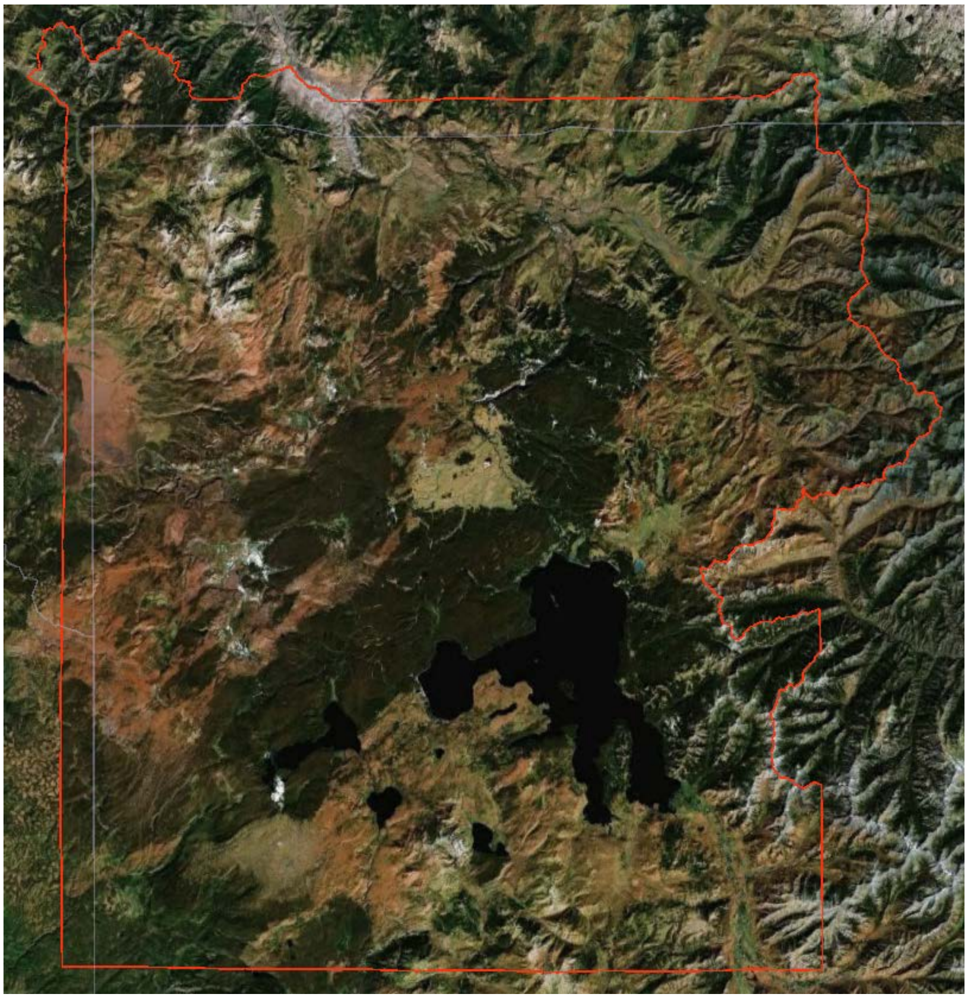
Welcome to

Bootcamp: Yellowstone!
A Field Trip Guide



By
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Yellowstone Volcano Observatory

June 11-23, 2012

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1 Introduction

1.1 Introduction to this Workshop

Welcome and thank you for joining Bootcamp: Yellowstone! This is a workshop and series of field trips for Flagstaff teachers. We will be studying the geologic and biologic diversity in the Northern Arizona San Francisco Volcanic Field and the Yellowstone Plateau Volcanic Field.

Sponsored by:
The Willow Bend Environmental Education Center
The U.S. Geological Survey, Astrogeology Science Center
The NASA New Investigator Program in Earth Sciences
The U.S. Forest Service, More Kids in the Woods Program
The Flagstaff Unified School District (FUSD)

The Willow Bend Environmental Education Center "Bootcamp" workshop series is a summer workshop for Flagstaff teachers interested in learning more about biologic and geologic sciences, and for FUSD teachers, an opportunity to earn professional development credits for attending. During the summer of 2009, participants in the first Bootcamp (Biodiversity Bootcamp) workshop took a trip to Hawaii!

We are looking forward to another successful workshop and field trip to Yellowstone, and hope to do more teacher Bootcamps in the future.

1.2 Workshop Itinerary

1.2.1 Orientation and Wine Tasting [Sunday, June 10 at 6 pm]

LOCATION: Vino Loco
22 E Birch Ave, Suite 1
928-226-1764
http://vinolocoflag.com/contact-us-flagstaff-wine.htm

Meet and greet, orientation, introduction, and wine tasting!

Goals of this work shop and field trip series:

1) To explore geologic and biologic diversity in the San Francisco Volcanic Field (northern Arizona) and the Yellowstone Plateau Volcanic Field (northeast Wyoming)

2) To investigate the challenges of managing and monitoring these natural (biologic, geologic, scenic, and educational) resources in the context of finding a balance between preservation of the natural features and making these areas accessible to millions of visitors through sustainable development

3) To provide teachers with materials and ideas for teaching about these topics: Geology, Volcanology, and Geothermal Processes; Wildlife (e.g., Predator-Prey Interactions); Fire Ecology and Botany (e.g., Invasive Species); Resource Management and Sustainability; and Cultural and Natural Histories

1.2.2 Field Excursions in the Flagstaff Area [June 11 – 14]

** For each of these local day-trips we will be carpooling from the Willow Bend parking lot

Monday, June 11	Red Mountain and Snowbowl parking lot (Greg)
Tuesday, June 12	Sunset Crater / Wupatki National Monument (Greg & Sunset Crater Staff)
Wednesday, June 13	Fire Ecology, Botany and Wildlife (Sapna)
Thursday, June 14	Grand Canyon and Resource Management (Cassandra)
Friday, June 15	Free day to organize and pack (Cassandra: pick up vehicles)

1.2.3 Field Trip to Yellowstone National Park [June 16 – 23]

** For the Yellowstone field trip, we will be leaving from the USGS parking lot on Gemini Dr. The parking area at the USGS is secured behind gates, which I will open the morning we leave. You WILL be able to leave your vehicles in the USGS parking lot for the week.

Saturday, June 16	leave Flagstaff and get to Layton, UT stop at Lake Powell and Glen Canyon Dam along the way
Sunday, June 17	leave Layton, UT and get to Yellowstone stop at Bear Lake and the Grand Tetons along the way
Monday, June 18	first full day of field excursions in Yellowstone Upper, Midway and Lower Geyser Basins
Tuesday, June 19	field excursions in Yellowstone Butte Point Overlook, Mary Bay, Mud Volcano area, Hayden Valley, Artist Point, Grand Canyon of Yellowstone
Wednesday, June 20	field excursions in Yellowstone Norris Geyser Basin, fire ecology tour along Norris-Canyon road
Thursday, June 21	field excursions in Yellowstone Mammoth Hot Springs, talk on wolves, numerous stops along Norris to Mammoth road (roaring mountain, Nymph Lake, Golden Gate, Hoodoos)
Friday, June 22	leave Yellowstone and get to Provo, UT
Saturday, June 23	leave Provo and get back to Flagstaff

See detailed road log in Section 2

1.3 List of Trip Participants

1.3.1 Trip Leaders

Dr. R. Greg Vaughan, USGS, Astrogeology Science Center, Flagstaff, AZ
Sapna Sopori, Director, Willow Bend Environmental Education Center
Cassandra Roberts, Program Manager, Willow Bend Environmental Education Center

1.3.2 Park Personnel

Dr. Roy Renkin, Research Scientist in Fire Ecology, Yellowstone Center for Resources
Dr. Douglas Smith, Senior Wildlife Biologist, Leader, Yellowstone Wolf Project, Yellowstone Center for Resources
Dr. Cheryl Jaworowski, Geologist, Yellowstone Center for Resources

1.3.3 Participants

Susan Alvin	Sechrist Middle School	2^{nd} Grade
Becky Cox	Knoles Elementary School	K – 4^{th} Grade Special Education
Erlinda Evans	Puente de Hozho	5^{th} Grade
Val Grimmett	Kinsey Elementary School	4^{th} Grade
Danielle Grimmett	Puente de Hozho	2^{nd} Grade
Linda Rae Jarmer	Homeschool teacher	Elementary
Nan Rankin	Flagstaff High School	9^{th} – 12^{th} Grade ASL
Roger Rankin	Flagstaff High School	10^{th} – 12^{th} Grade Special Education, World History
Richard Sidy	Non-formal educator	Willow Bend field trip leader
Alicia Vaughan	BASIS Flagstaff	5^{th} Grade Physical Geography, Robotics

1.4 Packing List (what to bring)

Regarding the variety of possible weather conditions we could encounter:
Air temperatures in June range from 1.7 ºC to 21.1 ºC (35 ºF to 70 ºF). The Yellowstone plateau elevation ranges from 5,280 – 11,400 feet, averaging about 8000 feet (a bit higher than Flagstaff). We could experience snow, rain, wind, cold, or warm and sunny conditions. We will be up early and out late, so even on warm days we will likely experience wide temperature extremes. Because the weather can be so variable, the Park recommends that visitors pack for all four seasons. However, we also all have to balance being prepared for variable weather conditions and packing lightly and efficiently. So, please minimize the number and size of your bags, because there will be limited room in the vehicles. Duffle bags are easier to pack than hard suitcases. You also may want to leave room to bring back souvenirs*.

*We are not allowed to collect samples of rocks or anything else from a National Park.

1.4.1 Field Equipment

rain coat, rain pants
hats: one warm hat for cold weather, a second hat to block the sun
ear band and/or scarf to keep ears and neck warm
pants (jeans, cargo, synthetic), shorts, or those pants that have zip-off legs to convert to shorts
gloves (for warmth)
polypropylene underwear (for warmth)
socks (good hiking socks)
boots: sturdy (preferably leather) with high ankle support strongly recommended
light shoes or sandals (for giving your feet a rest at the end of the day)
sweaters or sweat shirts or long sleeve shirts
fleece vest, light jacket (**layers** are key to staying comfortable in wide temperature fluctuations)
daypack (to carry all your stuff)
water bottles (at least 2)
toilet paper (in case nature calls when on a long hike)
sun block, aloe, and first aid kit
toiletries, medicines, etc.
sunglasses (must be cool and stylish)
flashlight with extra batteries, or even better, a headlamp
camera(s) (and film if you are old school, extra memory cards if you are new school)
money (paper and/or plastic)
pens, pencils, notebook(s), and this field trip guide!

1.5 Safety Considerations:

We are not going to be hiking in any remote backcountry areas that require special permits or anything like that. However, there are two safety issues to think about when in Yellowstone (above and beyond the safety issues you typically think about when hiking around Flagstaff): 1) wild life and 2) thermal areas.

1.5.1 Wildlife

Wildlife in Yellowstone includes bald eagles, bears, big horn sheep, bison, bobcats, coyotes, elk, lynx, moose, mountain lions, pronghorn antelope, rattlesnakes, and wolves (plus many more). The big ones that are most numerous and most often encountered are bison and elk. These animals can be unpredictable and every year numerous Park visitors are injured when they approach these animals too closely. **As a general rule, if an animal reacts to your presence, you are too close.** These large mammals are also a hazard when driving; in fact more people have been killed in the Park's history as a result of hitting an animal while driving. So, for those of us driving, sticking to the Park's (seemingly slow) 45 mph speed limit is important.

1.5.2 Thermal Areas

The thermal areas in Yellowstone are both delicate and dangerous. Special caution should be exercised when visiting them to avoid burning yourself or damaging the environment. Please stay on marked trails and boardwalks where present. Boiling pools of water are commonly covered by thin crusts of sinter. Assume that any water you see in a thermal area is hot enough to cause painful burns if it contacts your skin. Here is a nice photo of a human footprint, from someone who was hiking off the trail at Norris Geyser basin that broke through the crust and landed in boiling water. I imagine that flooding your boot and soaking your sock with boiling water would be a bad experience. This also happens to some Park visitors every year. Let's not let it happen to any of us.

1.6 Introduction to Yellowstone

In 1872 Yellowstone was designated a National Park, the first one in the world; and the presence of its spectacular geothermal features was the main reason for this designation. Yellowstone contains over 10,000 individual thermal features, including geysers, hot springs, pools, mud pots and fumaroles. These features range in size from just a few centimeters (the size of a quarter) to tens of meters across (the size of a football field) and they range in temperature from ~40 ºC (104 ºF) up to boiling, which is about 93 ºC (200 ºF) at elevations in Yellowstone. The Park contains over 500 geysers (2/3 of all the geysers in the world) and has a geothermal heat flow that exceeds that of the surrounding Rocky Mountain region by more than 30 times. There are many amazing sights in Yellowstone, from the scenery to the diverse wildlife, but the formation and evolution of all these things are all directly related to **the Yellowstone Hot Spot**.

1.6.1 The Yellowstone Hot Spot

A hot spot is a huge, nearly vertical region of upwelling heat and at least partially molten mass from deep in the Earth's mantle. There are about two dozen places on Earth where these mark the surface with volcanic activity (figure 1). As the tectonic plates move, these relatively stationary hot spots leave tracks of volcanic features at the surface. One classic example of this is Hawaii (figure 2). Another example is Yellowstone (figure 3). Beneath Yellowstone, the mantle plume extends to at least 500 km, perhaps as deep as 700 km (figure 4). Other mantle plumes, such as the one currently beneath Hawaii, extend down to the core-mantle boundary (~2900 km). At Yellowstone the hot spot causes melting of upper mantle rocks and feeds a large magma chamber, which sits 5-10 km below (figure 5). Whether it is refilling and heating up, or cooling off and solidifying, is one of the big questions scientists are trying to answer.

BOX 1:
The Yellowstone geothermal system owes its existence to:
1) the fact that this area sits atop a large hot spot in Earth's mantle, which feeds a partially molten magma chamber that is 5-10 km below the surface,
2) the regional climate, which brings an annual precipitation of >0.5 m/yr, plus about 2 m of snow per year, and
3) the fact that this is a tectonically active area, with many earthquakes that keep the fractures open to flowing hydrothermal fluids.

The cooling magma beneath Yellowstone conductively heats the rocks above it and also expels some magmatic fluids (H_2O steam, CO_2, and sulfur gases like SO_2 and H_2S). *Meteoric* water (water that infiltrates down from the surface from rain or snow melt) descends along a steep geothermal gradient and heats up. Heated (hydrothermal) fluids (mostly water) are more buoyant and rise, setting up a convection current, similar to that in a boiling pot of water, except that these fluids need fractures or faults to move through the rocks. The volcanic rocks that cover the region are normally not very permeable, but because this is a tectonically active area, there are many earthquakes that serve to keep the rocks fractured and open to flowing fluids. These hydrothermal fluids carry many dissolved gases and solids with them, and as they approach the surface the gases and solids come out of solution.

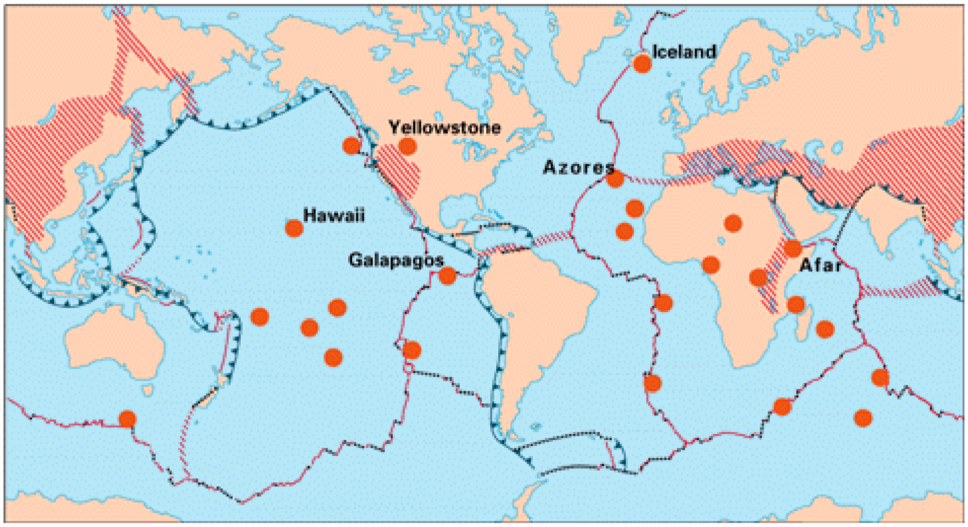


Figure 1. Map of Earth's tectonic plates and mantle hot spots. Most volcanoes and earthquakes are found along plate boundaries, however, there are a number of volcanoes that sit in the middle of plates. These volcanoes have formed above a hot spot - a single plume of hot, rising mantle. (from http://www.geo.cornell.edu/hawaii/220/PRI/PRI_PT_hotspot.html)

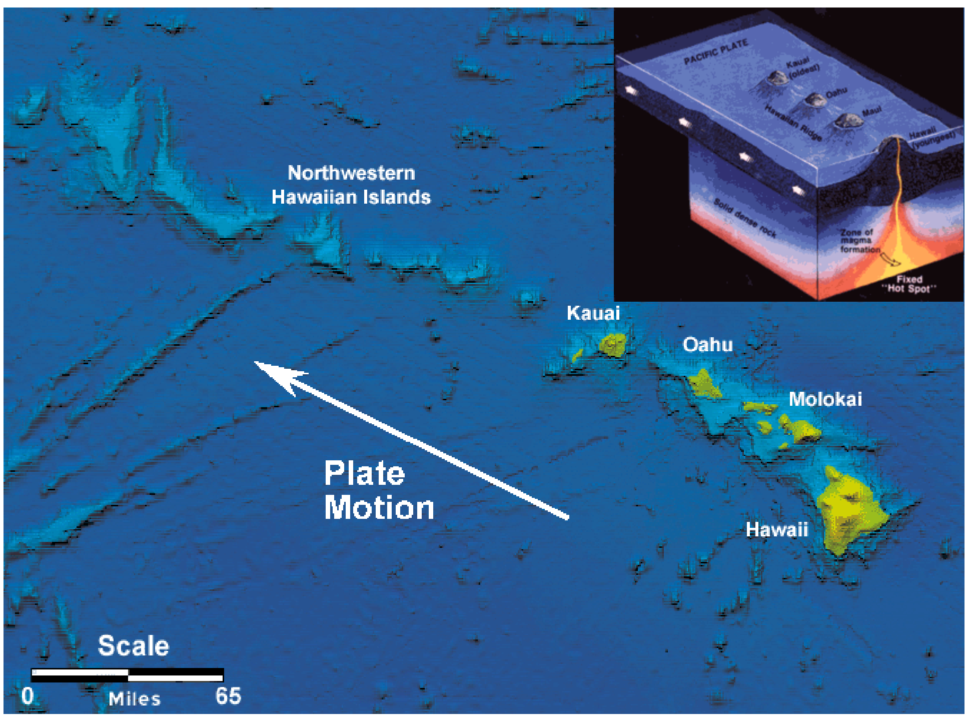


Figure 2. Hot spots often create a chain of volcanoes as a plate moves across a relatively stationary mantle plume. One example of a hot spot track is the chain of Hawaiian Islands. Knowing the age of each island in the track we can tell the direction of motion of the plate (to the NW) and the rate at which it moves (8.6 cm/year). (from http://www.geo.cornell.edu/hawaii/220/PRI/PRI_PT_hotspot.html)

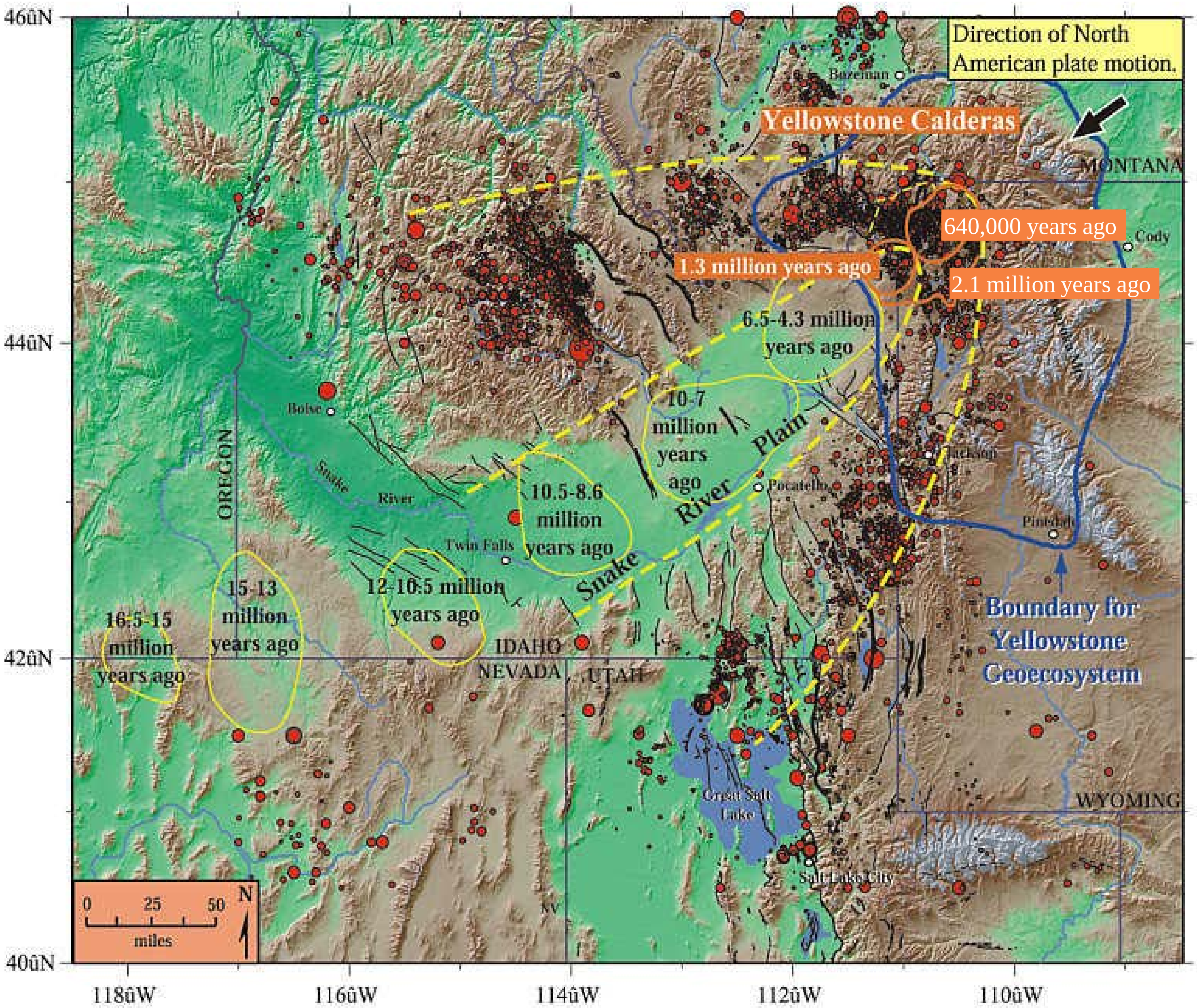


Figure 3. Path of the Yellowstone hotspot. Yellow and orange ovals show volcanic centers where the hotspot produced one or more caldera eruptions - essentially "ancient Yellowstones" - during the time periods indicated. As the North American tectonic plate drifted southwest over the hotspot, the volcanism progressed northeast, beginning in northern Nevada and southeast Oregon 16.5 million years ago and reaching Yellowstone National Park 2.1 million years ago. A bow-wave or parabola-shaped zone of mountains (browns and tans) and earthquakes (red dots) surrounds the low elevations (greens) of the seismically quiet Snake River Plain. The greater Yellowstone "geoecosystem" is outlined in blue. Faults are in black (modified from Smith and Siegel, 2000).

BOX 2:
Given the scale bar and the age constraints on past hot spot volcanism, calculate the rate of plate movement in kilometers per million years (km/my).

Think about how this differs from the San Francisco Volcanic Field in northern Arizona.

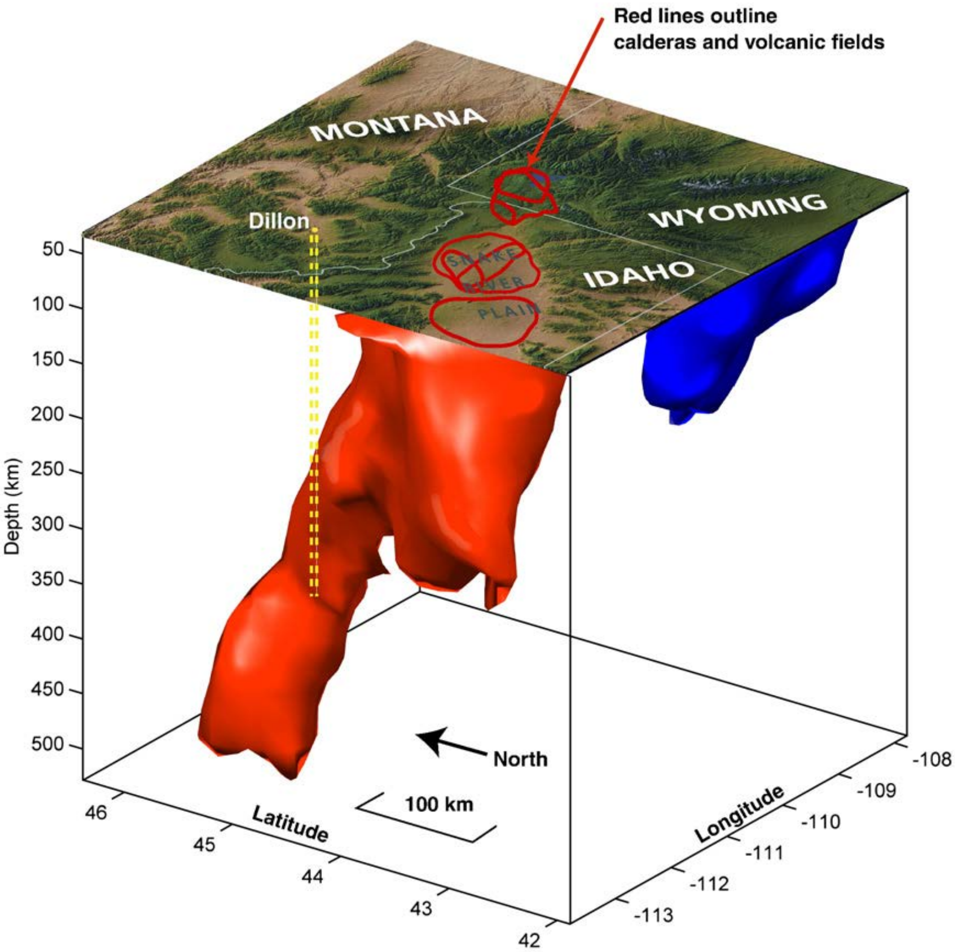


Figure 4. A technique for using seismic waves to probe the 3-D structure of features in the Earth's mantle called *seismic tomography* reveals an inclined conduit of warm mantle material (thermal plume) inclined to the northwest from beneath Yellowstone. At a depth of 500-700 km, the inferred plume is beneath Dillon, Montana (yellow dot and dashed lines). The red outlines on the surface denote previous hot spot calderas and the progression of volcanic fields (from Pierce and Morgan, 2009).

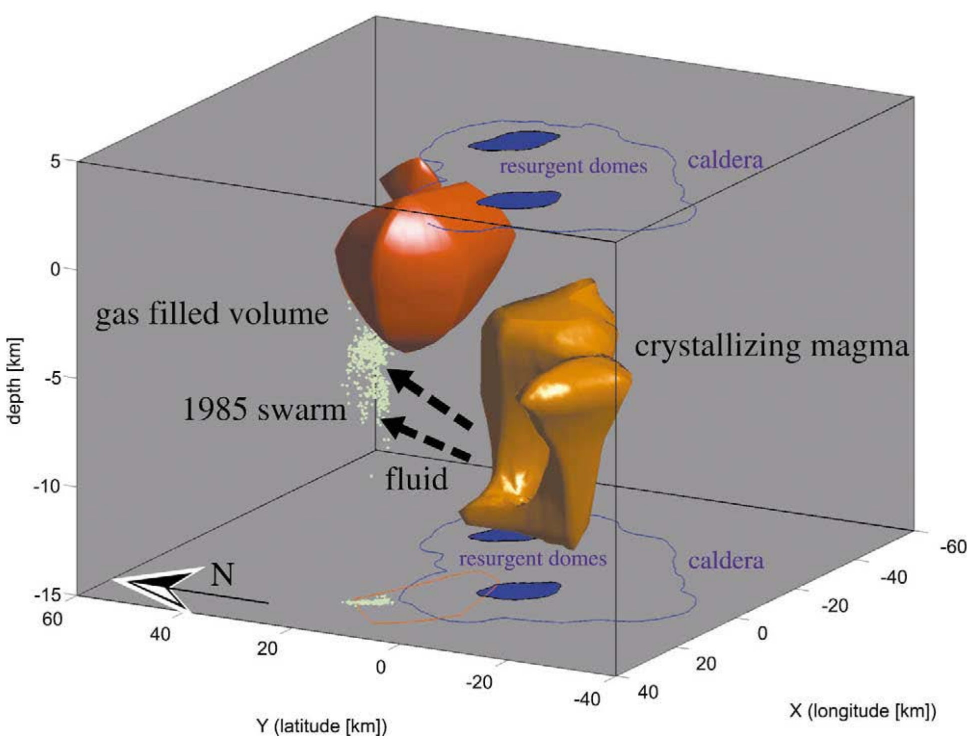


Figure 5. A 3-D view of hot/molten or low density regions beneath Yellowstone as imaged by local seismic tomography. The orange body outlines location of a possible crystallizing magma body beneath the Yellowstone caldera; the red body outlines location of shallow, possible gas-filled volume. Light green dots are hypocenter locations of the 1985 earthquake swarm. Dashed arrows denote possible fluid migration from the crystallizing magma body towards gas-filled volume thereby causing the 1985 swarm (from Husen et al., 2004).

When solids come out of solution due to the temperature decreasing as they rise, they precipitate various minerals in the fractures and at the surface. When gases come out of solution due to the pressure decreasing, they mix with moisture in the near surface, creating acids, or they erupt at the surface like opening a bottle of champagne. All of the hot springs in the Park are the surface manifestation of the hydrothermal system that moves heat and mass away from the magma at depth. The basic concept of the hydrothermal system here is shown in figure 6.

1.6.2 Earthquakes and Plate Tectonics

Now, let's step back and look at the Yellowstone region in a larger context (figure 3). The hot spot that now sits under Yellowstone and drives all of its volcanic and hydrothermal activity started making noise about 16.5 million years ago under what is now northern Nevada and southeastern Oregon. As the North American tectonic plate has moved toward the southwest, the stationary hot spot has plowed a path of volcanic destruction on the surface and uplifted a "bow wave" of land around it, much like the water waves forming around the bow of a moving ship. Just for fun sometime, take a look at the geologic map of the US and a topographic shaded relief image of the US at http://tapestry.usgs.gov/default.html.

Because Yellowstone is at the front of this mantle hot spot pushing up the crust and is also subject the other tectonic forces (e.g., the extensional forces of the Basin and Range), earthquakes are common in this area – the Yellowstone area experiences from 1,000 to 3,000 earthquakes every year (1-20 per day), with occasional seismic swarms of hundreds per day. Most of these are too small to be felt (magnitude <3), but sometimes earthquakes with magnitudes >3 or 4 occur and are felt throughout the region. There was a well-documented seismic swarm that occurred beneath Yellowstone Lake in January 2009 that is described here: http://volcanoes.usgs.gov/yvo/publications/2009/09swarm.php that included several events large enough to be felt. Such swarms could be caused by magma movement underground, or by hydrothermal fluids migrating, forcing their way through fractures.

On rare occasions there can be very large earthquakes in the region that constitute a significant hazard to people and structures. One such earthquake happened in 1959 at an area just outside the Park boundary to the west, near Hebgen Lake. On August 17, 1959 at ~11:30 pm there was a M6.3 foreshock followed seconds later by a M7.5 earthquake that sent a mountainside crashing down in a giant landslide that buried a campground full of campers and dammed the Madison River causing flooding. Overall, there were 28 deaths and millions of dollars in damage both in and outside the Park. The quake also affected Yellowstone's hydrothermal system: about 160 geysers erupted, some after decades of silence - some formerly gentle springs erupted as geysers for the first time. Interestingly, Old Faithful's eruptions became less frequent. This event is described in Smith and Seigel's book, "Windows into the Earth" (Smith and Siegel, 2000).

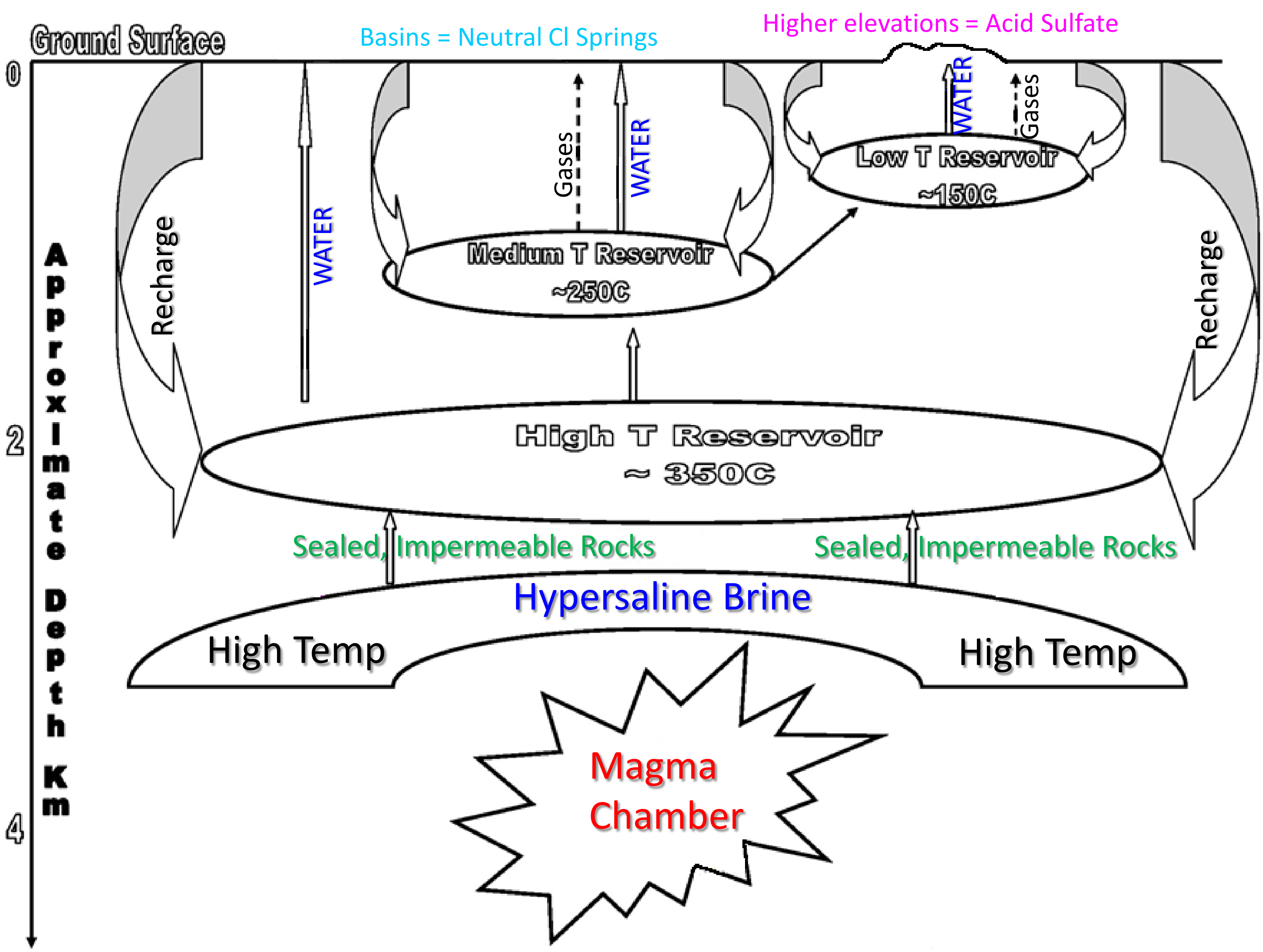


Figure 6. Schematic diagram of a geothermal system (modified from Fournier et al., 1994).

1.6.3 The Yellowstone Supervolcano and Other Hazards

For a volcano to erupt, magma has to find a path, or make its own path, to the Earth's surface. And this has happened at Yellowstone on dozens of occasions in the last 2.1 million years. Three of these many eruptions are among the largest eruptions that we know of that have ever occurred on Earth! The term supervolcano is an informal term used to classify volcanoes that have had eruptions that produced a volume of >300 km^3 of lava and tephra (Lowenstern et al., 2006). Yellowstone certainly falls into this category; its last three supereruptions have produced ~2500, ~300, and ~1000 km^3 of material, respectively (figure 7). The following table lists the timing and characteristics of these three large eruptions.

Date of Supereruption	Rock Formation	Caldera formed	Volume of Ejecta (km^3)
0.640±0.002 Ma	Lava Creek Tuff	Yellowstone	1,000
1.292±0.005 Ma	Mesa Falls Tuff	Henrys Fork	300
2.053±0.006 Ma	Huckleberry Ridge Tuff	Island Park	2,500

There was also a *relatively small** caldera-forming eruption ~150,000 years ago that formed the West Thumb region of Yellowstone Lake, and there have been >80 smaller, less explosive lava flow eruptions since then, the last one ~70,000 years ago. These lava flow eruptions range in composition from basalt to rhyolite (see figure 8 for a review of different lava types). Here is another good opportunity to think about how Yellowstone compares to the San Francisco Volcanic Field (SFVF) of Northern Arizona. Is the SFVF a hot spot? Compare and contrast the age relations, type of volcanism, type of resultant landforms.

**Relatively small* means merely the size of the eruption of Mount Mazama in Oregon 7,600 years ago that formed what is now Crater Lake, Oregon.

So, what are some of the hazards associated with Yellowstone's volcanic / hydrothermal system? The USGS Fact Sheet 2005-3024 (Lowenstern et al., 2005) provides a nice review of the various hazards in the Yellowstone region, as well as a great illustration of how the last three supereruptions compare to others in volume and extent. Hazards, in order of decreasing destructive power, include:

1) Large caldera-forming eruptions,
2) Smaller (but still big) lava flow eruptions,
3) Earthquakes large enough to damage buildings and cause landslides, and
4) Small to medium hydrothermal explosions.

BOX 3: Mythbuster

How many times have you heard, "Yellowstone erupts every 600,000 years" or "Yellowstone is due, or overdue, for another supereruption?" The next time you hear this, you can say, "Oh really? Let's do the math."

Using the ages of the last three supereruptions listed in the table above, calculate the average recurrence interval. Then subtract that recurrence interval from the date of the last supereruption. How much time do we have left?
Then point out that it is statistically meaningless to predict a recurrence interval based on only two data points, and that volcanoes do not erupt on regular, predictable schedules.

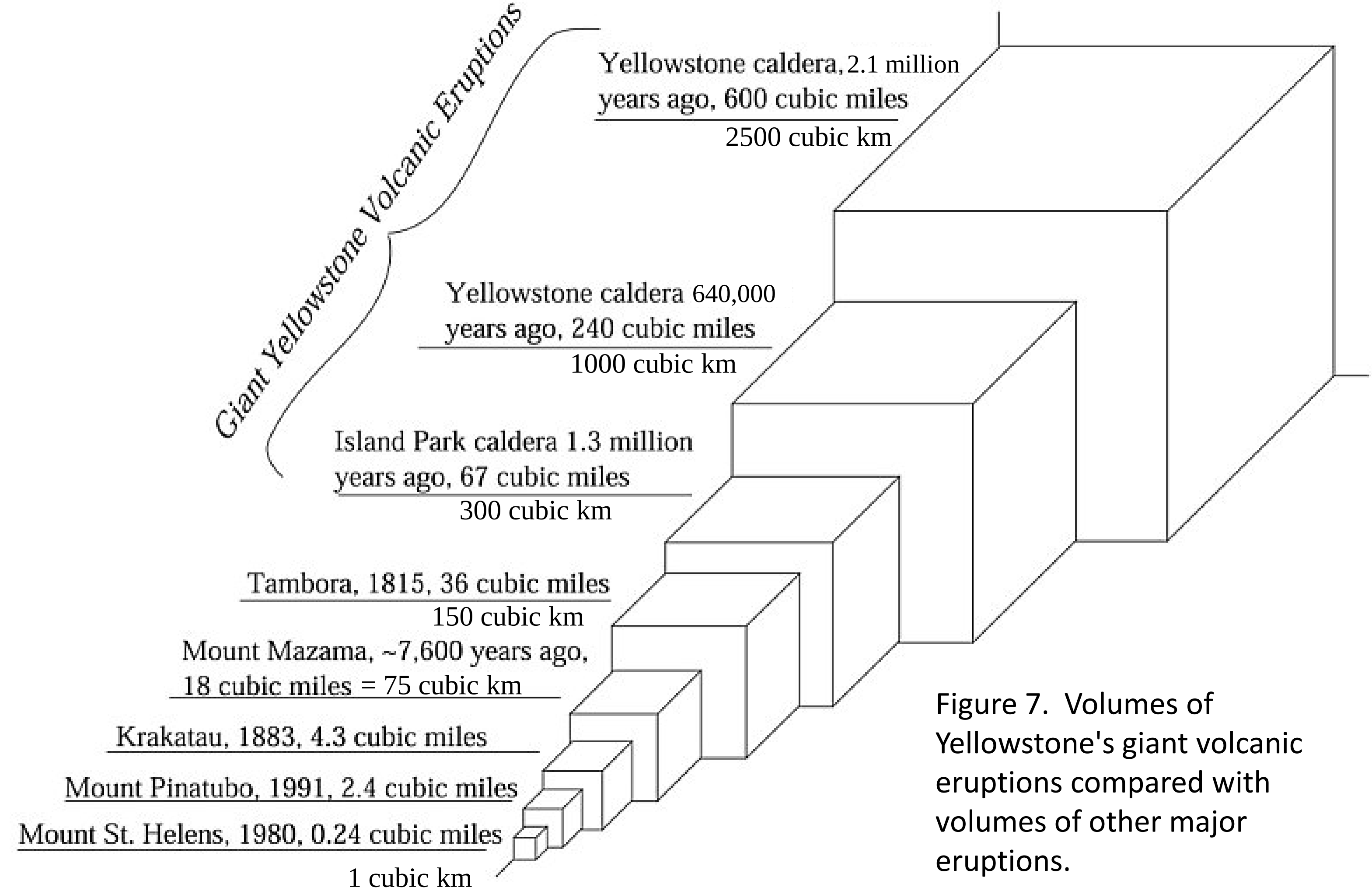


Figure 7. Volumes of Yellowstone's giant volcanic eruptions compared with volumes of other major eruptions.

Volcanic Rock Type	Melting / Eruption Temperature	Silica (SiO_2) Content	Magma Characteristics
Rhyolite	700 °C (1300 °F)	68-77%	Low viscosity (sticky) Higher gas content Explosive
Dacite	800 °C (1470 °F)	63-68%	
Andesite	900 °C (1650 °F)	52-63%	
Basalt	1150 °C (2100 °F)	48-52%	High viscosity (runny) Lower gas content Less explosive

Figure 8. Characteristics of different types of lavas and the resulting volcanic rock (modified from Duffield, 2011).

Large caldera-forming (super) eruptions are the most explosive, most violent eruptions on Earth. Fortunately they don't happen very often; only about 50 have been recognized in Earth's 4.55 billion year history, and the last one to happen (Toba Indonesia) was ~76,000 years ago (Duffield, 2011). Of course, the farther back one goes in the geologic record, the more difficult it is to decipher – there could have been many more, but none has occurred in modern human history. Calderas are collapse features that form from the eruption of a large volume of magma. Imagine a large magma chamber underground. Then all of that material gets erupted onto the surface rather quickly, leaving a large underground void. The ground then collapses to fill the void, forming a caldera. Smaller lava flow eruptions occur more frequently, as can be seen on the geologic map of Yellowstone (figure 9). More than 80 lava flow eruptions have occurred in Yellowstone since the last big supereruption 640,000 years ago. Some of these have been basaltic lava flows that erupted outside the Yellowstone caldera to the north, but most have been rhyolite flows and dome eruptions that have mostly filled up the caldera (figure 9).

Hydrothermal explosions are different from volcanic eruptions in that there is no new lava or tephra erupted in a hydrothermal explosion – it's just water and rock debris that was already there. Hydrothermal explosions are more like geyser eruptions that are forceful enough to eject some rocks. In fact, there is really a continuum of events that range from geyser eruptions that just eject water and steam; to forceful geyser eruptions that eject some rock material; to hydrothermal explosions that eject more, larger rocks even further away; to large hydrothermal explosions, to phreatic eruptions, which occur when magma comes into contact with ground water and heats it rapidly, causing it to flash to steam, generating a very large, violent eruption (but still with no magmatic material coming out).

Fortunately, there is an inverse relationship between the potential destructiveness of a hazard and how often it happens (Lowenstern et al., 2005). One important question is, are there precursors to these events? This is where volcano and geothermal monitoring come in. The purpose of monitoring is to try to prevent inevitable volcanic hazards from turning into preventable volcanic disasters (i.e., causing great loss of life or property). As far as scientists know, there are no precursor phenomena that signal impending earthquakes. Nor are there measureable precursors to the small hydrothermal explosions that occasionally rattle the thermal areas (*remind me to tell you a good story about a hydrothermal explosion that happened right in front of a bunch of geologists who had just finished talking about hydrothermal explosions*). There are, however, measureable precursor phenomena associated with volcanic eruptions. For magma to erupt it has to make its way to the surface; and it can't just sneak up on us (as long as we're listening). There are four phenomena that we look for to monitor volcanic activity, 1) anomalous seismic activity, 2) ground deformation, 3) anomalous gas emissions, and 4) anomalous thermal emissions. We engage in regular monitoring, even when the volcano is quiet, so that we can establish the background levels of activity - so we know how to recognize it if/when something unusual happens. The USGS, and it counterpart organizations in countries all over the world, monitor their volcanoes using every tool available, from field instruments right next to the volcano to satellite remote sensing observations. To learn more about the USGS Volcano Hazards Program, visit: http://volcanoes.usgs.gov/index.php. For the Yellowstone Volcano Observatory see: http://volcanoes.usgs.gov/yvo.

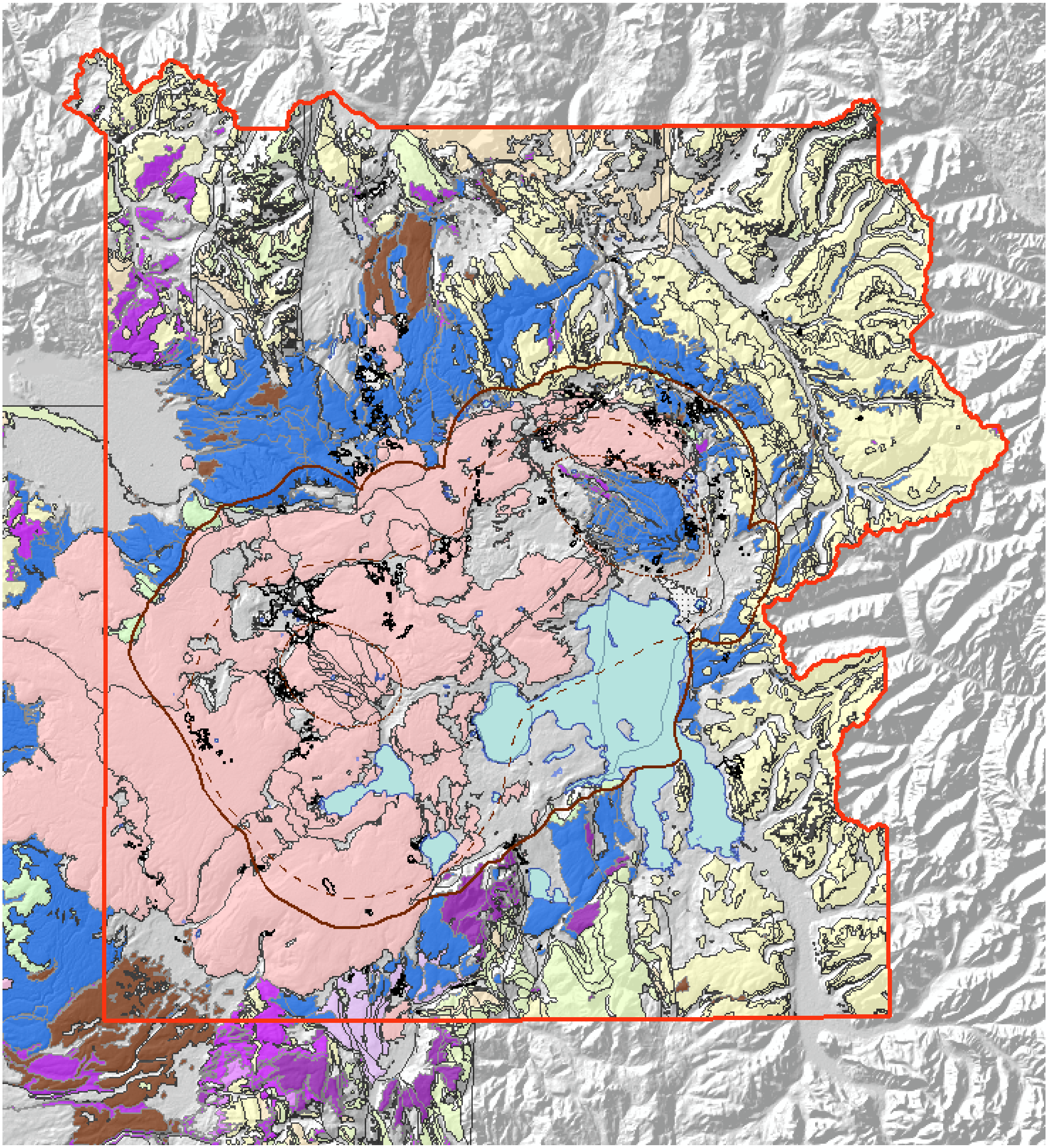


Figure 9. Geologic map of Yellowstone (modified from Christensen, 2001).

1.6.4 Biology, Ecology and Sustainable Resource Management

I have essentially a Wikipedia-level knowledge of these topics. So, I will provide some information and web links for you (Wikipedia is actually not a bad place to start learning about something new).

The Greater Yellowstone Ecosystem is one of the last remaining large, nearly intact ecosystems in the northern temperate zone of the Earth.
http://en.wikipedia.org/wiki/Greater_Yellowstone_Ecosystem
http://en.wikipedia.org/wiki/Yellowstone_National_Park
http://www.nrmsc.usgs.gov/science/gye

Yellowstone is home to the largest concentration of mammals in the lower 48 states. Sixty-seven different mammal species live here, including grizzly bears and black bears. Gray wolves were restored in 1995 and more than 200 live in the park now. Wolverine and lynx, which require large expanses of undisturbed habitat, are also found in the Yellowstone ecosystem. Seven native ungulate species - elk, mule deer, bison, moose, bighorn sheep, pronghorn, and white-tailed deer also live here. Non-native mountain goats have colonized northern portions of the park and numerous small mammals are found throughout the park. There are also 330 different species of birds that have been documented in the area, of which approximately 148 species are known to nest in the park.

Native cutthroat trout are the most ecologically important fish of the park and the most prized, and highly regarded by visiting anglers. Several factors, mostly related to exotic species introductions, are threatening the persistence of these fish. Yellowstone Lake is the last pristine habitat for the native Yellowstone cutthroat trout, but the survival of this species is threatened as a result of the illegal introduction of the non-native piscivorous lake trout into the lake sometime before 1994 (Kaeding et al., 1996; Chaffee et al., 2007). Lake trout feed on the cutthroat, who previously had no natural predators in the lake. The problem is that many of the Park's other animals (bears, birds and otters) rely on the cutthroat population for food. The lake trout reside in the deeper part of the lake and are not available as food to these animals at the surface. Another problem is the introduction of the invasive New Zealand mud snail. In 1994, New Zealand mud snails were discovered in the Madison River near the Park boundary. Since then there has been a rapid spread of this exotic species to the Firehole and lower Gibbon rivers. Similar to other invasions of aquatic nuisance species, long-term effects of this exotic species on the indigenous invertebrate fauna are unknown; however, studies conducted on the middle Snake river in central Idaho suggest that native mollusks may be reduced in abundance or eliminated entirely.

Yellowstone is also home to more than 1,350 species of vascular plants, of which 218 are non-native. It is a struggle that anyone who has ever tended a lawn or residential garden can relate to: the effort to keep weeds under control. Now imagine trying to do the same in an area the size of Yellowstone. For decades the park has been trying to prevent the spread of plants that don't belong in the park, such as spotted knapweed, houndstongue, and orange hawkweed. Non-native plant species are commonly introduced for food, landscape restoration, biological pest control, pets, and sport. However, many introduced invasive plant species have become established throughout the western US and have disrupted food chains and nutrient cycles by out-competing native plants. Economic damages from invasive species and costs associated with their control total nearly $120 billion annually in the U.S. Wetland, riparian, and disturbed areas

have an increased risk of invasion by non-native plants which can significantly reduce the biodiversity and the health of ecosystems by replacing riparian vegetation communities.
http://www.nps.gov/yell/index.htm
http://www.nps.gov/yell/naturescience/index.htm
http://www.yellowstonepark.com/2011/06/yellowstone-lake-cutthroat-trout-threatened-by-non-native-lake-trout/
http://www.nps.gov/yell/planyourvisit/mudsnail.htm
http://www.nps.gov/yell/parknews/11020.htm
http://www.greateryellowstonescience.org/topics/biological/vegetation/invasive

Landscapes in Yellowstone have long been shaped by fire. The natural history of fire in the park includes large-scale conflagrations sweeping across the park's vast volcanic plateaus, hot, wind-driven fires torching up the trunks to the crowns of the pine and fir trees at several hundred-year intervals. Such wildfires occurred across much of the ecosystem in the 1700s, prior to the arrival of European explorers, the designation of the park, and a pattern was established to battle all blazes in the belief that fire suppression was good stewardship.

The 1988 fires affected 793,880 acres or 36 percent of the park. Five fires burned into the park that year from adjacent public lands. The largest, the North Fork Fire, started from a discarded cigarette. It burned more than 410,000 acres.
http://www.nps.gov/yell/naturescience/wildlandfire.htm
http://www.windowsintowonderland.org/fire/index.html

In terms of resource management, the National Park Service is congressionally mandated to monitor, protect and preserve the natural features of the Park, including the naturally occurring wildlife, plants, and the geologic and geothermal features. On the other hand, about 3.5 million visitor cycle through the Park every year. The infrastructure to accommodate these visitors (roads, lodging, restaurants, stores, gas stations, amenities, waste disposal, and utilities) can be at odds with the goal of preserving the natural environment. One specific issue is the building of roads and other Park buildings in thermal areas. Thermal areas are defined as: contiguous geologic units generally including one or more thermal features, bounded by the maximum aerial extent of hydrothermally altered ground, thermal deposits, geothermal gas emissions, or heated ground. Yet at any given time, a significant portion of a thermal area may not be thermally active. Road building through these areas can be dangerous, as well as a waste of resources because renewed thermal activity or steady acid alteration of the substrate can damage roads such that they have to be repaired very frequently. A nice illustration that may help change the perception of thermal areas is shown in figure 10. In figure 10, is the bison habitat defined merely by where the bison happen to be standing right now? Or does their habitat encompass the entire area? Similarly, thermal areas are much broader than where active thermal features are currently located (figure 11). This is a constant battle between the scientists in the Park who are tasked with monitoring and protecting the thermal areas and those who want to build roads for visitor access. Another issue we will discuss is that of geothermal energy development outside the Park and how that might affect Yellowstone's thermal features.

Lastly, a little cultural history – the story of Chief Joseph of the Nez Perce:
http://www.windriverhistory.org/exhibits/chiefjoseph/chiefjoseph01.htm

Figure 10. Bison and bison habitat (top). Much like the fact that the bison habitat consists of more than just where the bison happen to be standing now, thermal areas are dynamic, consisting of more than just the ground that happens to be hot now.

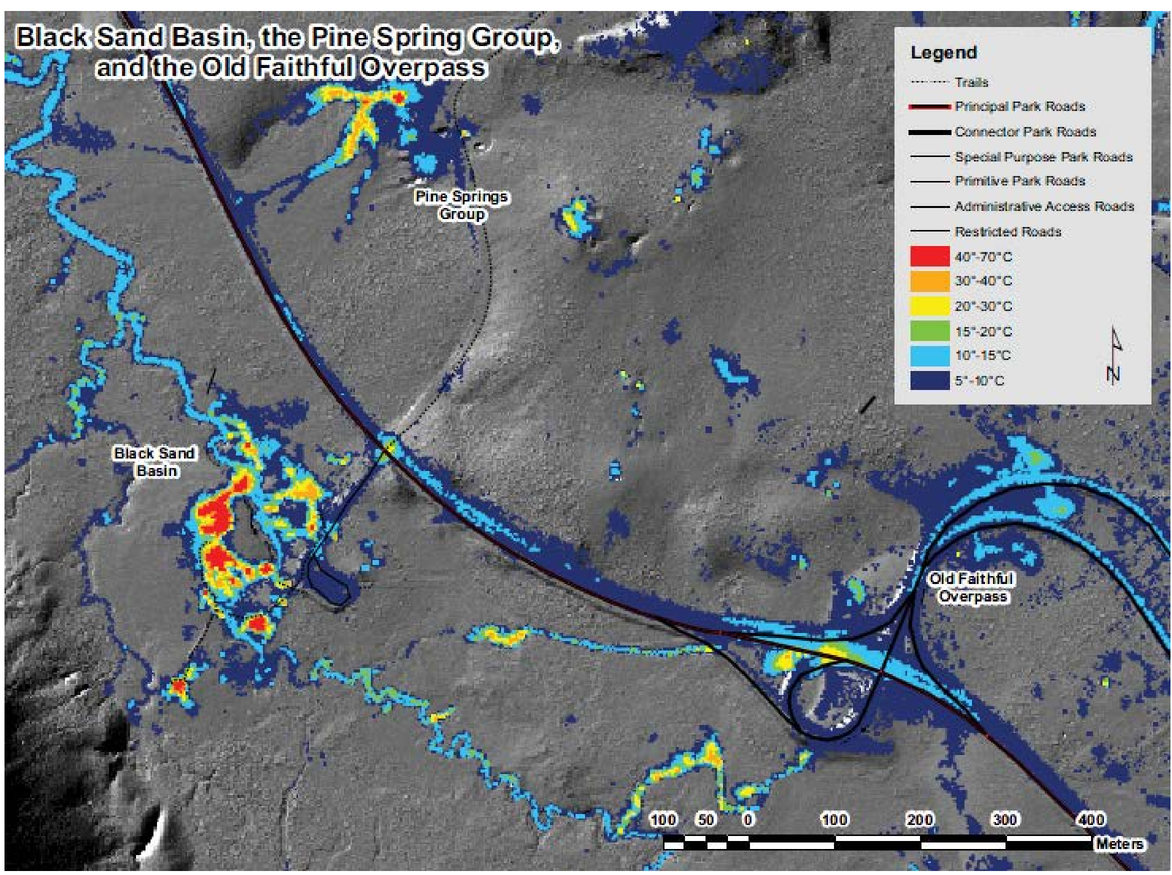


Figure 11. The Old Faithful overpass road as it intersects with active thermal features (bottom). From Jaworowski et al. (2010).

2 Field Trip Road Log and Time Line (like a slinky: structured, but flexible)

2.1 Saturday June 16 - Travel from Flagstaff, AZ to Layton, UT

5:12 am	Sunrise
7:00 am	Meet at USGS *(RRA = Restrooms Available)
8:00 am	Depart in vehicles from USGS parking lot
10:30 am	Glen Canyon Dam (RRA)
	Lunch and talk about the Colorado River, the Dam, and Lake Powell
	Note that as we cross into Utah, we lose an hour as we enter a different time zone
12:30 pm	Depart Glen Canyon Dam
2:00 pm	Arrive in Kanab, UT
4:30 pm	Arrive in Beaver, UT
8:00 pm	Arrive in Layton, UT (Just north of Salt Lake City)
	Dinner
	Stay at Hotel in Layton, UT
9:02 pm	Sunset

2.2 Sunday June 17 – Travel from Layton, UT to Yellowstone

5:55 am	Sunrise
7:00 am	Depart hotel in Layton, UT
8:00 am	Arrive in Logan, UT
9:00 am	Bear Lake Overlook (RRA)
10:30 am	Arrive in Montpelier, ID
12:30 pm	Arrive in Jackson, WY
1:00 pm	Arrive at Moose, WY (Grand Teton National Park)
	Picnic Lunch at Jenny Lake Area (RRA)
	Short Hike
2:30 pm	Depart Jenny Lake Area
4:00 pm	Arrive at West Thumb Geyser Basin
	Explore West Thumb Geyser Basin ***(Yellowstone Stop 1)***
	Head to Grant Village Visitor's Center (RRA) (***Stop 1b***)
6:30 pm	Depart Grant Village Visitor's Center
	Point out Isa Lake on Continental Divide
7:00 pm	Arrive at Old Faithful Lodge Cabins (RRA)
	Check in and get settled, have dinner
	Hopefully watch Old Faithful erupt!
9:12 pm	Sunset

2.3 Monday June 18 – Yellowstone Field Excursions (First full day in Park)

5:39 am	Sunrise
6:30 am	Breakfast
7:30 am	Depart Old Faithful Lodge Cabins **on foot**
	Explore Upper Geyser Basin ***<u>(Yellowstone Stop 2)</u>***
	Easy trail hiking (flat, partly paved) total 3-4 miles round trip
10:30 am	Return to Old Faithful area (RRA)
	Check out new Visitor's Center (opened in Sept 2010) (***<u>Stop 2b</u>***)
11:30 am	Depart Old Faithful Lodge Cabins **in vehicles (2 vans)**
	Lunch in vehicles
12:30 pm	Arrive at Lower Geyser Basin, Firehole Lake area ***<u>(Yellowstone Stop 3)</u>***
2:00 pm	Depart Firehole Lake area
	Check out Chief Joseph's Story (pullout)
2:45 pm	Arrive at Lower Geyser Basin, Fountain Paint Pots area ***<u>(Yellowstone Stop 4)</u>***
4:00 pm	Depart Fountain Paint Pots area (RRA)
4:30 pm	Arrive at Midway Geyser Basin, Grand Prismatic Spring ***<u>(Yellowstone Stop 5)</u>***
6:00 pm	Depart Midway Geyser Basin (RRA)
	Check out Biscuit Basin on the way back
6:30 pm	Return to Old Faithful Lodge Cabins (RRA)
	Dinner
9:13 pm	Sunset

2.4 Tuesday June 19 – Yellowstone Field Excursions (Second full day in Park)

5:39 am	Sunrise
6:30 am	Breakfast
7:30 am	Depart Old Faithful Lodge Cabins **in vehicles (2 vans)**
	Check out Fishing Bridge Museum and Visitor's Center
9:30 am	Arrive at Butte Point overlook ***<u>(Yellowstone Stop 6)</u>***
10:15 am	Depart Butte Point overlook
11:00 am	Arrive at Mud Volcano Area (RRA) ***<u>(Yellowstone Stop 7)</u>***
12:30 pm	Lunch
1:00 pm	Depart Mud Volcano Area and drive up Hayden Valley
	Look for herds of animals
2:00 pm	Arrive at Artist Point overlook ***<u>(Yellowstone Stop 8)</u>***
	Grand Canyon of Yellowstone
	Hike 2-3 miles roundtrip along canyon rim trail, see upper falls and lower falls
	(If there is time, we can go along the north rim drive as well to get different views of the Grand Canyon and the falls)
4:45 pm	Depart Grand Canyon of Yellowstone area
6:45 pm	Return to Old Faithful Lodge Cabins (RRA)
9:13 pm	Sunset

2.5 Wednesday June 20 – Yellowstone Field Excursions (Third full day in Park)

5:39 am	Sunrise
6:30 am	Breakfast
7:30 am	Depart Old Faithful Lodge Cabins **in vehicles (2 vans)**
9:00 am	Arrive at Norris Geyser Basin ***(Yellowstone Stop 9)***
	Hike around hot springs at Norris with Park Geologist, Dr. Cheryl Jaworowski
12:00 pm	Lunch at Norris Geyser Basin (RRA)
1:00 pm	Meet fire ecology expert, Dr. Roy Renkin, for afternoon tour of different aged burn areas along Norris to Canyon Road ***(Yellowstone Stop 10)***
5:00 pm	Finish fire ecology tour at Canyon Village (RRA)
	Check out the Canyon Visitor's Center (***Stop 10b***)
	Shop 'til you drop / Have dinner at Canyon Village?
7:30 pm	Depart Canyon Village
9:30 pm	Return to Old Faithful Lodge Cabins (RRA)
9:13 pm	Sunset

2.6 Thursday June 21 – Yellowstone Field Excursions (Last full day in Park)

5:39 am	Sunrise
6:30 am	Breakfast
7:30 am	Depart Old Faithful Lodge Cabins **in vehicles (2 vans)**
	Stops along Norris to Mammoth Road ***(Yellowstone Stop 11)***
	Roaring Mountain
	Obsidian Cliff (rhyolite obsidian)
	Golden Gate (waterfall)
	Hoodoos (giant landslide of older travertine)
11:00 am	Arrive at Mammoth Hot Springs, upper terrace ***(Yellowstone Stop 12)***
1:00 pm	Mammoth Visitor's Center for talk by Dr. Doug Smith about wolves and other wildlife (RRA)
2:30 pm	Group Presentations
4:00 pm	Depart Mammoth Hot Springs area
	Stop at Nymph Lake (see new fumaroles that opened up in March 2003)
5:00 pm	Detour along Firehole Canyon drive ***(Yellowstone Stop 13)***
	Outcrop with obsidian flow textures
	Waterfalls
6:30 pm	Return to Old Faithful Lodge Cabins (RRA)
9:13 pm	Sunset

2.7 Friday June 22 – Travel from Yellowstone to Salt Lake City, UT

5:39 am	Sunrise
6:30 am	Breakfast
7:30 am	Depart Old Faithful Lodge Cabins **in vehicles**
	Say Bye to Yellowstone
11:00 am	Arrive in Jackson, WY
	Shopping, Lunch
12:30 am	Depart Jackson, WY
6:00 pm	Arrive in Provo, UT
	Dinner
	Stay at Hotel in Provo, UT
9:00 pm	Sunset

2.8 Saturday June 23 – Travel from Salt Lake City, UT to Flagstaff, AZ

5:58 am	Sunrise
7:00 am	Breakfast
8:00 am	Depart Provo, UT
1:00 pm	Arrive in Kanab, UT
	Lunch
	Note that as we cross into AZ, we gain an hour as we enter a different time zone
4:00 pm	Arrive in Flagstaff, AZ
	Home Sweet Home
7:45 pm	Sunset

3 Field Stop Descriptions

3.1 Yellowstone Field Stop 1 – West Thumb Geyser Basin

The West Thumb Geyser Basin is located along the western shore of a section of Yellowstone Lake, called "West Thumb," which is a caldera within a caldera. The West Thumb of Yellowstone Lake formed as a result of a relatively small eruption and subsequent caldera collapse about 150,000 years ago (Fournier et al., 1994). The thermal area here exhibits occasional geyser eruptions, but most of the thermal features are deep, steep sided conical pools of hot (sub-boiling to boiling) water formed by small hydrothermal explosions (Morgan et al., 2008). There are also some mud pots located here at slightly higher elevations – this will be a recurring theme as we tour the Park this week (see BOX 4). Active *sublacustrine* (under the lake water level) hot vents are located off shore for several hundred meters (Morgan et al., 2008). In fact, even though Yellowstone Lake freezes every winter and stays frozen usually through May or June, there is a zone of warm water along the shore here that never freezes due to these underwater vents and runoff from the warm water at the West Thumb thermal area. One of the vents is called the "trout Jacuzzi" due to the abundance of cutthroat trout that feed on thriving populations of amphopods and bacteria. This leads to bioaccumulation of Hg in the cutthroat trout, and in the illegally introduced lake trout that feed on the native cutthroat populations (Chaffee et al., 2007; Kaeding et al., 1996; Morgan et al., 2008). Here we will walk along the ~0.5-mile boardwalk loop through the thermal area and along the lake shore. Note the thick sinter deposits along the lake shore and some partially submerged cones that formed when the lake level was lower and when this thermal area was much larger than present.

> BOX 4:
> Lower elevation thermal basins within Yellowstone are typified by pH-neutral to alkaline, Cl-rich, silica saturated, thermal waters that reach the surface as hot springs or geysers. These features precipitate amorphous silica (sinter) around the edges of pools and along outflow drainages of geysers (Fournier, 1989; Christiansen et al., 2007; Lowenstern and Hurwitz, 2008). The Cl-rich waters are less common at higher elevations, because before they reach the surface they undergo boiling to produce H_2O steam, CO_2, H_2S, and other gases that rise to the surface. Oxidation of H_2S, aided by microbial activity, creates sulfuric acid (H_2SO_4) that alters the rhyolitic subsurface rocks into clay minerals (forming mud pots) or steam-heated acid-sulfate thermal areas with abundant fumaroles (Fournier, 1989; Lowenstern and Hurwitz, 2008, Nordstrom et al., 2009, Vaughan et al., 2012).

Stop 1b – Grant Village Visitor's Center

Here we will also visit the Grant Village Visitor Center, located on the shore of the West Thumb of Yellowstone Lake one mile off of the main park road at Grant Village Junction. The facility was constructed during the 1970s and, along with the entire Grant development, was and is a controversial Yellowstone development due to its location in prime grizzly bear habitat and coincides with the location of several major cutthroat trout spawning streams. The visitor center hosts an exhibit that interprets fire's role in the environment, using the fires of 1988 as the example. Hopefully we can catch the movie *Ten Years after Fire* while we are there.

On the way to our cabins at Old Faithful, we will do a short stop at Isa lake, which is very unusual as it sits right on the continental divide and drains to both sides.

Stop 1 – West Thumb Geyser Basin

Stop 1c – Isa Lake

This is an unusual little lake as it sits right on the continental divide. One side of the lake drains to the south and west of the divide, ultimately draining to the Pacific Ocean. The other side of the lake drains to the north and east, ultimately draining to the Gulf of Mexico

3.2 Yellowstone Field Stop 2 – Upper Geyser Basin

Geysers are springs that erupt intermittently due to a constriction in the hydrothermal plumbing system beneath. Water from precipitation and snowmelt seeps deep into the Earth until it comes into contact with hot rocks and hot water reservoirs at depth. The superheated (more buoyant) water rises though fissures, faults, and other weak places in the overlying rock. A constriction in the hydrothermal plumbing system temporarily traps the hot water, which contains abundant dissolved minerals and gases. Pressure and heat build until the confined gases expand enough to force water through the constriction. This release of pressure causes much of the water in the system to flash to steam and forces the remaining water from the geyser's vent. The periodicity of these eruptions is a function of several factors, including the amount of water flux, the amount of dissolved gases, the temperature, the duration of the previous eruption, and the size of the constriction. Probably the most famous geyser in Upper Geyser Basin (UGB) is Old Faithful, which erupts with a periodicity of ~90 min, although this can range from 30-120 min. There are dozens of other geysers here as well, and as we walk around this area we will hope for good timing to see as many geyser eruptions as possible. Here we will spend the morning on a meandering, walking tour of part of Upper Geyser Basin. Starting at the Old Faithful area and walking north along the Firehole River for about 1.5 miles (one way) along easy trails and boardwalks, we will see many geysers, hot spring pools, and sinter deposits.

There is also a new visitor's center at the Old Faithful area (opened in September, 2010) with some excellent exhibits on the Yellowstone hydrothermal system. Set a side and hour or so this morning to explore this exhibit. Or, since we are staying in this area, there should be plenty of other occasions to check this place out as well.

3.3 Yellowstone Field Stop 3 – Lower Geyser Basin, Firehole Lake

As we leave Upper Geyser Basin the road follows along the Firehole River, which drains most of the thermal areas in the western part of the Yellowstone Caldera to the north and flows through the open valleys of Midway and Lower Geyser Basins (Fournier et al., 1994). More than 2/3 of all the geysers in the world are located along this stretch of road (Fournier et al., 1994). At Madison Junction, the Firehole River meets the Gibbon River to form the Madison River.

When we get to the Firehole Lake drive turnoff we will check to see if it will be feasible to catch an eruption of Great Fountain Geyser – this is one of the most impressive geysers in the Park, but we'll have to get lucky as it erupts with a period of 8-14 ±4 hours – then head up to Firehole Lake. Along the way we will pass White Dome Geyser, which has one of the largest mounds of sinter in the Park. Firehole Lake sits at a slightly higher elevation than the sinter-depositing springs in the rest of the Lower Geyer Basin, at the head of a small valley where there is discharge of relatively dilute thermal waters that precipitate travertine and manganese oxides, although it has deposited silica sinter in the past (Fournier et al., 1994). As we walk the short loop trail, there a several small thermal features to see, including Steady Geyser, which, as its name implies, is perpetually spouting.

3.4 Yellowstone Field Stop 4 – Lower Geyser Basin, Fountain Paint Pots

The short boardwalk loop around this area has it all: hot springs, geysers, fumaroles and mud pots. The large, clear hot springs are rich in Cl and silica, have a near neutral pH, and represent unrestricted discharge of hot water from a deeper reservoir (Fournier et al., 1994). Geysers result from constrictions in the hydrothermal plumbing system just beneath the surface. Fumaroles (steam vents) discharge gases through fractures because water doesn't make it to the surface here without boiling to steam. Several new fumaroles opened up in this area after the 1959 Hebgen Lake earthquake (Fournier et al., 1994). During wetter seasons, the sulfur-rich gases exiting from the fumaroles mixes with excess water from condensed steam in the subsurface, and, aided by microbial activity, forms acid-sulfate springs where the sulfuric acid attacks the surrounding rocks and forms clay-mineral-rich mud pots. The variably reddish brown colors of the mud pots are caused by differing amounts of ferric iron oxide minerals.

Also, from here you can see the north edge of the Yellowstone caldera wall.

3.5 Yellowstone Field Stop 5 – Midway Geyser Basin

Across the basin to the west are the steep walls of the West Yellowstone rhyolite flow (117,000 years old) (Fournier et al., 1994). From the parking lot, across the Firehole River bridge, there is a short boardwalk loop through two of the larger thermal features in Yellowstone, Grand Prismatic Spring and Excelsior Geyser Crater. Grand Prismatic Spring is about 90 m across, boiling at the center and cooler at the edges, and famous for the colorful bacterial mats that grow around the edges of the mineral-rich thermal water that surrounds and drains away from the pool. The colors are the result of pigments in the bacteria, which depend on the amount of chlorophyll and carotenoids (pigments in photosynthetic organisms) and on the temperature of the water which favors one bacteria species over another. The center of the pool is sterile because it is at boiling temperature (~93 °C; 200 °F). **Let's try to figure out which color bacteria correspond to which temperature range.** Excelsior Geyser Crater is a boiling pool about 70 m across that was formed from a hydrothermal explosion. All of the hot water draining out of this pool and from Grand Prismatic Spring flow into the Firehole River thermal drainage, locally increasing the temperature of the river. From the bridge is a good place to see the thermal waters enter into the Firehole River.

Home Base – The Old Faithful Lodge Cabins

Stop 2 – Upper Geyser Basin

OF = Old Faithful
GG = Grand Geyser
CG = Castle Geyser
MGP = Morning Glory Pool
VC = Visitor's Center
BB = Biscuit Basin
BSB = Black Sand Basin

Stop 3 – Firehole Lake (Lower Geyser Basin)
GFG = Great Fountain Geyser
WD = White Dome Geyser

Stop 4 – Fountain Paint Pots (Lower Geyser Basin)

Stop 5 – Midway Geyser Basin
Grand Prismatic Spring (the largest boiling pool in the Park)
Excelsior Geyser Crater (a hydrothermal explosion crater)

3.6 Yellowstone Field Stop 6 – Butte Point

On the way to Butte Point overlook, we drive by Mary Bay and Indian Pond, both formed by large hydrothermal explosions. Indian Pond is dated to have formed about 3,000 years ago and is the youngest dated large hydrothermal explosion event in Yellowstone (Morgan et al., 2008). Most of these large hydrothermal explosion craters are found within the caldera where geothermal heat flow values area high. It is thought that many of these formed near the end of, or just after, the last glacial maximum (Pinedale Glaciation: 10,000-14,000 years ago) and that the retreat of the glaciers caused the depressurization of these thermal areas, resulting in large hydrothermal explosions. Hydrothermal explosions are locally violent events that may have little to no warming, thus pose a significant hazard in Yellowstone (Morgan et al., 2008).

Here we'll discuss various natural hazards in Yellowstone (see USGS Fact Sheet 2005-3024 (Lowenstern et al., 2005)).

At the Butte Point overlook, we are standing on outcrop of 640,000 year old Lava Creek Tuff. From here, on a clear day, you can see part of the caldera boundary to the northwest, and the Grand Tetons to the southwest. This is also a place where the 2003 East Fire burned. To the south you can see some burn areas from 2011.

On the way back, we will stop at the Fishing Bridge Museum and Visitor Center, located along the East Entrance Road. Built in 1931, it is a National Historic Landmark. Its distinctive stone-and-log architecture, known as "parkitecture," became a prototype for park buildings all around the country. The historic bird specimens were installed in 1931 and provide a good overview of the birds of Yellowstone. Other taxidermied animals here include a grizzly sow and two cubs and a family of river otters. (http://www.nps.gov/yell/planyourvisit/lakevc.htm)

3.7 Yellowstone Field Stop 7 – Mud Volcano area

The Mud Volcano thermal area is an example of a vapor-dominated acid-sulfate hydrothermal system (Fournier et al., 1994). There are different types of thermal features here as compared to the lower elevation geyser basins. That rotten egg smell is H_2S gas. The darker grey colors of the mud are due to the presence of iron sulfide minerals.

There is another interesting area here called "cooking hillside" where there have been some tree kills due to CO_2 flux, similar to vegetation dieback that has occurred at Mammoth Mountain, CA. There is some evidence linking these tree kills to seismic swarms. Swarms of earthquakes (hundreds per day for several days – totaling a few thousand) in a particular area occur commonly in Yellowstone. Some of the larger ones have been in 1978 and 1985. Over the last few years there have been two swarms: ~900 earthquakes occurred between December 26, 2008 and January 8, 2009 in the Yellowstone Lake area; and 2347 earthquakes occurred between January 15, 2010 and April 6, 2010 in the West Yellowstone area. The 1978 seismic swarm in the Mud Volcano area was followed by increased heat output and dieback of vegetation in an area called "Cooking Hillside" (Evans et al., 2010). In fact, the swarm itself may have been caused by increased gas pressures within the geothermal system that underlies Mud Volcano and much of the caldera (Evans et al., 2010).

As we leave Mud Volcano and drive north up through Hayden Valley toward Canyon Village, there may be some good opportunities to see some large animal herds. Also, along this drive note the flat terraces in the hill side – these are former lake shore terraces, indicating a period of time when Yellowstone Lake was much higher.

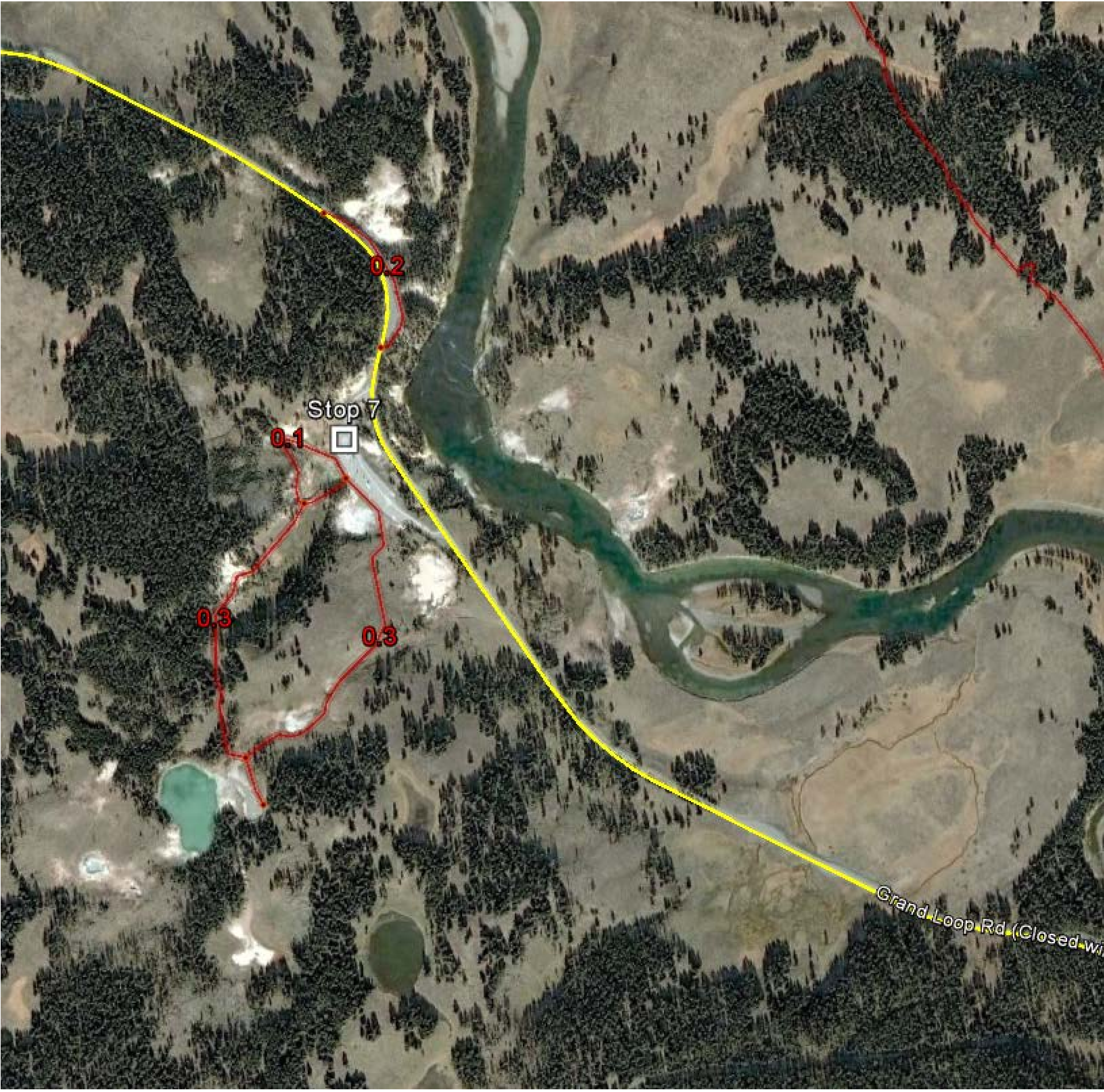
3.8 Yellowstone Field Stop 8 – Artist Point: the Grand Canyon of Yellowstone

Here we will skip the Wapiti Lake trailhead parking area on the right (the Wapiti Lake trail is one of the two places where there was a fatal grizzly bear attack in 2011) and park at the first parking area on the left. From here there are short trails which lead to great views of both Upper and Lower Falls on the Yellowstone River.

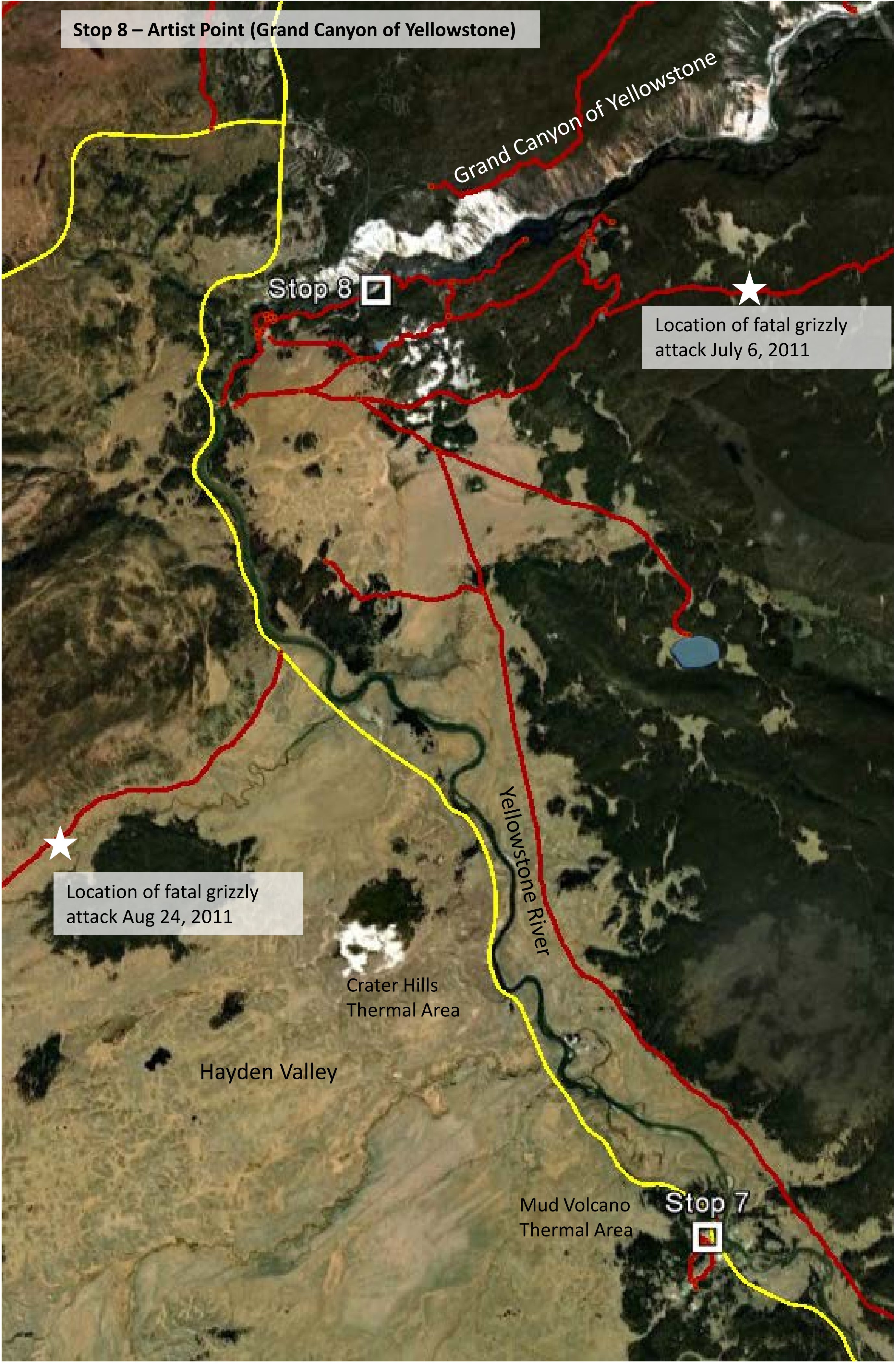
The Grand Canyon of Yellowstone is about 24 miles long and 1200 feet deep. It begins with two large waterfalls and is deeply carved by the Yellowstone River into heavily altered rocks of the Canyon rhyolite flow (~484,000 years old). There is still hydrothermal activity at springs along the river, but hydrothermal activity here has been going on for a long time. Hydrothermal alteration along the deep, narrow part of the Canyon is mainly controlled by fractures associated with the ring fracture zone of the 640,000 year old Yellowstone Caldera (Fournier et al., 1994). The yellowish colors of the altered rocks give Yellowstone its name and result from the acidic alteration of pre-existing rocks. This alteration is also the reason for the deep canyon, as such rocks are more easily eroded. Other lava flows periodically blocked the flow of the ancestral Yellowstone River, forming lakes, which then over flowed and carved more deeply in the softened rocks. Past glacial periods also figure prominently into the formation of the deep canyon here. At least three times during the last few hundred thousand years, glaciers blocked the flow of the river. Later, floods from melting glaciers at the end of the glacial periods carved the canyon even deeper. **Think about how this compares to the formation of the Grand Canyon in northern Arizona.**

Stop 6 – Butte Point Overlook

Mary Bay, Indian Pond, and Turbid Lake are all large hydrothermal explosion craters



Stop 7 – Mud Volcano Area


Stop 8 – Artist Point (Grand Canyon of Yellowstone)
Grand Canyon of Yellowstone
Stop 8
Location of fatal grizzly attack July 6, 2011
Yellowstone River
Location of fatal grizzly attack Aug 24, 2011
Crater Hills Thermal Area
Hayden Valley
Mud Volcano Thermal Area
Stop 7

3.9 Yellowstone Field Stop 9 – Norris Geyser Basin

Here we will get a tour of Norris Geyser Basin (NGB) with one of the Yellowstone Park geologists, Dr. Cheryl Jaworowski. Norris Geyser Basin is one of the larger, hotter, and more chemically complex thermal areas in the Park. Hydrothermal waters here consist of several distinct chemical types that result from variable mixing in shallow subsurface reservoirs (Morgan et al., 2008). There are two loop trails to explore here, the back basin trail and the porcelain basin trail. Along the back basin trail there are boiling pools of pH-neutral to alkaline water, boiling fumaroles, acid-sulfate muds, and one of the few acidic geysers in Yellowstone (Echinus Geyser, pH= 3.3, eruptions every 50-60 min). The NGB back basin trail also has Steamboat Geyser, the tallest active geyser in the world. It erupts very rarely, with periods of dormancy lasting decades, but when it does erupt, it can reach 115 m (380 feet). It last erupted in May, 2005.

Norris is also known for exhibiting thermal disturbances every year or so. Thermal disturbances are not completely understood, but thought to be related to seasonal changes in groundwater recharge and fluid pressure in the hydrothermal reservoirs beneath NGB. They often result in increased thermal activity, including: increased water turbidity, increased discharge of thermal waters and steam, warmer ground, larger areas of warm ground, hydrothermal explosions, rare geyser eruptions, and thermal features appearing in new places. In 1989, Porkchop Geyser experienced a steam explosion that destroyed the geyser nozzle, sent hot mud and rock fragments 60-70 m into the air, and created a 4-m wide pool of boiling water. In 2003, there was a series of new fumaroles that opened up north of Nymph Lake (in March), and eruption of Porkchop Geyser (in July), and a large area along the back basin trail had to be closed due to increased areas of boiling near the boardwalk. Also, Steamboat Geyser erupted three times in 2003 (March, April, and October).

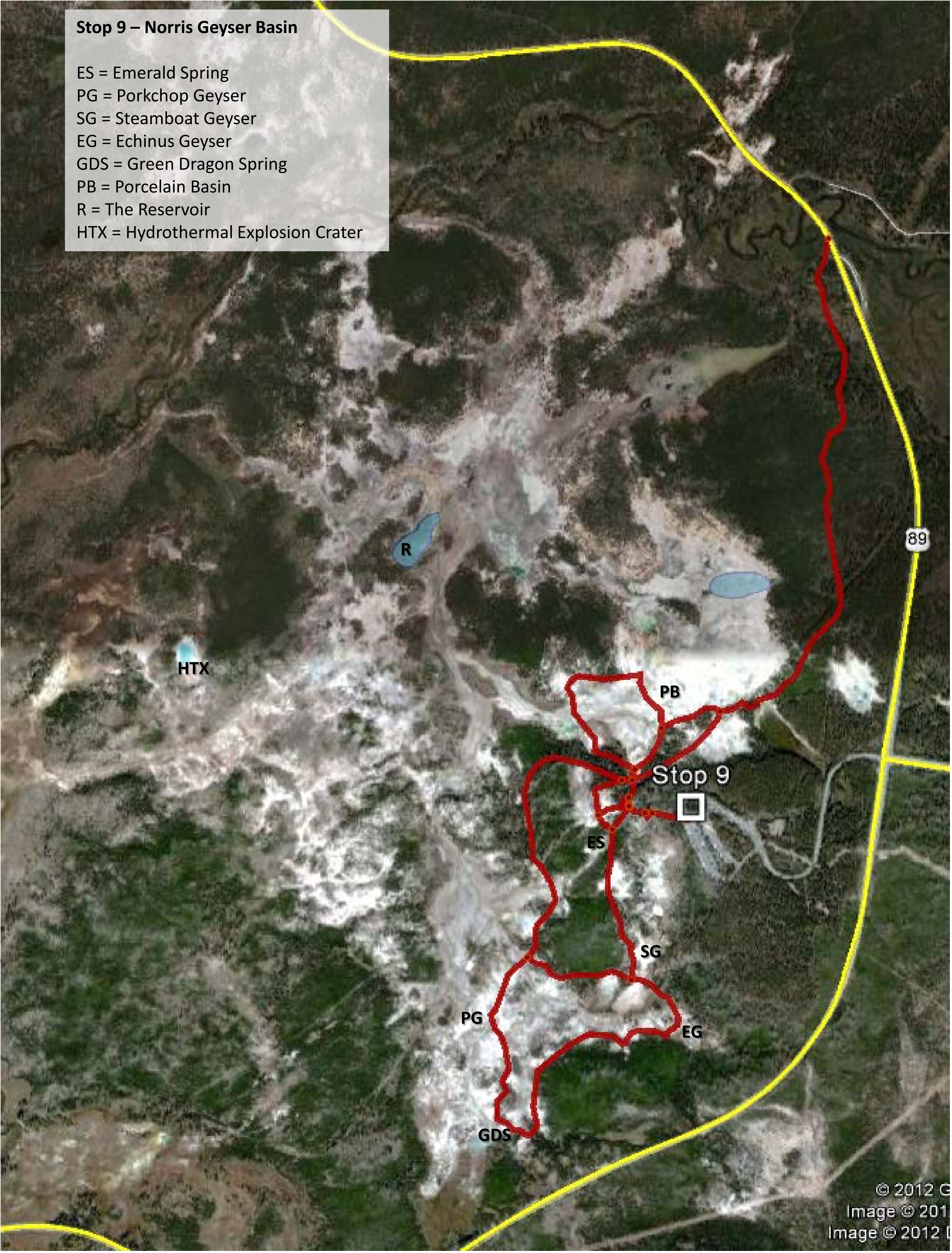
Along the porcelain basin trail there are many jetting fumaroles and acid pools. Above the porcelain basin is porcelain terrace. The acid-sulfate pools at porcelain terrace all formed after the 1959 Hebgen Lake earthquake, which caused new fractures that allowed hot spring waters to leak sideways out to the side of the terrace. Before the earthquake, this area consisted of neutral-Cl, Si-rich waters depositing sinter. After the earthquake, these waters drained leaving cavities under the surface, which started being attacked by sulfuric acid-rich water, which causes the sinter to crumble away easily. As a result, the porcelain terrace is probably one of the most dangerous places to hike off trail in Yellowstone Park (Fournier et al., 1994).

The bedrock at NGB is Lava Creek Tuff (rhyolite), but it is highly fractured and acid-leached. Many of the thermal features clearly follow these structural trends.

3.10 Yellowstone Field Stop 10 – Fire Ecology Tour along Norris to Canyon Road

This will actually be a series of stops along the road from Norris to Canyon. Guided by National Park Service fire ecology expert, Dr. Roy Renkin, we will see different burn areas from 2008, 1988, 1953, 1852, and from about 300 years ago, plus an area of multiple wind/fire disturbances. Maybe we will get to drive along the side road to a nice area called Virginia Cascade, where there an outcrop of Lava Creek Tuff.

We will end our fire ecology tour at Canyon Village. While here, in addition to shopping and eating dinner, let’s spend some time in the visitor’s center, which has some great exhibits about the geology of Yellowstone.


Stop 9 – Norris Geyser Basin
ES = Emerald Spring
PG = Porkchop Geyser
SG = Steamboat Geyser
EG = Echinus Geyser
GDS = Green Dragon Spring
PB = Porcelain Basin
R = The Reservoir
HTX = Hydrothermal Explosion Crater
R
HTX
PB
Stop 9
ES
SG
PG
EG
GDS
89

Stop 10 – Fire ecology tour along Norris to Canyon road

3.11 Yellowstone Field Stop 11 – Road from Norris to Mammoth

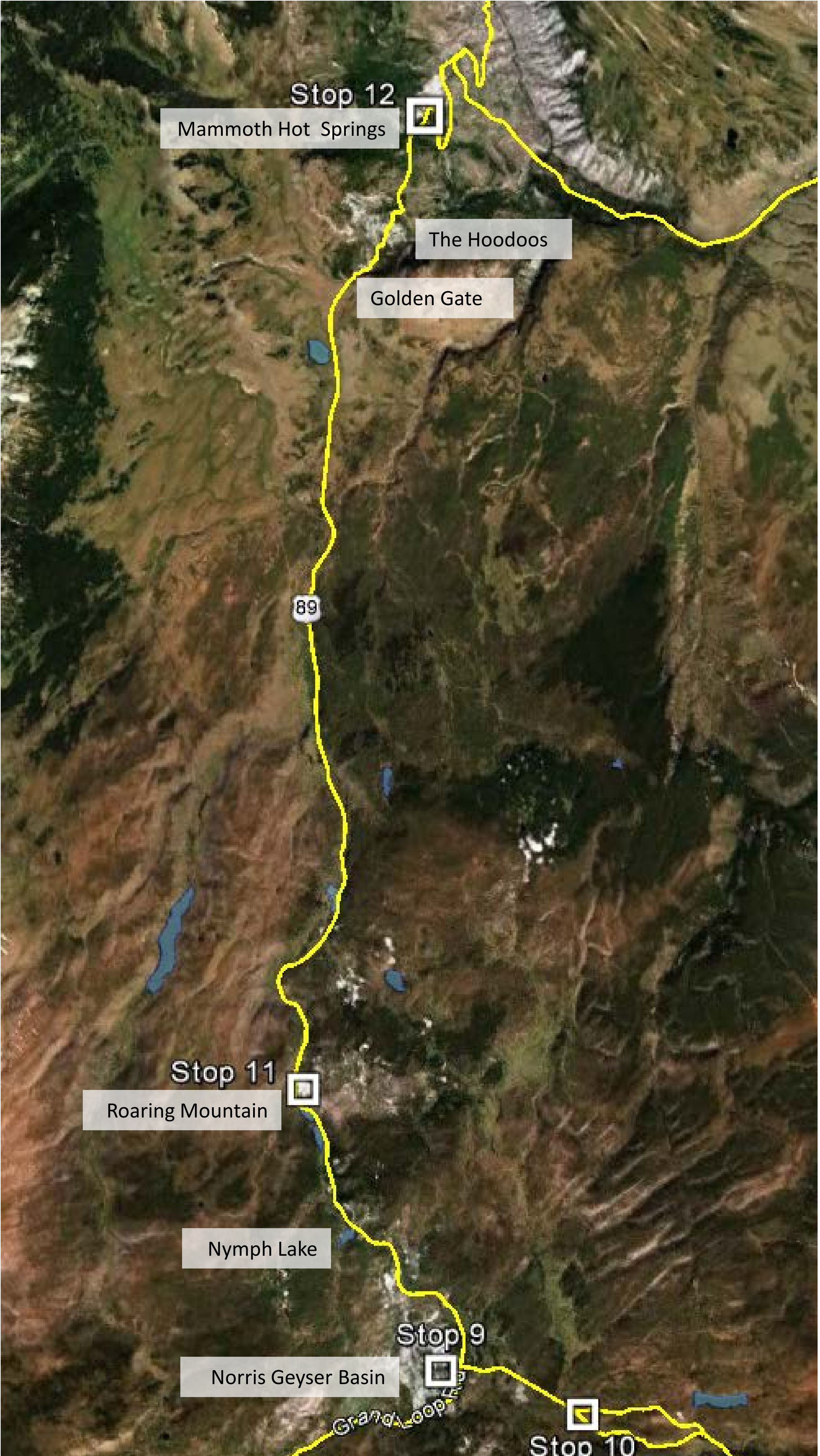
There are several short-duration stops worth exploring along this stretch of road: Roaring Mountain, Obsidian Cliff, Golden Gate, and the Hoodoos. Roaring Mountain is an acid-sulfate thermal area and a great example of what eons of acid alteration can do to initially very hard rock. The bedrock here is mostly Lava Creek Tuff, a pretty hard, impermeable rock, but here it has been broken down into crumbly clay minerals by numerous jetting fumaroles and acid-sulfate seeps (Fournier et al., 1994). Not visible from the road, the top of Roaring Mountain is flat and covered with several craters surrounded with aprons of jagged rock fragments. These craters were formed by large hydrothermal explosions that ejected rocks and mud almost 1 km away, probably during the end of the last glaciation (12,000-14,000 years ago) (Fournier et al., 1994). Obsidian Cliff is at the edge of a rhyolitic lava flow - a glassy rhyolitic flow-banded obsidian about 183,000 years old - and is a good place to see obsidian flows and crystallization textures. Large columnar joints mark the base of the flow near the road and steep contorted layering can be seen near the top. There are some sites away from the road, along other margins of this same flow where Native Americans used the obsidian for arrowheads and other cutting tools – e.g., obsidian knives as along as 25 cm from this flow have been found in mound-builder sites as far away as Ohio (Morgan et al., 2008; Fournier et al., 1994). The Golden Gate is the place where the road narrows and cuts through the 2.05 Ma Huckleberry Ridge Tuff. Here there is a nice view and a spectacular water fall (Morgan et al., 2008). The Hoodoos is a post-glacial land slide deposit of large blocks of travertine, although much older and unrelated to the modern travertine deposits at Mammoth Hot Springs (Morgan et al., 2008; Fournier et al., 1994).

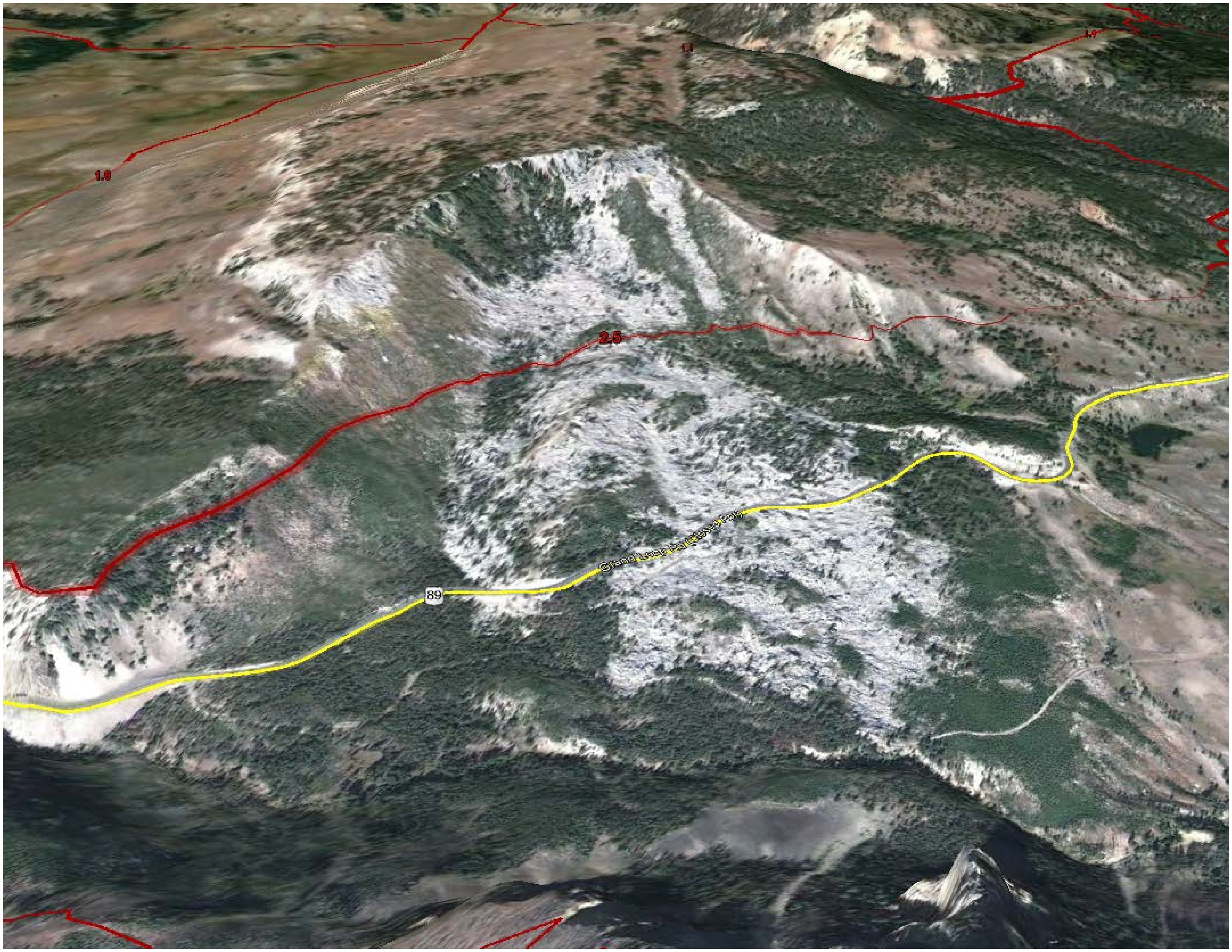
3.12 Yellowstone Field Stop 12 – Mammoth Hot Springs

Mammoth sits on the steep west side of the Gardener River valley. The bedrock consists of Mesozoic sandstones and shales, underlain by a thick limestone aquifer (Fournier et al., 1994). Across the valley you can see Mount Everts, which consists of Cretaceous sandstones and shales, capped by the 2.05-Ma Huckleberry Ridge Tuff. Hydrothermal activity at Mammoth is different than any other areas in Yellowstone – the waters here are not as hot as in the rest of the Park, with maximum temperatures of ~73 °C (163 °F); and instead of depositing silica sinter (SiO_2) the waters here deposit travertine ($CaCO_3$) which is the same carbonate mineral that limestone is made of. In fact, it is because the hydrothermal fluids travel through Mesozoic limestone at depth that they have this composition. Mammoth Hot Springs is the largest carbonate-depositing spring system in the world (Morgan et al., 2008; Fournier et al., 1994). Travertine here can be deposited at a rate of ~1 m per year!

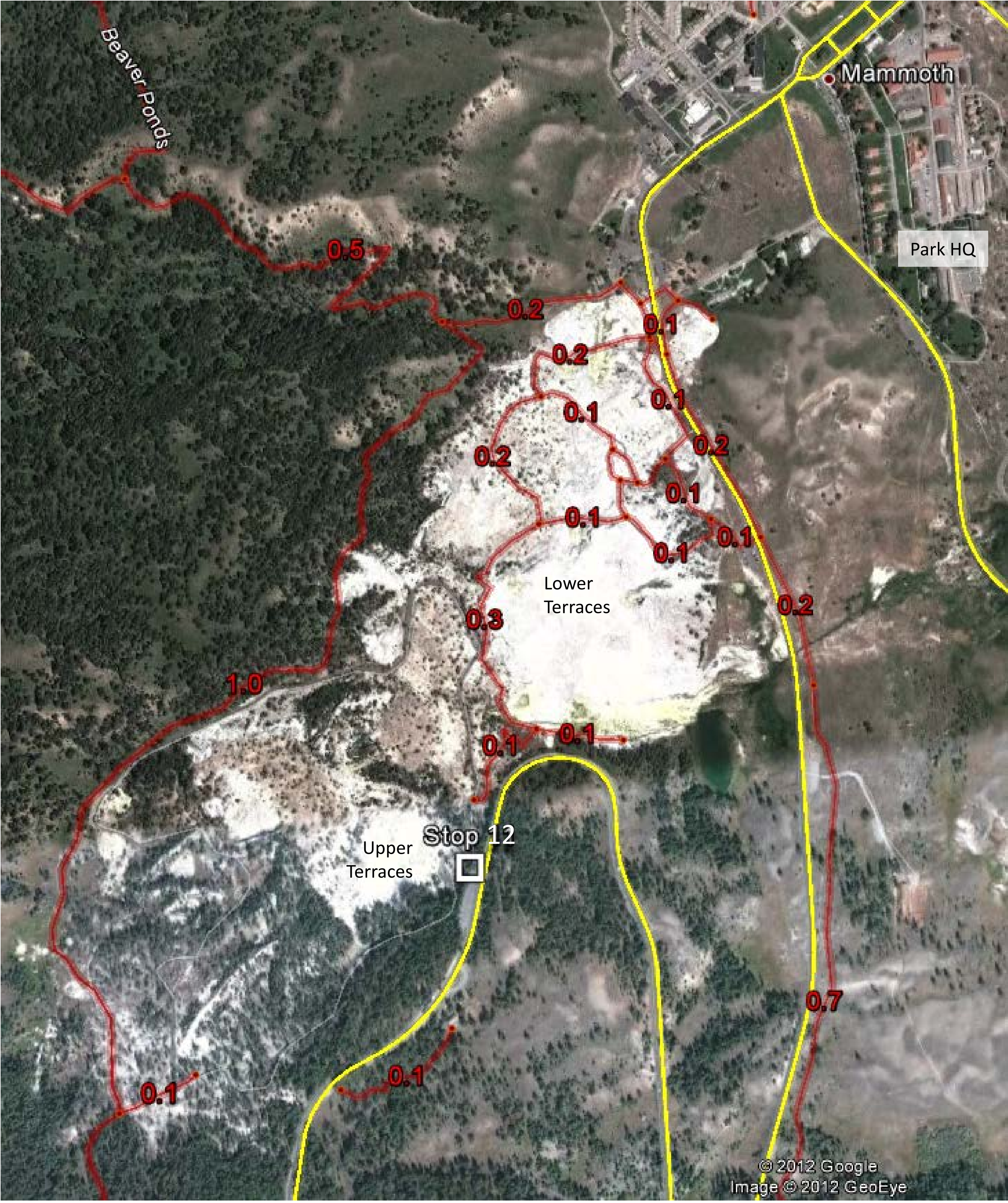
3.13 Yellowstone Field Stop 13 – Firehole Canyon Drive

Just south of Madison Junction and the beginning of the Madison River, which forms from the confluence of the Firehole and Gibbon Rivers, the Firehole River flows through Firehole canyon. A one-way 3.2 km loop road provides some good views of flow structures in the rhyolite lavas as well as some nice waterfalls and rapids (for those of you sick of looking at rocks). Here, the course of the River is controlled by the contact between two different intra-caldera rhyolite flows – the 150,000-year old Nez Perce flow to the east and the 177,000-year old Central Plateau flow to the west (Fournier et al., 1994). Outcrops along the road demonstrate some features typical of viscous rhyolite flows. Viscous lavas generally flow by marginal shear and plug-like movement of partly fluid core. The chilled surfaces break up into rafts of blocky rubble (from Fournier et al., 1994).

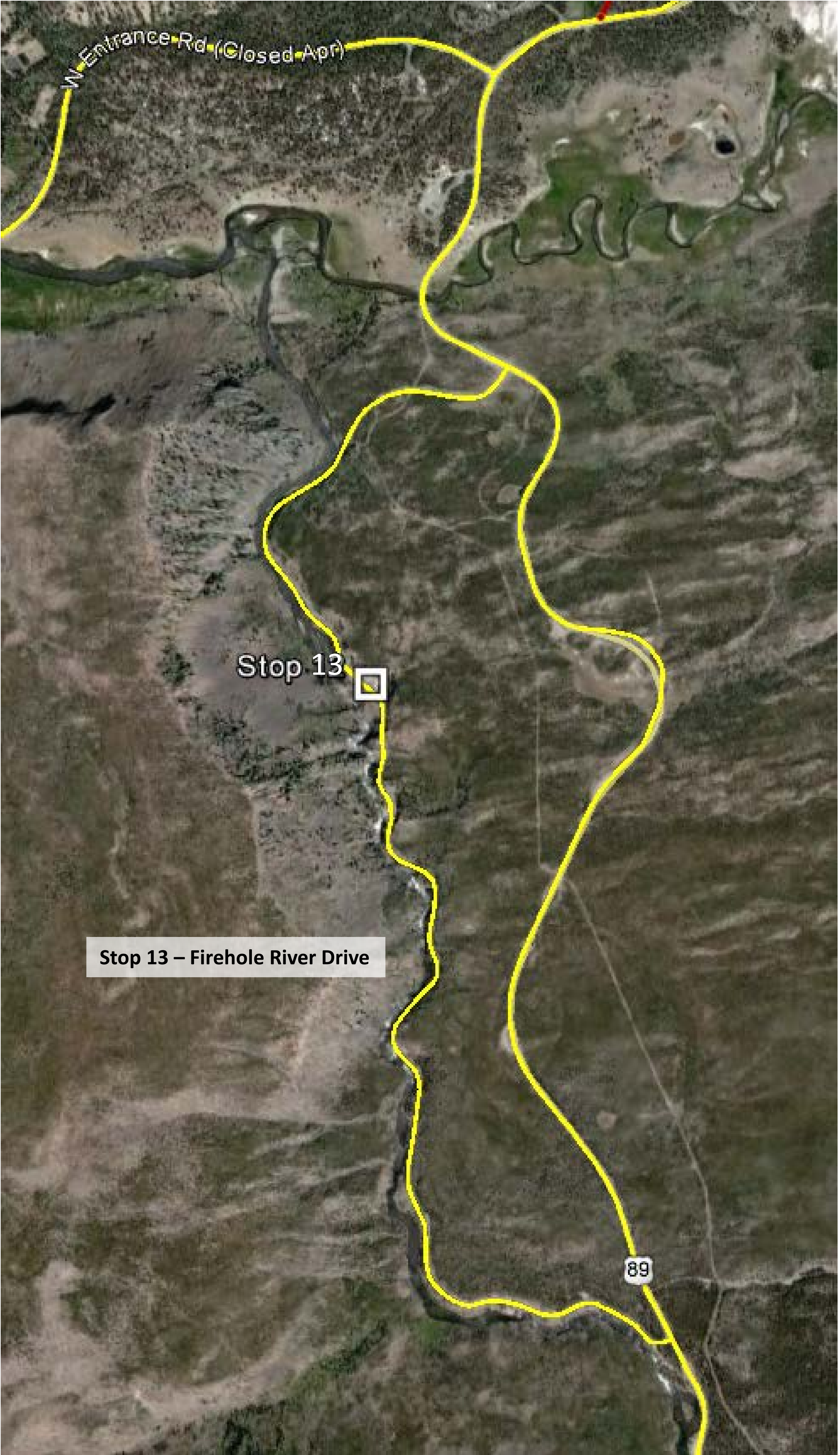

Stop 12
Mammoth Hot Springs
The Hoodoos
Golden Gate
89
Stop 11
Roaring Mountain
Nymph Lake
Stop 9
Norris Geyser Basin
Grand Loop Rd
Stop 10



Stop 11c – Oblique Google Earth view looking northwest of the landslide at the Hoodoos.



Stop 12 – Mammoth Hot Springs


W Entrance Rd (Closed Apr)
Stop 13
89
Stop 13 – Firehole River Drive

4 References and Web Links

4.1 References

Brantley S.R., Lowenstern J.B., Christiansen R.L., Smith R.B., Heasler H., Waite G., and Wicks C. (2004) Tracking Changes in Yellowstone's Restless Volcanic System. USGS Fact Sheet 100-03, 4 pp. (http://pubs.usgs.gov/fs/fs100-03).

Chaffee, M.A., Shanks, W.C., III, Rye, R.O., Schwartz, C.C., Carlson, R.R., Crock, J.G., Adams, M., Gemery, P.A., Gunther, K.A., Kester, C.L., King, H.D., and Podruzny, S.R. (2007) Applications of trace-element and stable-isotope geochemistry to wildlife issues, Yellowstone National Park and vicinity. In: Morgan, L.A. (ed.) Integrated Geoscience Studies in the Greater Yellowstone Area: Volcanic, Hydrothermal and Tectonic Processes in the Yellowstone Geoecosystem. U.S. Geological Survey Professional Paper 1717, p. 299–334.

Christiansen RL (2001) The Quaternary and Pliocene Yellowstone Plateau Volcanic Field of Wyoming, Idaho, and Montana. U.S. Geological Survey Professional Paper 729-G, 145 pp.

Christiansen, R.L., Lowenstern, J.B., Smith, R.B., Heasler, H., Morgan, L.A., Nathenson, M., Mastin, L.G., Muffler, L.J.P., and Robinson, J.E. (2007) Preliminary Assessment of Volcanic and Hydrothermal Hazards in Yellowstone National Park and Vicinity. U.S. Geological Survey Open-File Report 2007-071, 94 pp.

Duffield, W.A. (2011) What's So Hot About Volcanoes?, Mountain Press Publishing, Missoula, MT, 89 pp.

Evans WC, Bergfeld D, McGeehin JP, King JC, and Heasler H (2010). Tree-ring 14C links seismic swarm to CO2 spike at Yellowstone, USA, Geology 38, 1075-1078.

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, USGS Bulletin 2099, 46 pp.

Fournier, R.O. (1989) Geochemistry and Dynamics of the Yellowstone National Park Hydrothermal System. Annual Review of Earth and Planetary Sciences, 17, 13-53.

Husen, S., Smith, R.B., and Waite, G.P. (2004) Evidence for gas and magmatic sources beneath the Yellowstone volcanic field from seismic tomographic imaging, Journal of Volcanology and Geothermal Research, 131, 397-410.

Jaworowski, C., Heasler, H.P., Neale, C.M.U. and Sivarajan, S. (2010) Using Thermal Infrared Imagery and LiDAR in Yellowstone Geyser Basins. *Yellowstone Science*, 18(1), 8-19.

Kaeding, L.R., Boltz, G.D., and Carty, D.G. (1996) Lake trout discovered in Yellowstone Lake threaten native cutthroat trout: Fisheries, 21, 16–20.

Lowenstern, J.B., Christiansen, R.L., Smith, R.B., Morgan, L.A., and Heasler, H. (2005) Steam Explosions, Earthquakes, and Volcanic Eruptions- What's in Yellowstone's Future? USGS Fact Sheet 2005-3024, 6 pp. (http://pubs.usgs.gov/fs/old.2005/3024).

Lowenstern, J.B., Smith, R.B., and Hill, D.P. (2006) Monitoring super-volcanoes: Geophysical and geochemical signals at Yellowstone and other large caldera systems. Philosophical Transactions of the Royal Society, A364, 2055-2072.

Lowenstern, J.B. and Hurwitz, S. (2008) Monitoring a Supervolcano in Repose: Heat and Volatile Flux at the Yellowstone Caldera. Elements, 4, 35-40.

Morgan, L.A., Pierce, K.L., and Shanks, W.C. (2008) Track of the Yellowstone Hotspot: Young and Ongoing Geologic Processes from the Snake River Plain to the Yellowstone Plateau and Tetons,,in: R.G. Raynolds (Ed.), Roaming the Rocky Mountains and Environs: Geological Field Trips, Geological Society of America Field Guide, 10, 139–173.

Nordstrom, D.K., McCleskey, R.B., and Ball, J.W. (2009) Sulfur geochemistry of hydrothermal waters in Yellowstone National Park: IV Acid-sulfate waters, App. Geochem. 24, 191-207.
Pierce, K.L. and Morgan, L.A. (2009) Is the track of the Yellowstone hotspot driven by a deep mantle plume? - Review of volcanism, faulting, and uplift in light of new data, Journal of Volcanology and Geothermal Research, 188, 1–25.
Smith, R.B. and Siegel, L. (2000) Windows into the Earth: the Geology of Yellowstone and Grand Teton National Parks, Oxford, UK: Oxford University Press, 247 pp.
Vaughan, R.G., Keszthelyi, L.P., Lowenstern, J.B., Jaworowski, C., Heasler, H. (2012) Use of ASTER and MODIS Thermal Infrared Data to Quantify Heat Flow and Hydrothermal Change at Yellowstone National Park, Journal of Volcanology and Geothermal Research, In Review.

4.2 Web Links

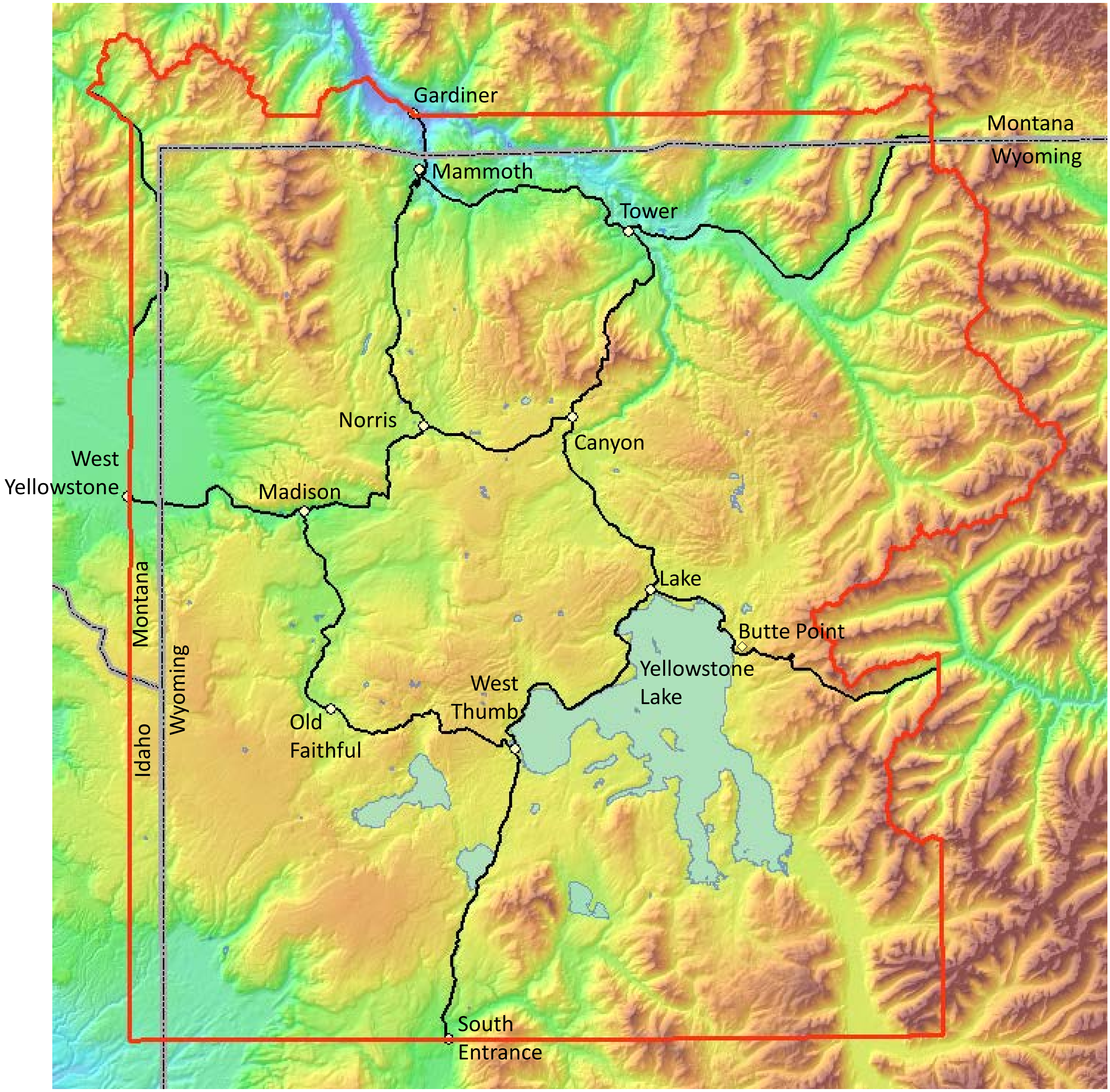
4.2.1 Volcanoes

USGS Volcano Hazards Program (http://volcanoes.usgs.gov)
Smithsonian Institution Global Volcanism Program (http://www.volcano.si.edu/index.cfm)
Volcano World (http://volcano.oregonstate.edu)
Google Earth (http://earth.google.com)
NASA Earth Observatory (http://earthobservatory.nasa.gov/NaturalHazards)

4.2.2 Yellowstone

Yellowstone National Park Home Page (National Park Service)
http://www.nps.gov/yell/index.htm
http://www.nps.gov/yell/naturescience/index.htm
http://www.nps.gov/yell/forteachers/index.htm

5 Appendix (More Maps)

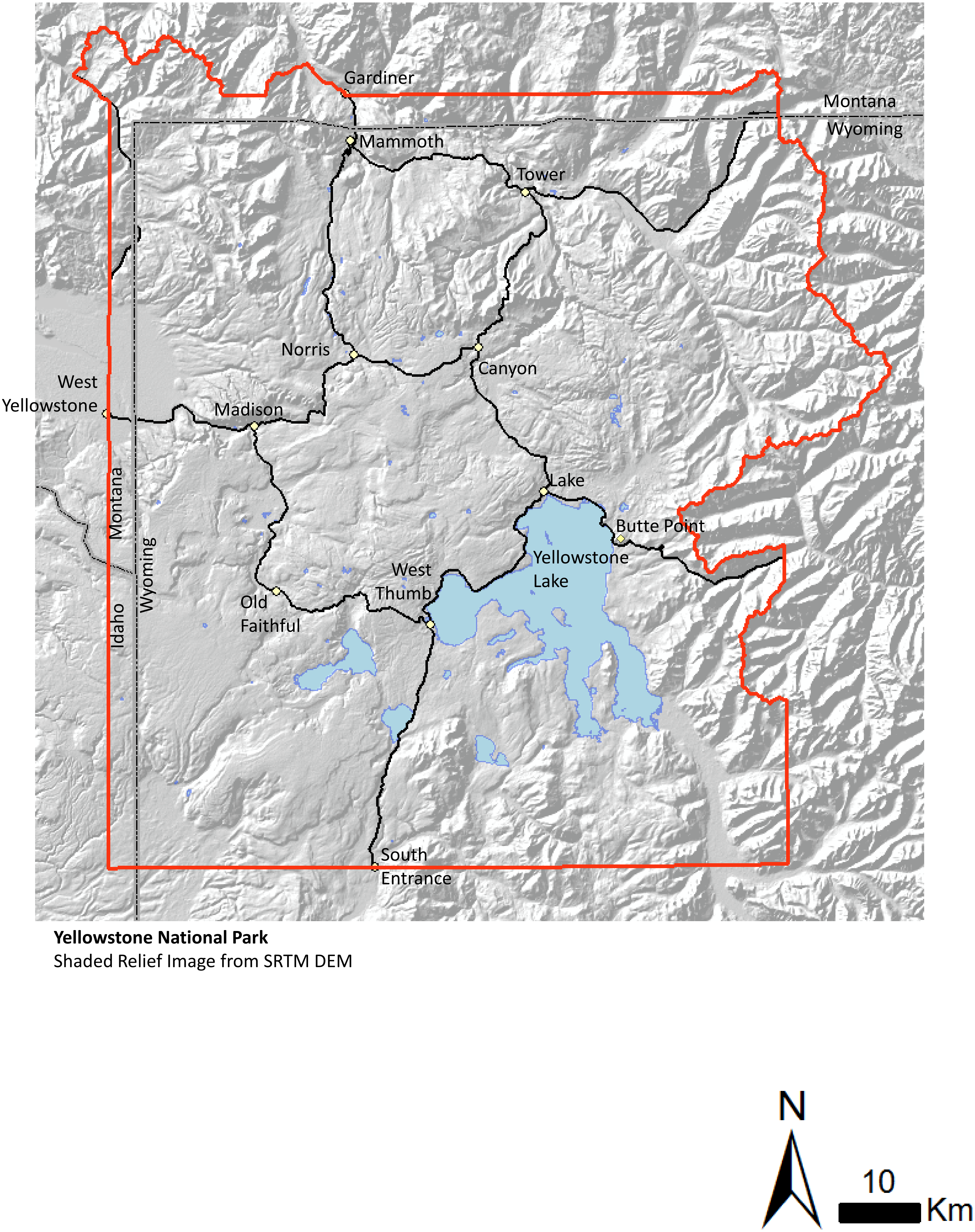


Yellowstone National Park

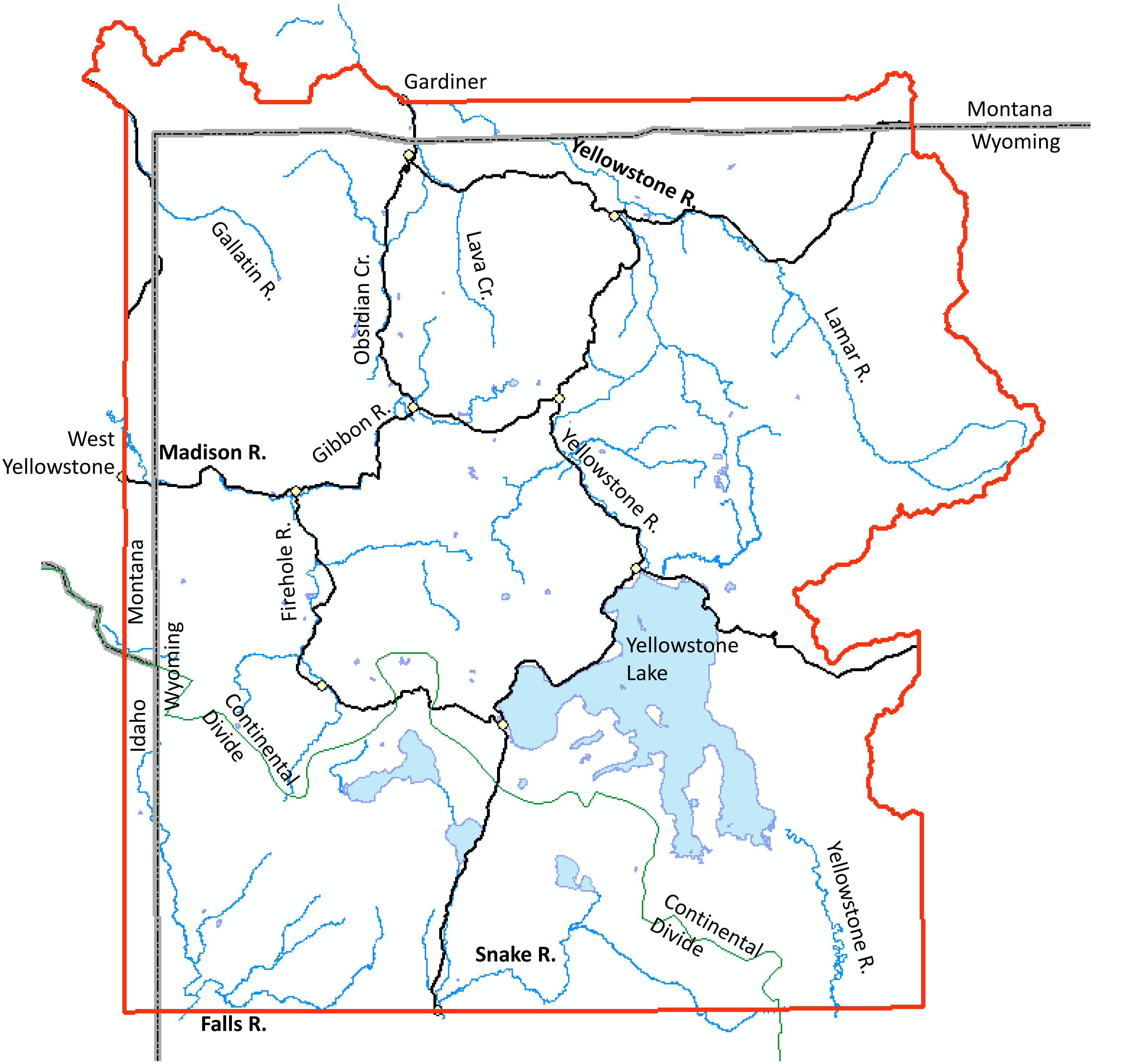
Colored Digital Elevation Model (derived from the NASA Shuttle Radar Topography Mission (SRTM))

<u>Typical Travel Times between Junctions (not including traffic or animal jams)</u>

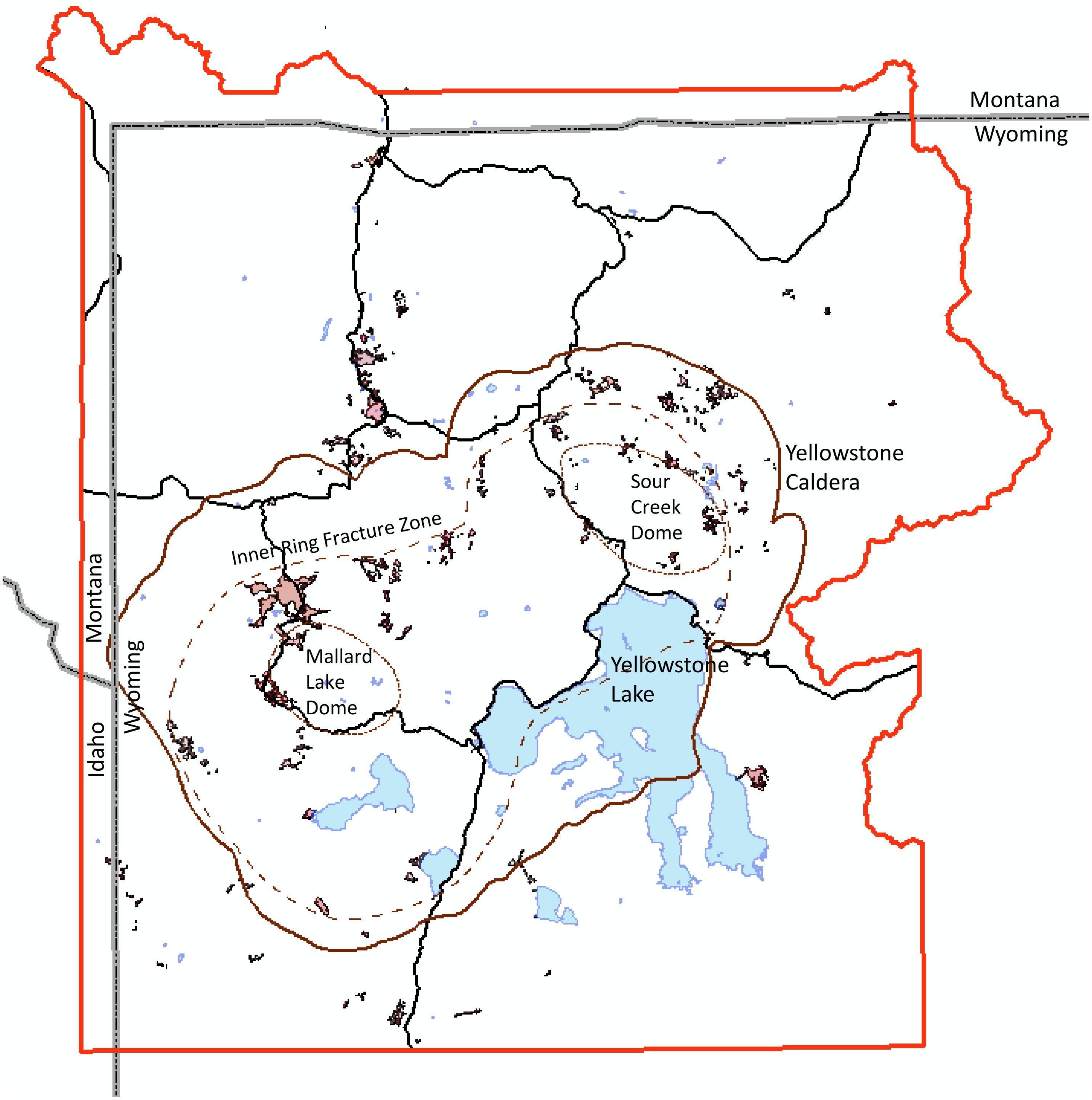
South Entrance to West Thumb – 30 min (20 mi)
West Thumb to Old Faithful – 30 min (15 mi)
Old Faithful to Madison – 35 min (16 mi)
Madison to West Yellowstone – 30 min (12 mi)
Madison to Norris – 20 min (15 mi)
Norris to Mammoth – 40 min (20 mi)
Norris to Canyon – 25 min (12 mi)
West Thumb to Lake Village – 45 min (20 mi)
Lake Village to Butte Point – 20 min (10 mi)
Lake Village to Canyon – 30 min (15 mi)



Yellowstone National Park
Shaded Relief Image from SRTM DEM

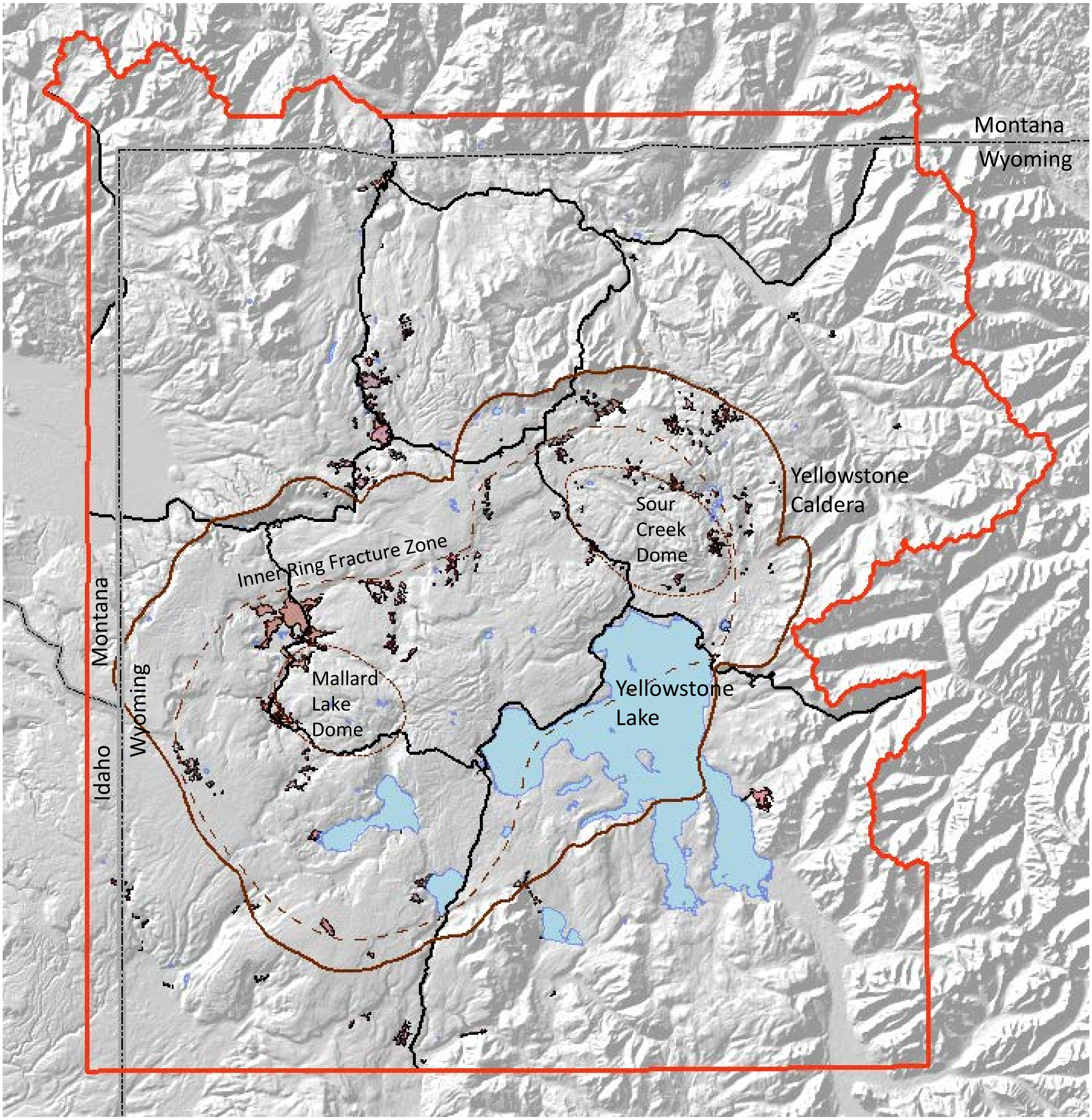


The Rivers of Yellowstone National Park
Note the Continental Divide (green line) that separates waters that drain to the south and west, ultimately into the Pacific Ocean; and waters that drain to the north and east, ultimately into the Gulf of Mexico. There are five main rivers that drain the Yellowstone Plateau: The Snake and Falls Rivers (on the south/west side of the Continental Divide) and the Madison, Gallatin, and Yellowstone Rivers (on the north/east side of the Continental Divide).



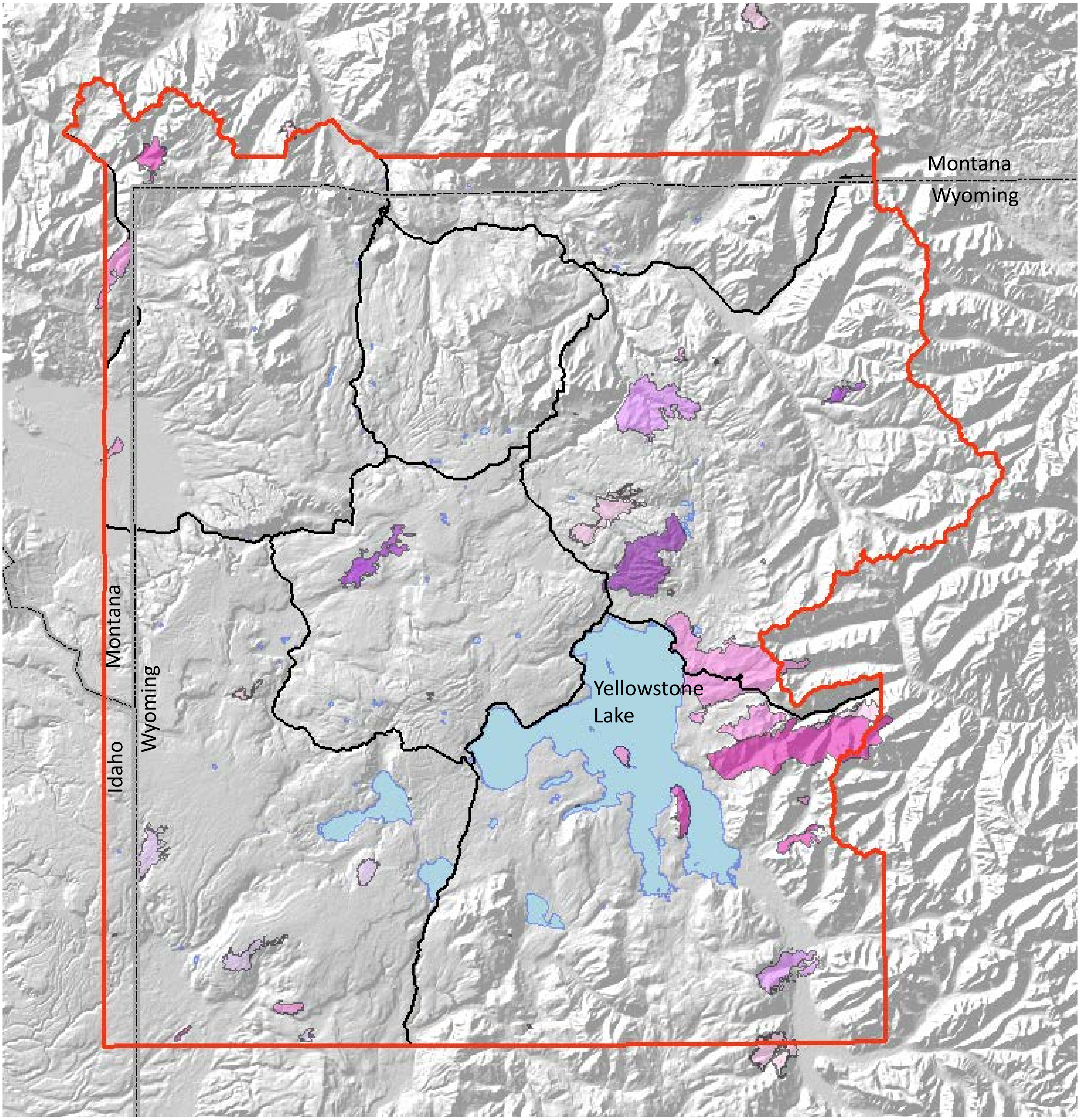
The Thermal Areas of Yellowstone National Park

Yellowstone contains >10,000 individual thermal features in the Park (some the size of a quarter; some the size of a football field), but they tend to be concentrated into about 100 distinct thermal areas (highlighted in shades red). They also tend to be located along pre-existing geologic structures, like the ring fracture system of the 0.64 Ma Yellowstone Caldera (brown lines), the edges of the two resurgent domes (brown dotted lines), or along edges of intra-caldera rhyolite flows .

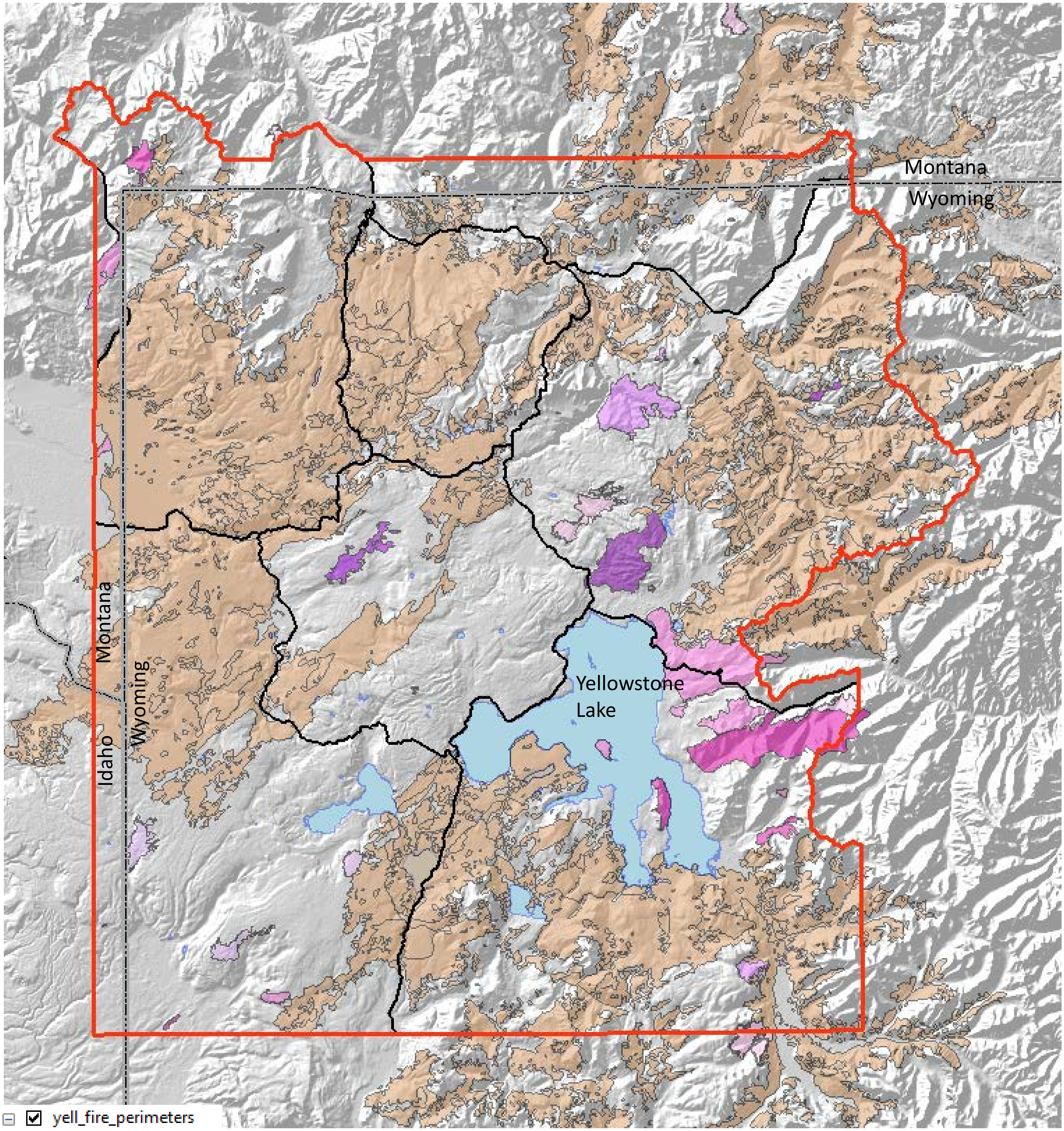


The Thermal Areas of Yellowstone National Park

Yellowstone contains > 10,000 individual thermal features in the Park (some the size of a quarter; some the size of a football field), but they tend to be concentrated into about 100 distinct thermal areas (highlighted in shades red). They also tend to be located along pre-existing geologic structures, like the ring fracture system of the 0.64 Ma Yellowstone Caldera (brown lines), the edges of the two resurgent domes (brown dotted lines), or along edges of intra-caldera rhyolite flows .

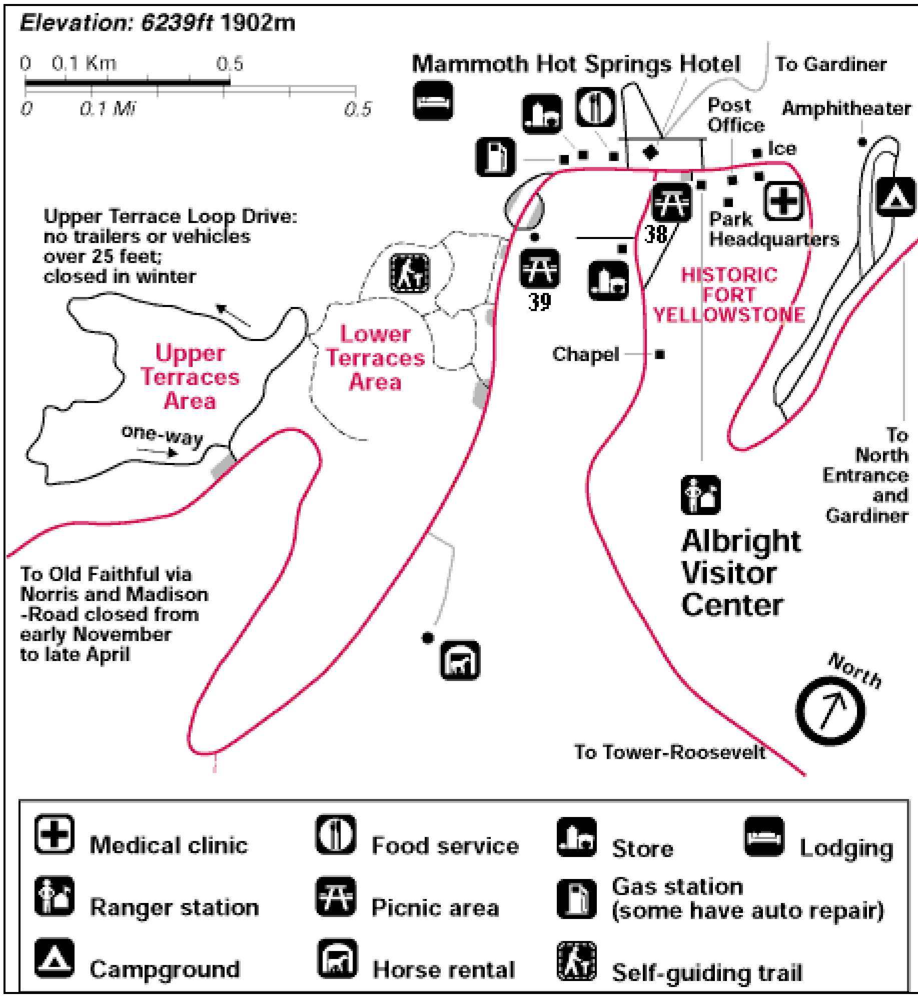


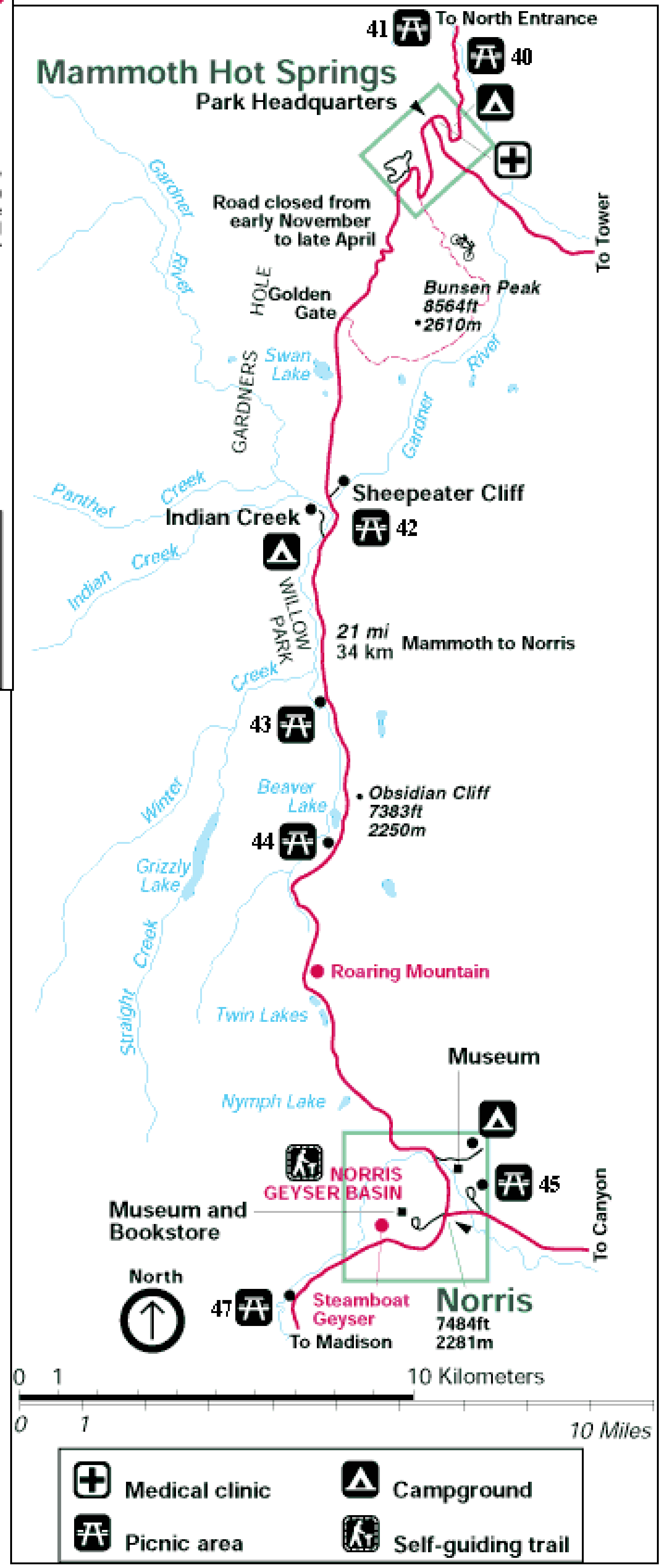
The Fires of Yellowstone National Park (some of them)
Shown in shades of purple are the areas burned by fires from 2000 to 2008.

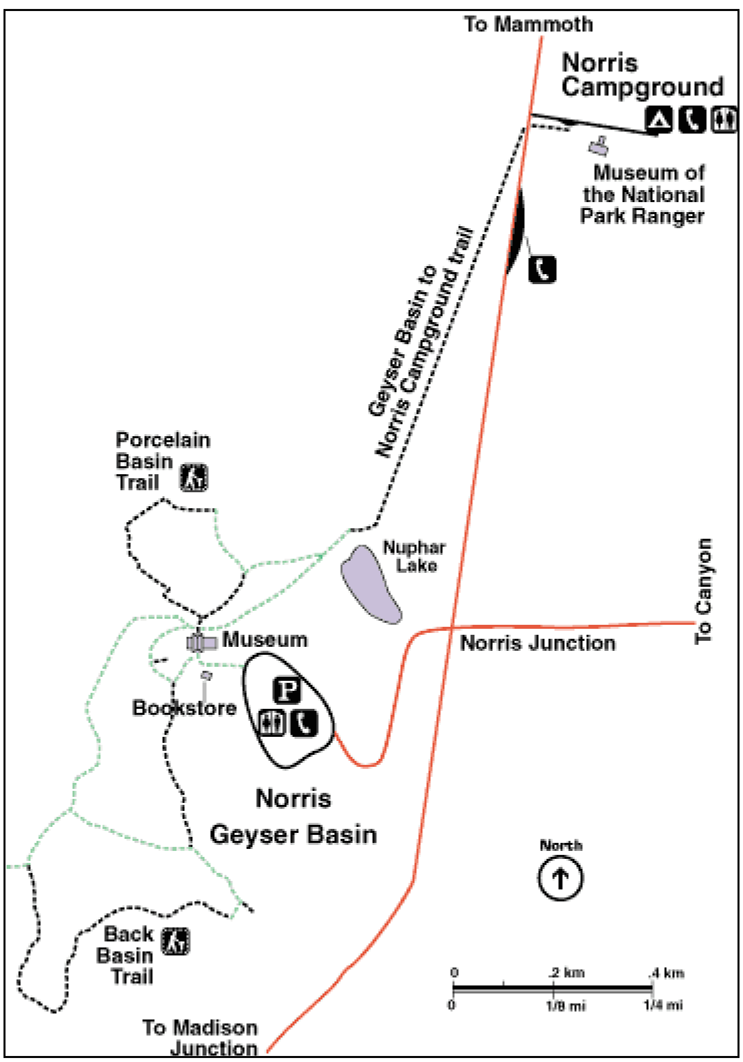


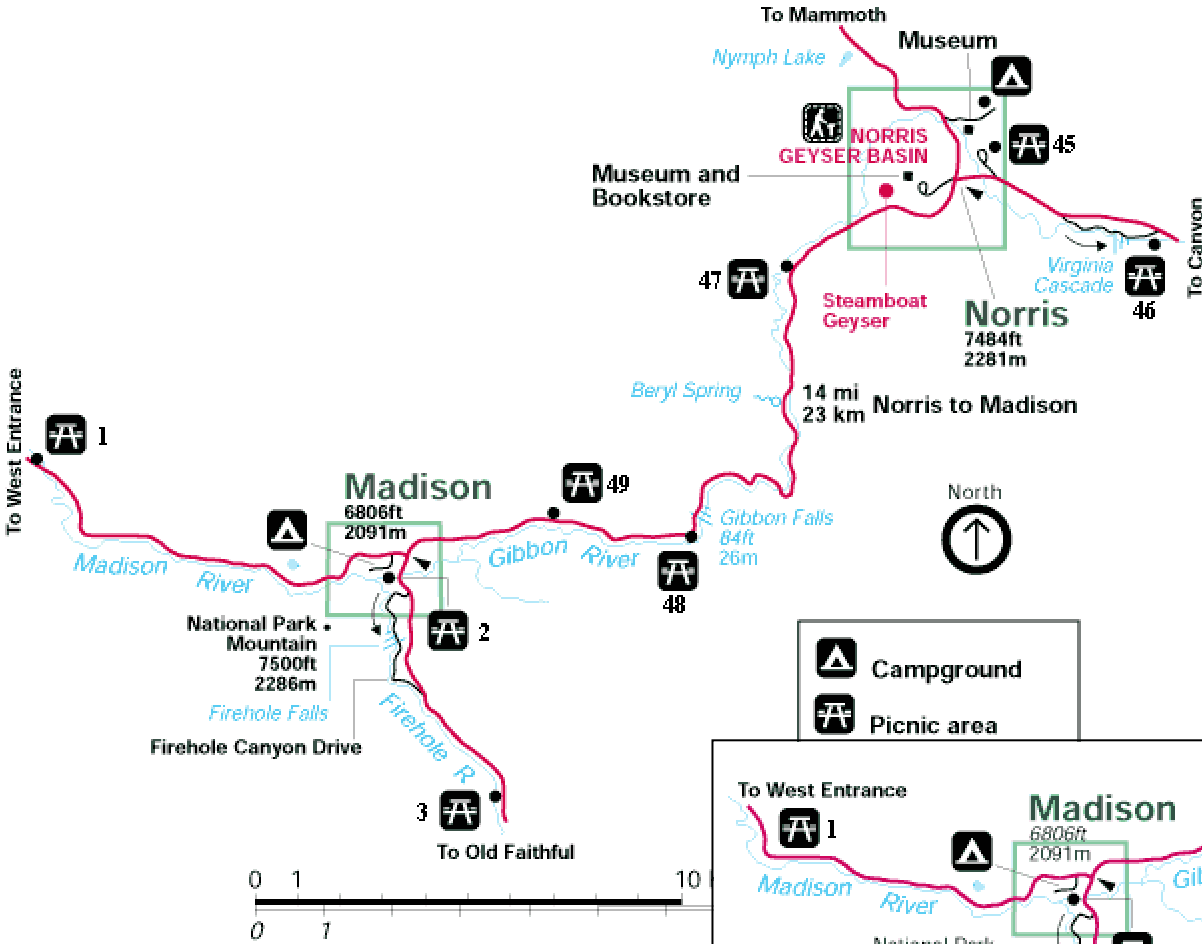
yell_fire_perimeters
<all other values>
YEAR
1988
2000
2001
2002
2003
2004
2005
2006
2007
2008

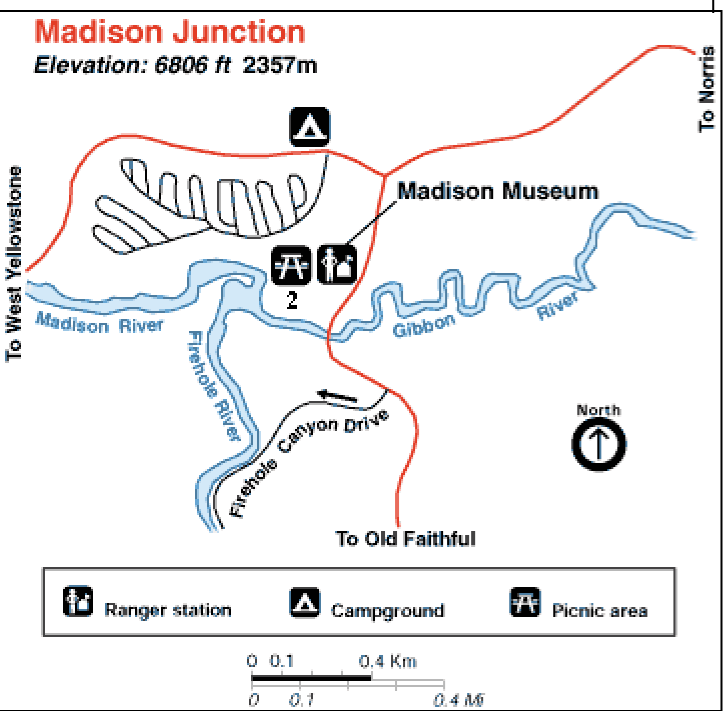
The Fires of Yellowstone National Park (some of them)
Shown in shades of purple are the areas burned by fires from 2000 to 2008.
Shown in orange are the areas burned in the 1988 fire.

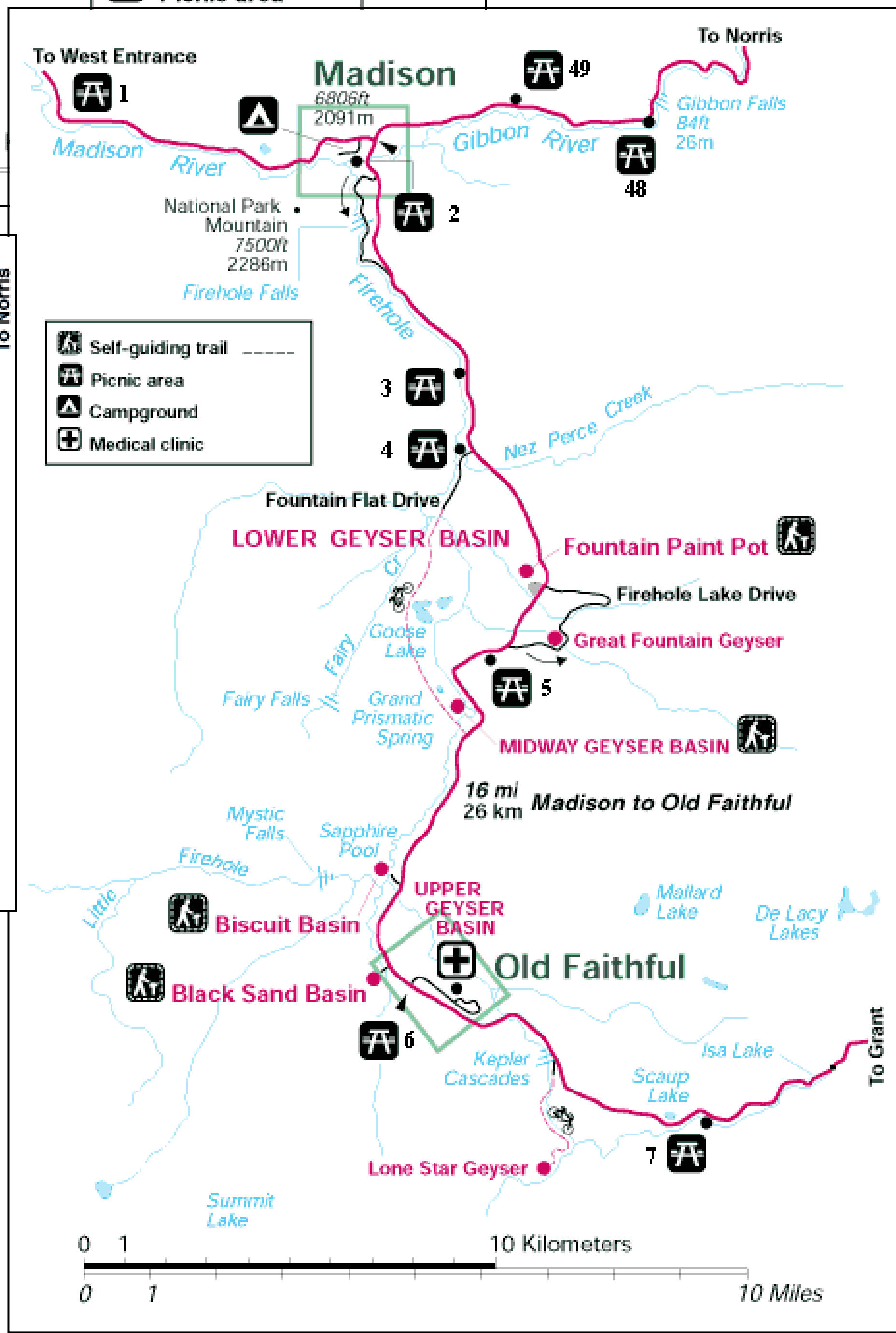

Elevation: 6239ft 1902m
0 0.1 Km 0.5
0 0.1 Mi 0.5
Mammoth Hot Springs Hotel
To Gardiner
Post Office
Amphitheater
Ice
Upper Terrace Loop Drive: no trailers or vehicles over 25 feet; closed in winter
38
Park Headquarters
39
HISTORIC FORT YELLOWSTONE
Upper Terraces Area
Lower Terraces Area
Chapel
one-way
To North Entrance and Gardiner
Albright Visitor Center
To Old Faithful via Norris and Madison -Road closed from early November to late April
North
To Tower-Roosevelt
Medical clinic
Food service
Store
Lodging
Ranger station
Picnic area
Gas station (some have auto repair)
Campground
Horse rental
Self-guiding trail

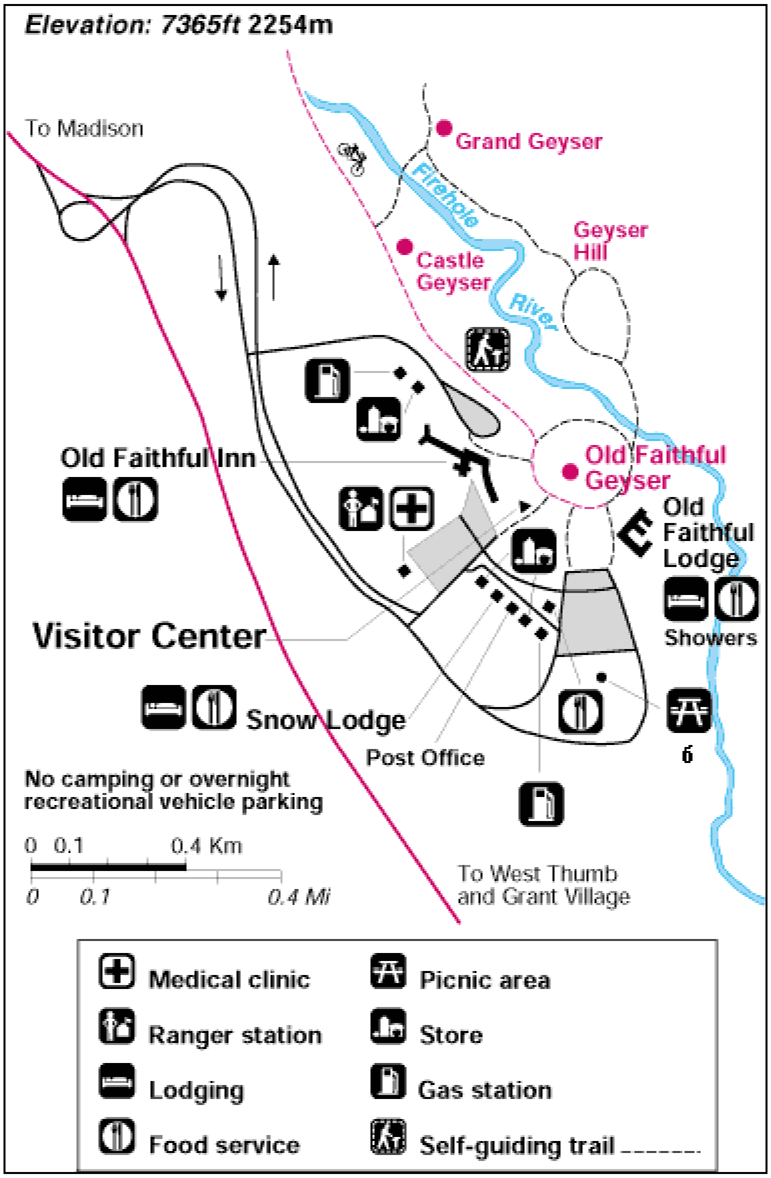

To North Entrance
41
40
Mammoth Hot Springs
Park Headquarters
Gardner River
Road closed from early November to late April
To Tower
HOLE
Golden Gate
Bunsen Peak 8564ft 2610m
Swan Lake
River
Gardner
GARDNERS
Panther Creek
Sheepeater Cliff
Indian Creek
42
Indian Creek
WILLOW PARK
21 mi 34 km Mammoth to Norris
Creek
43
Winter
Beaver Lake
Obsidian Cliff 7383ft 2250m
44
Grizzly Lake
Creek
Roaring Mountain
Straight
Twin Lakes
Museum
Nymph Lake
NORRIS GEYSER BASIN
45
To Canyon
Museum and Bookstore
North
47
Steamboat Geyser
Norris 7484ft 2281m
To Madison
0 1 10 Kilometers
0 1 10 Miles
Medical clinic
Campground
Picnic area
Self-guiding trail

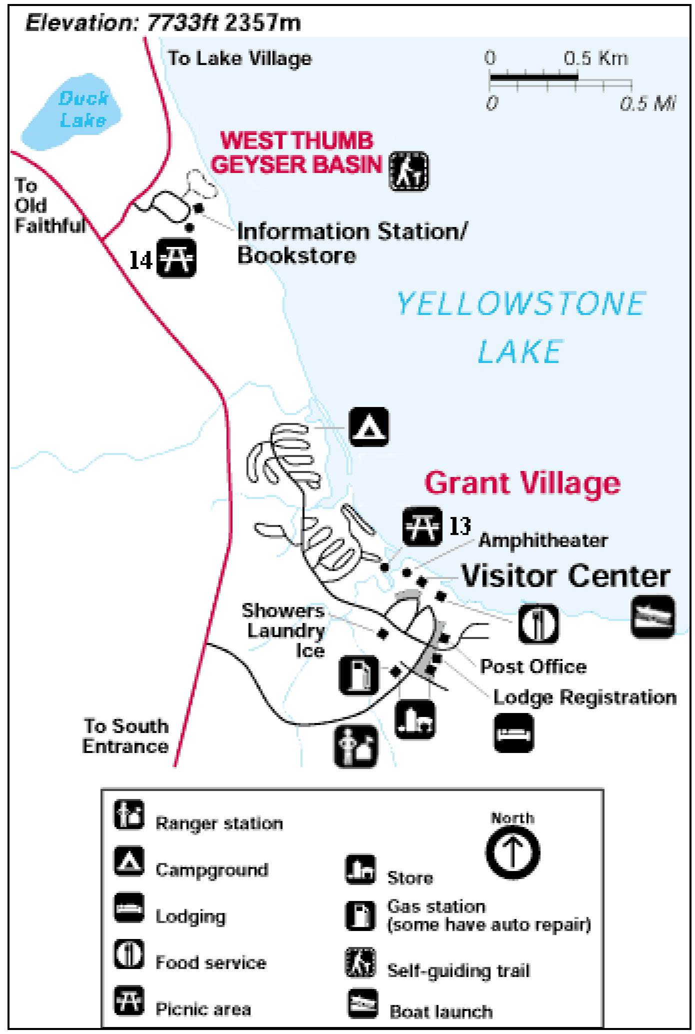

To Mammoth
Norris Campground
Museum of the National Park Ranger
Geyser Basin to Norris Campground trail
Porcelain Basin Trail
Nuphar Lake
Museum
Norris Junction
To Canyon
Bookstore
Norris Geyser Basin
North
Back Basin Trail
0 .2 km .4 km
0 1/8 mi 1/4 mi
To Madison Junction

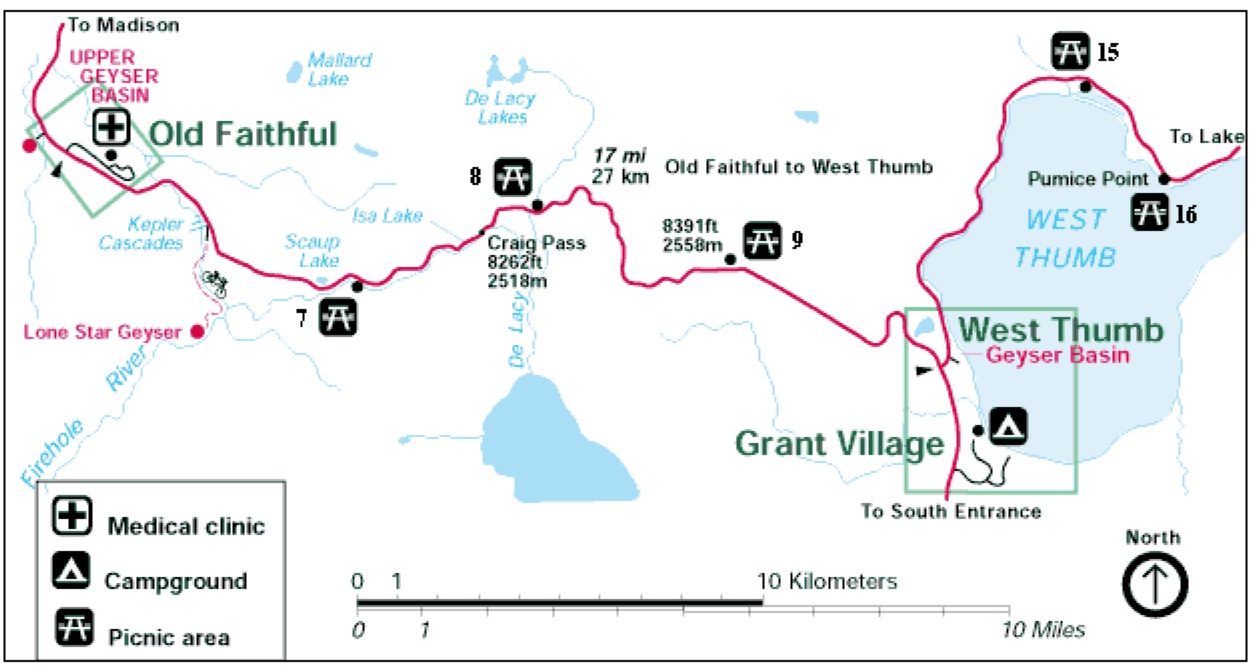

To Mammoth
Museum
Nymph Lake
NORRIS
GEYSER BASIN
45
Museum and
Bookstore
To Canyon
Virginia
Cascade
46
47
Steamboat
Geyser
Norris
7484ft
2281m
Beryl Spring
14 mi
23 km
Norris to Madison
To West Entrance
1
Madison
6806ft
2091m
49
Gibbon Falls
84ft
26m
North
Madison
River
Gibbon
River
48
National Park
Mountain
7500ft
2286m
2
Firehole Falls
Firehole Canyon Drive
Firehole R
Campground
Picnic area
3
To Old Faithful
0
1
10

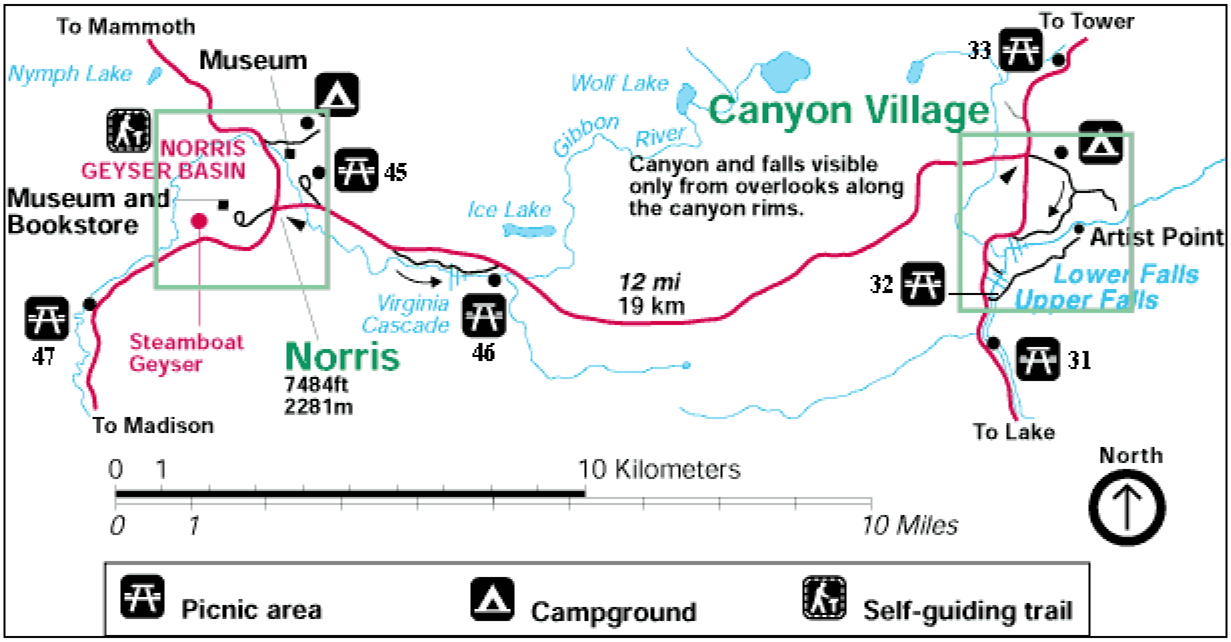

Madison Junction
Elevation: 6806 ft 2357m
To Norris
To West Yellowstone
Madison Museum
2
Madison River
Gibbon
River
Firehole River
Firehole Canyon Drive
North
To Old Faithful
Ranger station
Campground
Picnic area
0 0.1 0.4 Km
0 0.1 0.4 Mi


To Norris
To West Entrance
Madison
6806ft
2091m
49
1
Gibbon Falls
84ft
26m
Madison
River
Gibbon
River
48
National Park
Mountain
7500ft
2286m
2
Firehole Falls
Firehole
Self-guiding trail
Picnic area
Campground
Medical clinic
3
Nez Perce Creek
4
Fountain Flat Drive
LOWER GEYSER BASIN
Fountain Paint Pot
Firehole Lake Drive
Goose
Lake
Great Fountain Geyser
Fairy
5
Fairy Falls
Grand
Prismatic
Spring
MIDWAY GEYSER BASIN
16 mi
26 km
Madison to Old Faithful
Mystic
Falls
Sapphire
Pool
Firehole
Little
UPPER
GEYSER
BASIN
Mallard
Lake
De Lacy
Lakes
Biscuit Basin
Old Faithful
Black Sand Basin
6
Kepler
Cascades
Isa Lake
Scaup
Lake
To Grant
7
Lone Star Geyser
Summit
Lake
0 1 10 Kilometers
0 1 10 Miles


Elevation: 7365ft 2254m
To Madison
Grand Geyser
Firehole
Geyser Hill
Castle Geyser
River
Old Faithful Inn
Old Faithful Geyser
Old Faithful Lodge
Showers
Visitor Center
Snow Lodge
Post Office
6
No camping or overnight recreational vehicle parking
0 0.1 0.4 Km
0 0.1 0.4 Mi
To West Thumb and Grant Village
Medical clinic
Ranger station
Lodging
Food service
Picnic area
Store
Gas station
Self-guiding trail

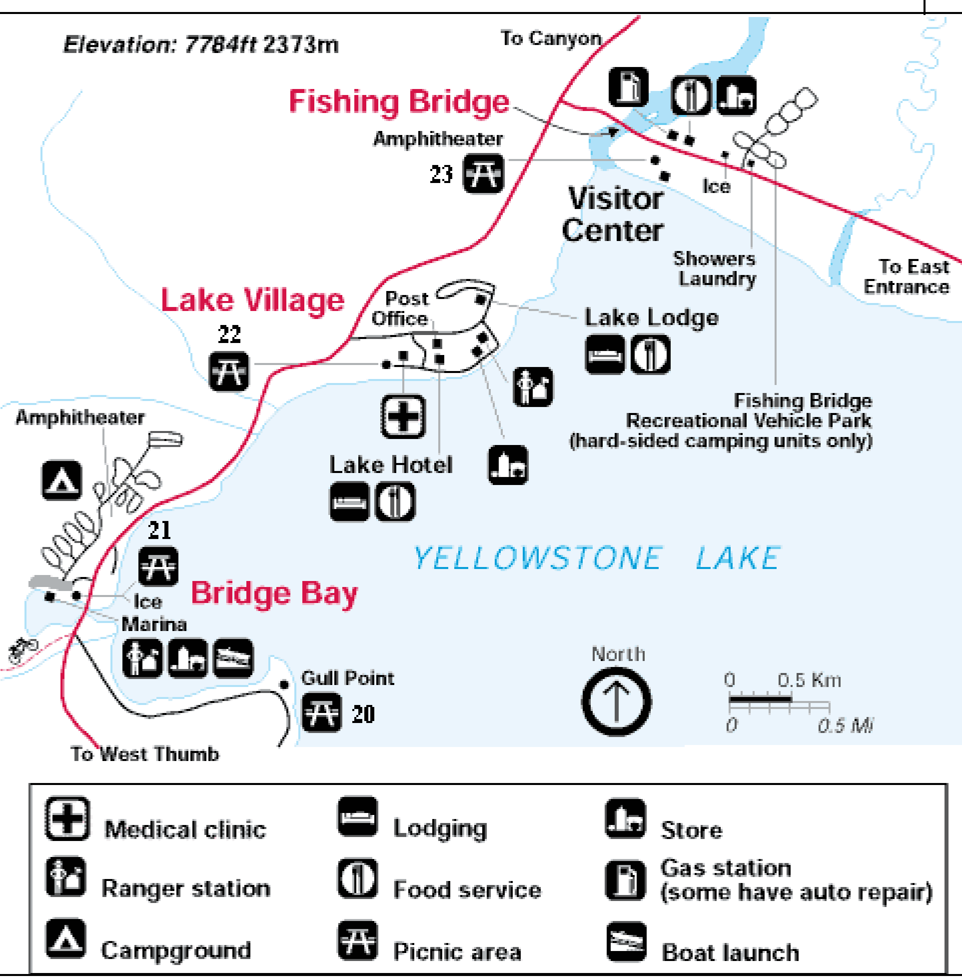

Elevation: 7733ft 2357m
To Lake Village
0 0.5 Km
0 0.5 Mi
Duck Lake
WEST THUMB GEYSER BASIN
To Old Faithful
Information Station/ Bookstore
14
YELLOWSTONE LAKE
Grant Village
13
Amphitheater
Visitor Center
Showers Laundry Ice
Post Office
Lodge Registration
To South Entrance
Ranger station
Campground
Lodging
Food service
Picnic area
Store
Gas station (some have auto repair)
Self-guiding trail
Boat launch
North


To Madison
UPPER GEYSER BASIN
Old Faithful
Mallard Lake
De Lacy Lakes
8
17 mi 27 km
Old Faithful to West Thumb
15
To Lake
Pumice Point
16
WEST THUMB
Kepler Cascades
Isa Lake
Scaup Lake
Craig Pass 8262ft 2518m
8391ft 2558m
9
7
Lone Star Geyser
River
Firehole
De Lacy
West Thumb
Geyser Basin
Grant Village
To South Entrance
Medical clinic
Campground
Picnic area
0 1 10 Kilometers
0 1 10 Miles
North

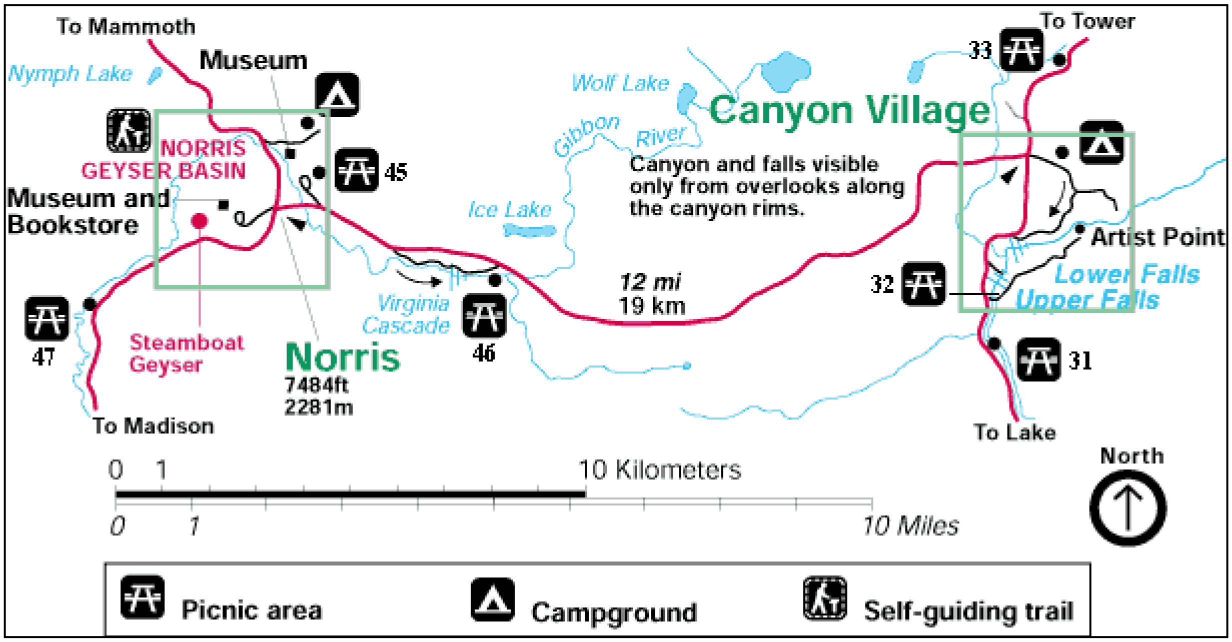


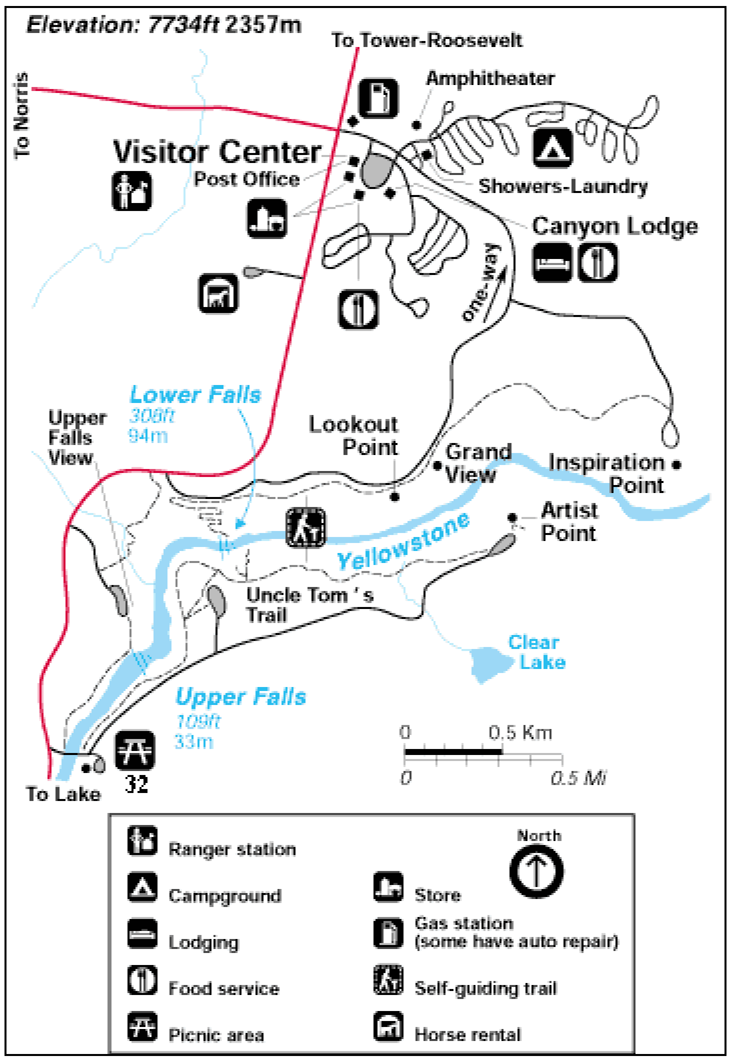
To Mammoth
Nymph Lake
Museum
NORRIS GEYSER BASIN
45
Museum and Bookstore
Wolf Lake
Gibbon River
Canyon Village
Canyon and falls visible only from overlooks along the canyon rims.
Ice Lake
33
To Tower
Artist Point
Lower Falls
Upper Falls
32
47
Steamboat Geyser
Norris
7484ft
2281m
Virginia Cascade
46
12 mi
19 km
31
To Madison
To Lake
0 1 10 Kilometers
0 1 10 Miles
North
Picnic area
Campground
Self-guiding trail

To Tower
To Norris
Canyon Village
Artist Point
32
Lower Falls
Upper Falls
Canyon and falls visible only from overlooks along the canyon rims.
31
Yellowstone River
16 mi
26 km
Canyon to Fishing Bridge
HAYDEN VALLEY
Sulphur Caldron
30
Mud Volcano
29
28
Le Hardy Rapids
Fishing Bridge Recreational Vehicle Park (hard-sided camping units only)
Fishing Bridge
Lake Village
To East Entrance
H
Bridge Bay
North
Natural Bridge
20
To Grant
1 10 Kilometers
1 10 Miles
Hospital
Campground
Picnic area
Self-guiding trail

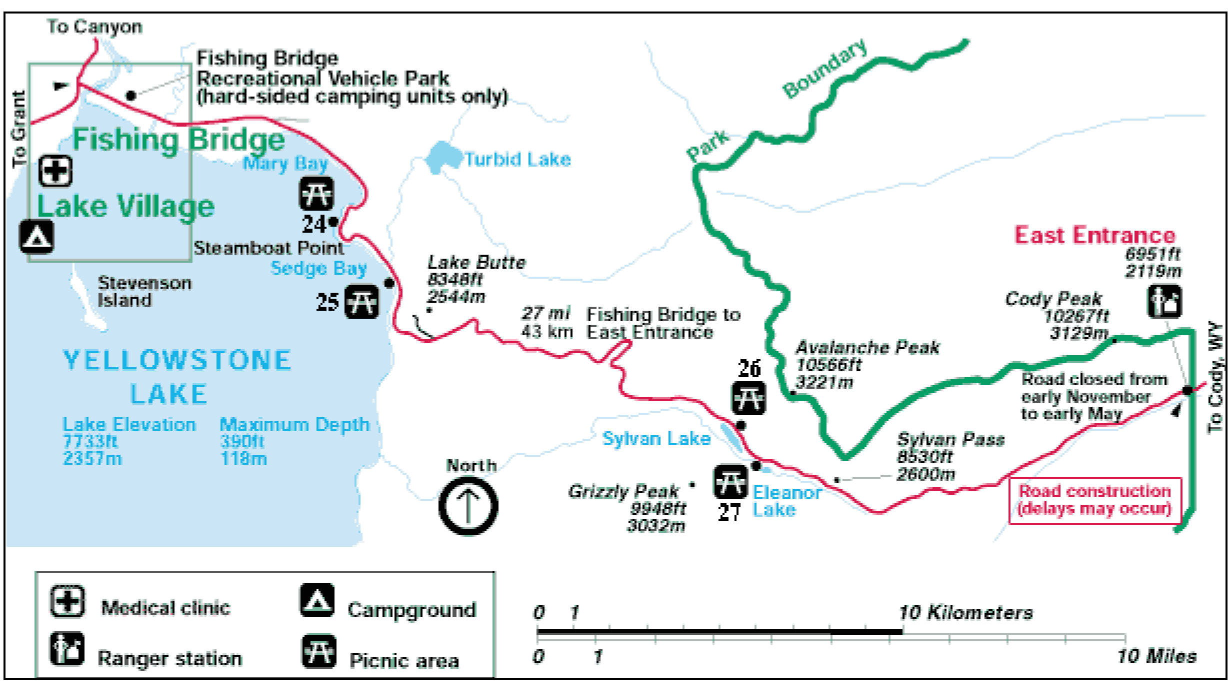


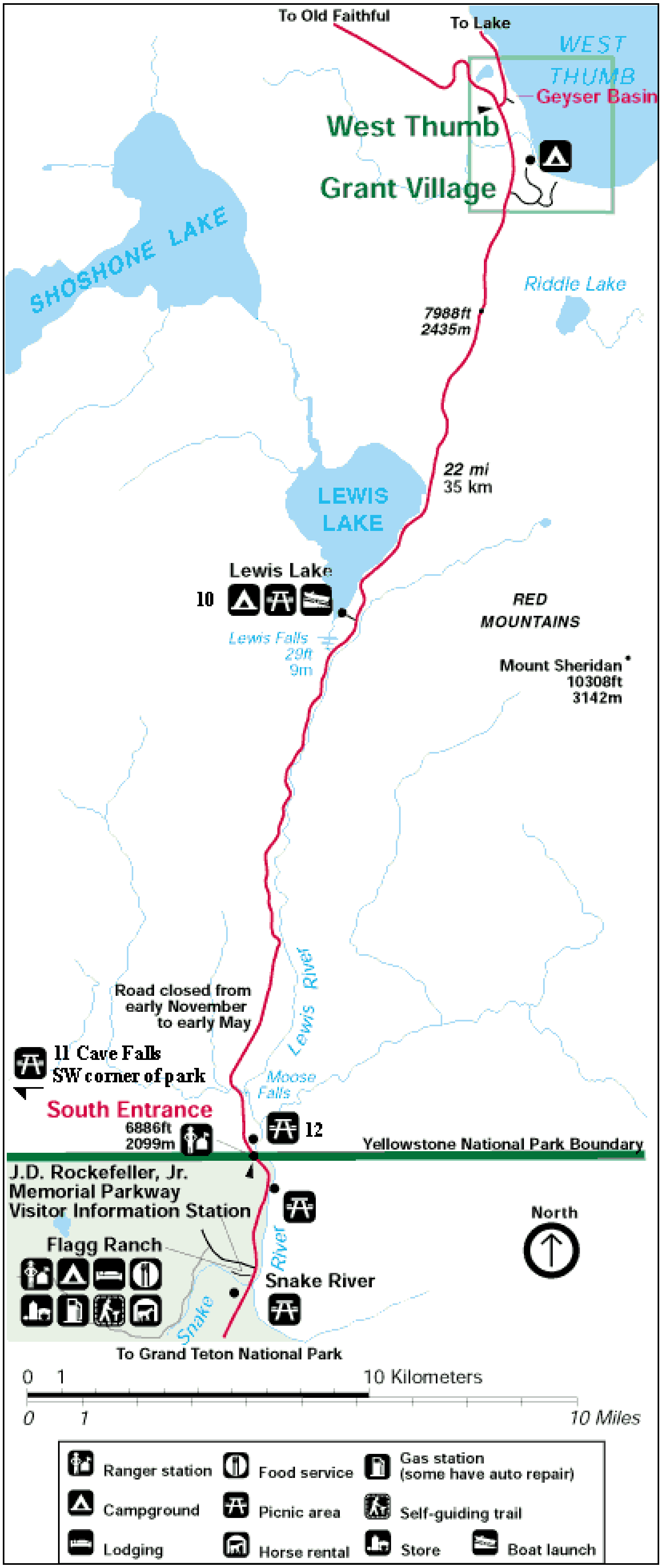
Elevation: 7784ft 2373m
To Canyon
Fishing Bridge
Amphitheater
23
Visitor Center
Ice
Showers
Laundry
To East Entrance
Lake Village
Post Office
Lake Lodge
22
Fishing Bridge Recreational Vehicle Park (hard-sided camping units only)
Amphitheater
Lake Hotel
21
YELLOWSTONE LAKE
Ice
Bridge Bay
Marina
Gull Point
20
North
0 0.5 Km
0 0.5 Mi
To West Thumb
Medical clinic
Ranger station
Campground
Lodging
Food service
Picnic area
Store
Gas station (some have auto repair)
Boat launch


To Mammoth
Museum
Nymph Lake
NORRIS
GEYSER BASIN
45
Museum and
Bookstore
Wolf Lake
Canyon Village
Gibbon
River
Canyon and falls visible
only from overlooks along
the canyon rims.
Ice Lake
To Tower
33
Artist Point
Lower Falls
Upper Falls
32
31
12 mi
19 km
Virginia
Cascade
46
47
Steamboat
Geyser
Norris
7484ft
2281m
To Madison
To Lake
North
0 1 10 Kilometers
0 1 10 Miles
Picnic area
Campground
Self-guiding trail

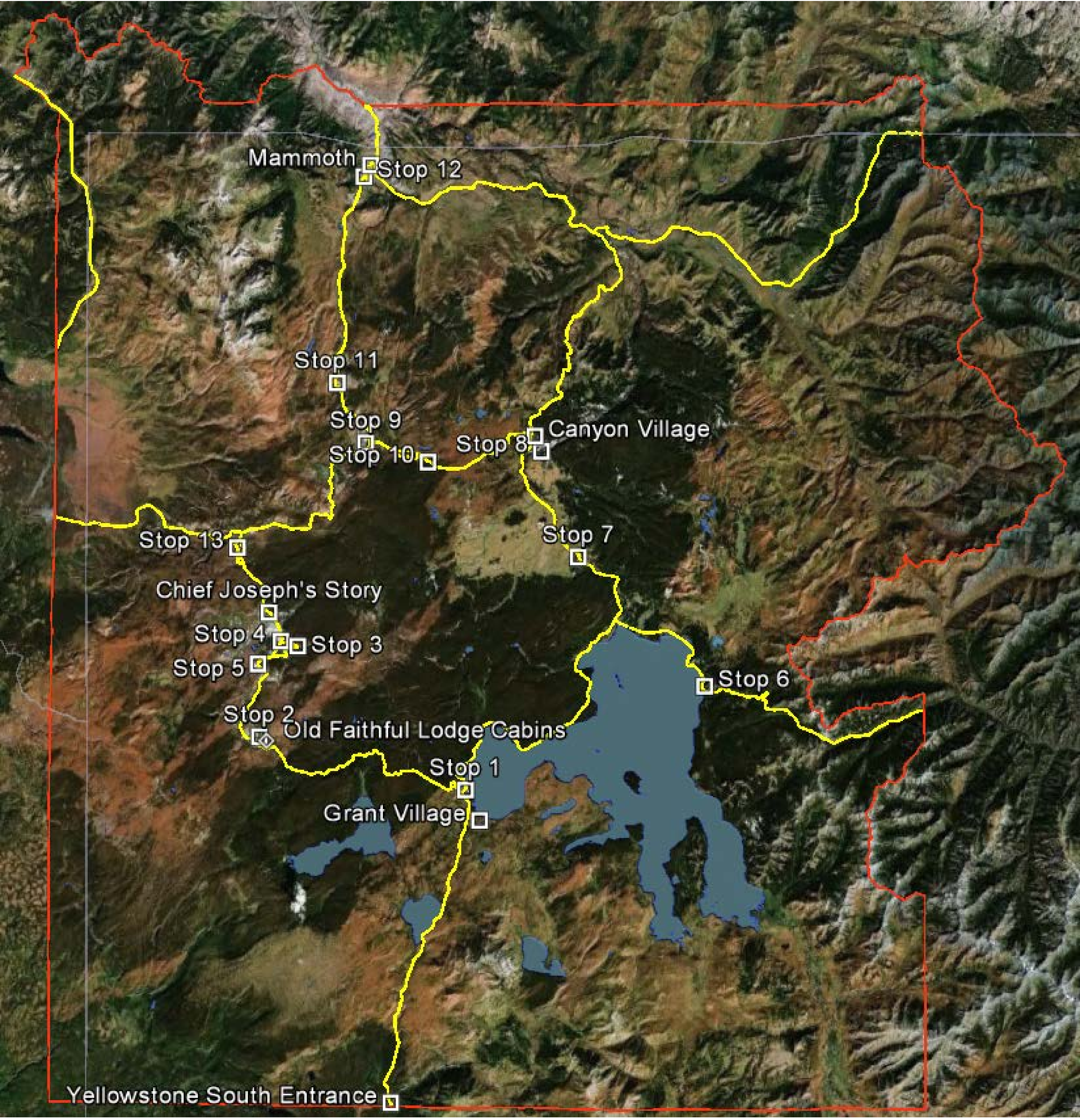

Elevation: 7734ft 2357m
To Tower-Roosevelt
To Norris
Amphitheater
Visitor Center
Post Office
Showers-Laundry
Canyon Lodge
one-way
Lower Falls
308ft
94m
Upper
Falls
View
Lookout
Point
Grand
View
Inspiration
Point
Artist
Point
Yellowstone
Uncle Tom's
Trail
Clear
Lake
Upper Falls
109ft
33m
0 0.5 Km
0 0.5 Mi
To Lake
32
North
Ranger station
Campground
Lodging
Food service
Picnic area
Store
Gas station
(some have auto repair)
Self-guiding trail
Horse rental


To Canyon
Fishing Bridge
Recreational Vehicle Park
(hard-sided camping units only)
Fishing Bridge
Lake Village
To East Entrance
Beach Lake
Bridge Bay
Natural
Bridge
20
Stevenson
Island
19
North
15
21 mi
34 km
18
17
YELLOWSTONE
LAKE
Pumice Point
16
WEST
THUMB
Frank
Island
To Old Faithful
West Thumb
Geyser Basin
Delusion
Lake
Grant Village
To South Entrance
0 1 10 Kilometers
0 1 10 Miles
Picnic area
Campground


To Canyon
Fishing Bridge
Recreational Vehicle Park
(hard-sided camping units only)
Boundary
Park
To Grant
Fishing Bridge
Mary Bay
Turbid Lake
Lake Village
24
Steamboat Point
Sedge Bay
East Entrance
6951ft
2119m
Stevenson
Island
Lake Butte
8348ft
2544m
25
Cody Peak
10267ft
3129m
27 mi
43 km
Fishing Bridge to
East Entrance
YELLOWSTONE
LAKE
Avalanche Peak
10566ft
3221m
26
Road closed from
early November
to early May
To Cody, WY
Lake Elevation
7733ft
2357m
Maximum Depth
390ft
118m
Sylvan Lake
North
Sylvan Pass
8530ft
2600m
Grizzly Peak
9948ft
3032m
27
Eleanor
Lake
Road construction
(delays may occur)
Medical clinic
Campground
Ranger station
Picnic area
0 1 10 Kilometers
0 1 10 Miles



To Old Faithful
To Lake
WEST THUMB
Geyser Basin
West Thumb
Grant Village
SHOSHONE LAKE
Riddle Lake
7988ft
2435m
22 mi
35 km
LEWIS LAKE
Lewis Lake
10
Lewis Falls
29ft
9m
RED MOUNTAINS
Mount Sheridan
10308ft
3142m
Lewis River
Road closed from
early November
to early May
11 Cave Falls
SW corner of park
Moose Falls
South Entrance
6886ft
2099m
12
Yellowstone National Park Boundary
J.D. Rockefeller, Jr.
Memorial Parkway
Visitor Information Station
Flagg Ranch
Snake River
North
To Grand Teton National Park
0 1 10 Kilometers
0 1 10 Miles
Ranger station
Food service
Gas station
(some have auto repair)
Campground
Picnic area
Self-guiding trail
Lodging
Horse rental
Store
Boat launch



Yellowstone National Park
Map showing Roads (yellow), Lakes (blue), our field stops, and other points of interest.