Survey Professional paper 729-G, 145 p.

Christiansen, R. L. 1975. Geologic map of the Norris Junction quadrangle, Yellowstone National Park, Wyoming: U.S. Geological Survey Geologic quadrangle map GQ1193, Scale 1:62, 500.

Christiansen, R. L. 1966. Preliminary evaluation of radar imagery of the Yellowstone rhyolite plateau. *In* Preliminary evaluation of radar imagery of Yellowstone Park, Wyoming. Technical letter NASA-30 prepared by the U.S. Geological Survey for the National Aeronautics and Space Administration. Denver, Colo.

Fournier, R. O., Christiansen, R. L., Hutchinson, R. A. and Pierce, K. L. 1994. A field trip-guide to Yellowstone National Park, Wyoming, Montana, and Idaho-volcanic, hydrothermal, and glacial activity in the region: U.S. Geological Survey Bulletin 2009, 46 p.

Keefer, W. R. 1968. Evaluation of radar and infrared imagery of sedimentary rock terrane, south-central Yellowstone National Park, Wyoming. Technical letter NASA-106 prepared by the U.S. Geological Survey for the National Aeronautics and Space Administration. Denver, Colo.

Haines, A. L. 1996. *Yellowstone Place Names: Mirrors of History.* University Press of Colorado, Niwot, Colorado. 318 p.

Hardy, C. C. 2005. Characterizing thermal features from multi-spectral remote sensing data using dynamic calibration procedures. University of Montana, PhD dissertation, 153 p.

Richmond, G. M., and Waldrop, H. A. 1975. Surficial geologic map of the Norris Junction quadrangle, Yellowstone National Park, Wyoming: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-650, Scale 1:62,500 p.

Pierce, K. L. 1968. Evaluation of infrared imagery applications to studies of surficial geology, Yellowstone Park. Technical letter NASA-93 prepared by the U.S. Geological Survey for the National Aeronautics and Space Administration. Denver, Colo.

Pierce, K. L. 1966. Comments on relation of radar imagery to surficial geology in Yellowstone Park. *In* Preliminary evaluation of radar imagery of Yellowstone Park, Wyoming. Technical letter NASA-30 prepared by the U.S. Geological Survey for the National Aeronautics and Space Administration. Denver, Colo.

Prostka, H. J. 1966. Preliminary general evaluation of radar imagery in Yellowstone Park. *In* Preliminary evaluation of radar imagery of Yellowstone Park, Wyoming. Technical letter NASA-30 prepared by the U.S. Geological Survey for the National Aeronautics and Space Administration. Denver, Colo.

Ruppel, E. T. 1966. Preliminary evaluation of radar imagery, southern Gallatin Range and vicinity (Flights 89-#1, 89-#2, 89-#3, 94-#2). *In* Preliminary evaluation of radar imagery of Yellowstone Park, Wyoming. Technical letter NASA-30 prepared by the U.S. Geological Survey for the National Aeronautics and Space Administration. Denver, Colo.

Smedes, H. W. 1968. Geological evaluation of infrared imagery, eastern part of Yellowstone National Park, Wyoming and Montana. Technical letter NASA-83 prepared by the U.S. Geological Survey for the National Aeronautics and Space Administration. Denver, Colo.

Susong, D. and Heasler, H. P. 2004. Unpublished data.

White, D. E., Hutchinson, R. A., and Keith, T. E. C. 1988. The geology and remarkable thermal activity of Norris Geyser Basin, Yellowstone National Park, Wyoming: U.S. Geological Survey Professional Paper 1456, 84 p.

University of Utah. 2006. Earthquake data, accessed October 2006 from seismic station website, <www.seis.utah.edu/catalog/ynp.shtml>.

U.S. Geological Survey. 2006. Quaternary fault and fold database for the United States, accessed October 2006, from USGS web site: <http://earthquakes.usgs.gov/regional/qfaults/>.

U.S. Geological Survey. 2006. USGS surface water data for USA-USGS surface-water annual statistics, accessed October 2006 from USGS web site, <http://waterdata.usgs.gov/nwis/annual/>.

Wikipedia, accessed August 2006, <http://en.wikipedia.org/wiki/Philetus_Norris>.