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The Yellowstone Hotspot, Greater Yellowstone Ecosystem, and Human Geography

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Chapter A *of*

Integrated Geoscience Studies in the Greater Yellowstone Area—Volcanic, Tectonic, and Hydrothermal Processes in the Yellowstone Geoecosystem

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By Kenneth L. Pierce,[1] Don G. Despain,[1] Lisa A. Morgan,[2] and John M. Good[3]

Abstract

Active geologic processes associated with the Yellowstone hotspot are fundamental in shaping the landscapes of the greater Yellowstone ecosystem (GYE), a high volcanic plateau flanked by a crescent of still higher mountainous terrain. The processes associated with the Yellowstone hotspot are volcanism, faulting, and uplift and are observed in the geology at the surface. We attribute the driving forces responsible for the northeastward progression of these processes to a thermal plume rising through the Earth's mantle into the base of the southwest-moving North American plate. This progression began 16 million years ago (Ma) near the Nevada-Oregon border and arrived at Yellowstone about 2 Ma. Before arrival of the hotspot, an older landscape existed, particularly mountains created during the Laramide orogeny about 70–50 Ma and volcanic terrain formed by Absaroka andesitic volcanism mostly between 50–45 Ma. These landscapes were more muted than the present, hotspot-modified landscape because the Laramide-age mountains had worn down and an erosion surface of low relief had developed on the Absaroka volcanic terrain.

The Yellowstone Plateau was built by hotspot volcanism of rhyolitic lavas and caldera-forming rhyolite tuffs (ignimbrites). Streams eroding back into the edges of this plateau have created scenic waterfalls and canyons such as the Grand Canyon of the Yellowstone and Lewis Canyon. Rhyolite is poor in plant nutrients and forms sandy, well-drained soils that support the monotonous, fire-adapted lodgepole pine forests of the Yellowstone Plateau. Non-rhyolitic rocks surround this plateau and sustain more varied vegetation, including spruce, fir, and whitebark pine forests broken by grassy meadows. Heat from the hotspot rises upward and drives Yellowstone's famed geysers, hot springs, and mudpots. These thermal waters are home to specialized, primitive ecosystems, rich in algae and bacteria. The rock alteration associated with hydrothermal systems creates the bright colors of Yellowstone's Grand Canyon.

Basin-and-range-style faulting has accompanied migration of the hotspot to Yellowstone and formed the linear mountains and valleys that occur north and south of the hotspot track, which is the present-day eastern Snake River Plain. High rates of basin-and-range faulting occurred adjacent to the migrating Yellowstone hotspot, creating distinctive landscapes within the GYE such as the Teton Range/Jackson Hole, with characteristic rugged, forested ranges and adjacent flat-floored grassy valleys. The difference in altitude between the mountains and valleys provides a topographic gradient in which vegetation maturation advances with altitude; animal-migration patterns also follow this trend. The valleys provide natural meadows, agricultural land, town sites, and corridors for roads.

Uplift of the GYE by as much as 1 km (3,000 ft) during the last 5 million years has resulted in ongoing erosion of deep, steep-walled valleys. Many prominent ecological characteristics of Yellowstone derive from this hotspot-induced uplift, including the moderate- to high-altitude terrain and associated cool temperatures and deep snowfall.

Modern and Pleistocene climate and associated vegetation patterns strongly relate to the topography created by the hotspot and its track along the eastern Snake River Plain. Winter air masses from the moist northern Pacific Ocean traverse the topographic low of the Snake River Plain to where orographic rise onto the Yellowstone Plateau and adjacent mountains produces deep snow. A winter precipitation shadow forms on the lee (eastern) sides of the GYE. During Pleistocene glacial times, this moisture conduit provided by the hotspot-track-produced ice-age glaciers that covered the core of the present GYE. These glaciers sculpted bedrock and produced glacial moraines that are both forested and unforested, sand and gravel of ice-marginal streams and outwash gravels that are commonly covered with sagebrush-grassland, and silty lake sediments that are commonly covered by lush grassland such as Hayden Valley.

The effects of the Yellowstone hotspot also profoundly shaped the human history in the GYE. Uplift associated with the hotspot elevates the GYE to form the Continental Divide, and streams drain radially outward like spokes from a hub. Inhabitants of the GYE 12,000–10,000 years ago, as well as more recent inhabitants, followed the seasonal green-up of plants and migrating animals up into the mountain areas. During European immigration, people settled around Yellowstone in the lower parts of the drainages and established roads, irrigation systems, and cultural associations. The core Yellowstone highland is too harsh for agriculture and inhospitable to people in the winter. Beyond this core, urban and rural communities exist in valleys and are separated by upland areas. The partitioning inhibits any physical connection of communities, which in turn complicates pursuit of common interests across the whole GYE. Settlements thus geographically isolated evolved as diverse, independent communities.

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Introduction

Studies of the geology of Yellowstone National Park (the Park) began in the early 1870s with the Hayden Survey followed by the Hague Surveys. The Hayden Survey provided documentation by scientific studies, photography, and paintings of Yellowstone's wonders that were critical to its establishment in 1872 as the world's first national park. More than 125 years after these pioneering geologic studies, we have relied on the foundation of their work and incorporated more recent concepts such as plate tectonics, hotspot tracks, and possible mantle plumes to explain the geologic phenomena that influence the climate and distribution of plant and animal communities and human geography in the Yellowstone region today.

Overviews of the geology in the greater Yellowstone ecosystem (GYE) are found in Good and Pierce (1996), Smith and Siegel (2000), and Love and others (2003). Don Despain (1990) described vegetation of Yellowstone and many relations to the geology. Eversman and Carr (1992) composed a road guide to the ecology of the greater Yellowstone area. Pierce and others (2003) described a week-long field trip to the Quaternary geology and ecology of the GYE. For a mountainous area immediately northwest of Yellowstone, Duncan Patten (1963) made a pioneering study of the relation between geology and vegetation and determined that grassland and sagebrush are associated with claystones, siltstones, and alluvium.

Our central theme is that active geologic processes associated with the track of the Yellowstone hotspot have a profound effect on the geography, topography, climate, soils, and biota of the GYE (figs. 1 and 2). In fact, the hotspot and its associated processes may explain much of the character of the GYE. The salient geologic processes associated with the track of the Yellowstone hotspot (Pierce and Morgan, 1992) include (1) volcanism that produces such features as the Yellowstone rhyolite plateau and the eastern Snake River Plain, (2) faulting that created such features as the Teton Range/Jackson Hole and the Madison Range/Madison Valley, and particularly important, (3) uplift that resulted in the generally high altitude of the GYE and incision to form deep valleys, commonly in highly erodible rocks. The geothermal features of Yellowstone attest to deep-seated hotspot heat. Of course, prior to the hotspot's arrival in the last few million years, older landscapes existed, particularly those formed by Laramide mountain building about 70–50 million years ago (Ma) and by extensive Absaroka andesitic volcanism mostly about 50–45 Ma. These ancient landscapes were more muted than the present, hotspot-modified landscape because by about 20–10 Ma, the Laramide-age mountains had worn down and an erosion surface of moderate to low relief characterized the Absaroka volcanic basin and the old Laramide uplifts.

This shaping of the geography by hotspot processes has, in turn, influenced human settlement and use (fig. 2). Much of the ecosystem consists of an arc of mountains that wrap around the Yellowstone Plateau and include (clockwise from west) Centennial Mountains, Madison Range, Gallatin Range, Beartooth Mountains, Absaroka Range, Wind River Range, Gros Ventre Range, Wyoming Range, Salt River Range, and Teton Range, as well as a number of smaller mountain ranges in adjacent parts of Wyoming, Idaho, and Montana.

The location of the GYE in a hotspot-uplifted highland along the Continental Divide resulted in boundaries of Federal, State, and county jurisdictions being established within the GYE. Such Federal, State, and county jurisdictions with their attendant laws, regulations, and agencies often have conflicting goals. Two national parks (Yellowstone and Grand Teton) and seven national forests (Beaverhead, Gallatin, Custer, Shoshone, Bridger-Teton, Caribou, and Targhee) including three national forest regions compose the political core of the GYE (fig. 1). The States of Wyoming, Montana, and Idaho have responsibilities in the GYE, as do 21 counties. Thus, political decision-making in the GYE is cumbersome and complex.

Definition of the Greater Yellowstone Ecosystem (GYE)

The GYE extends outward from Yellowstone to include contiguous mountain ranges, foothills, and included valleys (fig. 1). The boundary of the GYE shown in figure 1 is based on ecological land units delineated as part of the Greater Yellowstone Cooperative Regional Transportation Study (U.S. National Park Service and U.S. Forest Service, 1979). The central and perhaps defining feature of the greater Yellowstone ecosystem is a group of about 24 conterminous mountain ranges extending from southwestern Montana to most of the western third of Wyoming and adjacent southeastern Idaho. The ecosystem considered here (fig. 1) includes all terrain from the foothills life zone (Daubenmire, 1943) and above. Where foothills do not exist at the base of the montane slopes, the GYE boundary is drawn on the basal plain 10 km (6 mi) from the base of the montane slopes. Locally, some mountain areas contiguous to the GYE are not included, such as the Owl Creek Mountains and the Bridger Range. These ranges form bridges to other mountain ecosystems. Our boundary is quite similar to that of others who have delineated this ecosystem (Glick and others, 1991; Marston and Anderson, 1991).

Influence of the Yellowstone Hotspot on Landscape Formation

The Yellowstone hotspot exerts a major influence on the ecology and human geography of the GYE (fig. 2) by shaping the larger scale features of the landscape. By human geography, we mean how humans and their works are organized on the landscape. Four types of geologic processes important to landscape formation are associated with the Yellowstone hotspot: (1) volcanism, (2) hot springs and associated thermal features, (3) active faulting, and (4) uplift followed by subsidence. Over

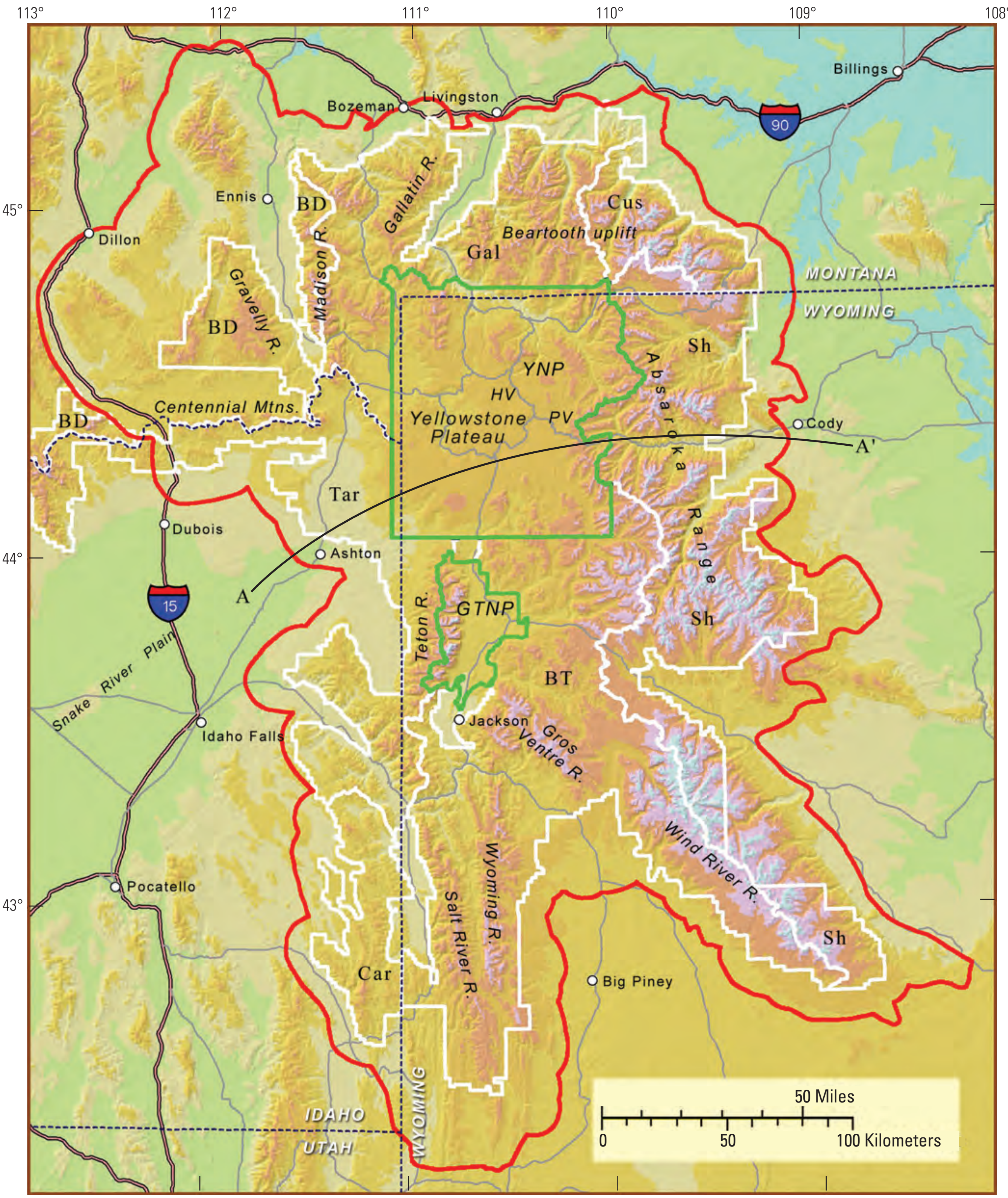


Figure 1. Shaded-relief map of the greater Yellowstone ecosystem (GYE, red line). The GYE incorporates Yellowstone and Grand Teton National Parks (YNP, GTNP outlined by green lines), 7 national forests (outlined in white), 3 States, and 21 counties (not shown). Roads are shown as thin gray lines. Designations of seven national forests: BD, Beaverhead-Deerlodge; Gal, Gallatin; Cus, Custer; Sh, Shoshone; BT, Bridger-Teton; Car, Caribou; and Tar, Targhee. Also designated, HV, Hayden Valley; PV, Pelican Valley. Map from Lisa Landenburger (written commun., 2004). A–A' line of section for figure 14.

the last 10 million years, Yellowstone hotspot activity has progressed northeastward at a rate of about 2.5 cm (1 in) per year[1] and has left in its wake the eastern Snake River Plain (figs. 3 and 4). The hotspot is a relatively fixed thermal disturbance in the Earth's mantle that is below the southwest-moving North American plate; thus, the associated geologic activity appears to be progressing northeastward.

From a geologist's perspective, the best way to understand the Yellowstone hotspot is to look at its influence through time. We think that the hotspot track originated about 16 Ma as a mantle "plume head" (Richards and others, 1989) centered near the McDermitt volcanic caldera complex on the Nevada-Oregon border (fig. 3) (Malde, 1991; Draper, 1991; Pierce and Morgan, 1992; Smith and Braile, 1993; Parsons and others, 1994; Pierce and others, 2000, 2003). From 17–14 Ma, the inferred plume head produced widespread volcanism, including the Columbia River and Oregon Plateau flood basalts (Hooper, 1997; Coffin and Eldholm, 1994; Camp, 1995; Camp and Ross, 2004) as well as widely dispersed rhyolitic fields (fig. 3) and the Nevada-Oregon rift zone (Zoback and Thompson, 1978). About 10 Ma, voluminous rhyolitic volcanism contributed to the Twin Falls and Picabo volcanic fields, an east-west belt 200 km (125 mi) long (Morgan and others, 1999; Morgan and McIntosh, 2005). From about 10 Ma to present, the leading edge of the hotspot volcanism defined a linear track and produced a sequence of three volcanic fields each containing overlapping or nested calderas. Each field started with a large caldera eruption (fig. 4)—the Picabo volcanic field at 10.23 Ma (Morgan and others, 1997), the Heise volcanic field at 6.65 Ma (Morgan and others, 1999; Morgan and McIntosh, 2005), and the Yellowstone Plateau volcanic field at 2.1 Ma (Christiansen, 2001). This sequence left in its wake the eastern Snake River Plain (fig. 4).

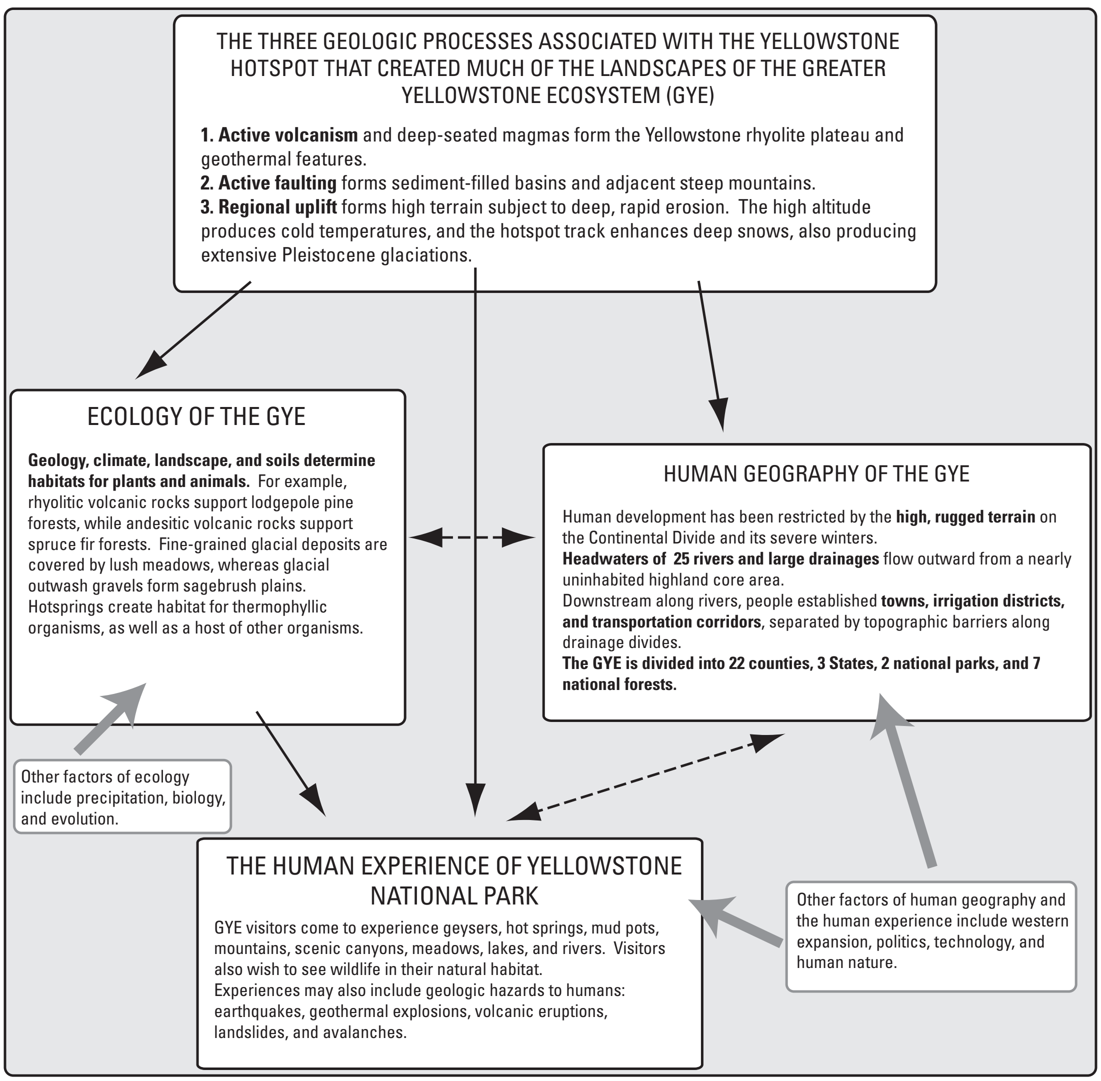


Figure 2. Diagram of the main thesis of this report showing the cascade of effects from the geology of the Yellowstone hotspot, to ecology and human geography, to human experience.

[1]For the hotspot track and motion of the North American plate during the last 10 million years, several approaches yield results of between about 2.2 and 2.9 cm/yr to the SSW. For the inferred motion of the North American plate: (1) a plate motion of about 2.5 cm/year S. 55° W. using the global solution of plate motion in the hotspot reference frame but with the Yellowstone hotspot track deleted (Alice Gripp, *in* Pierce and Morgan, 1992), (2) a track progression (opposite to plate motion) of about 2.9 cm/year to the N. 55° E. based on volcanic progression but not subtracting out post-volcanic extension (Rodgers and others, 1990; Pierce and Morgan, 1992; Smith and Braile, 1993), and (3) a track-associated fault progression of about 2.2 cm/yr to the NE. based on the migration of most active faulting associated with the hotspot and also subtracting the effect of post-volcanic extension (Anders, 1994).

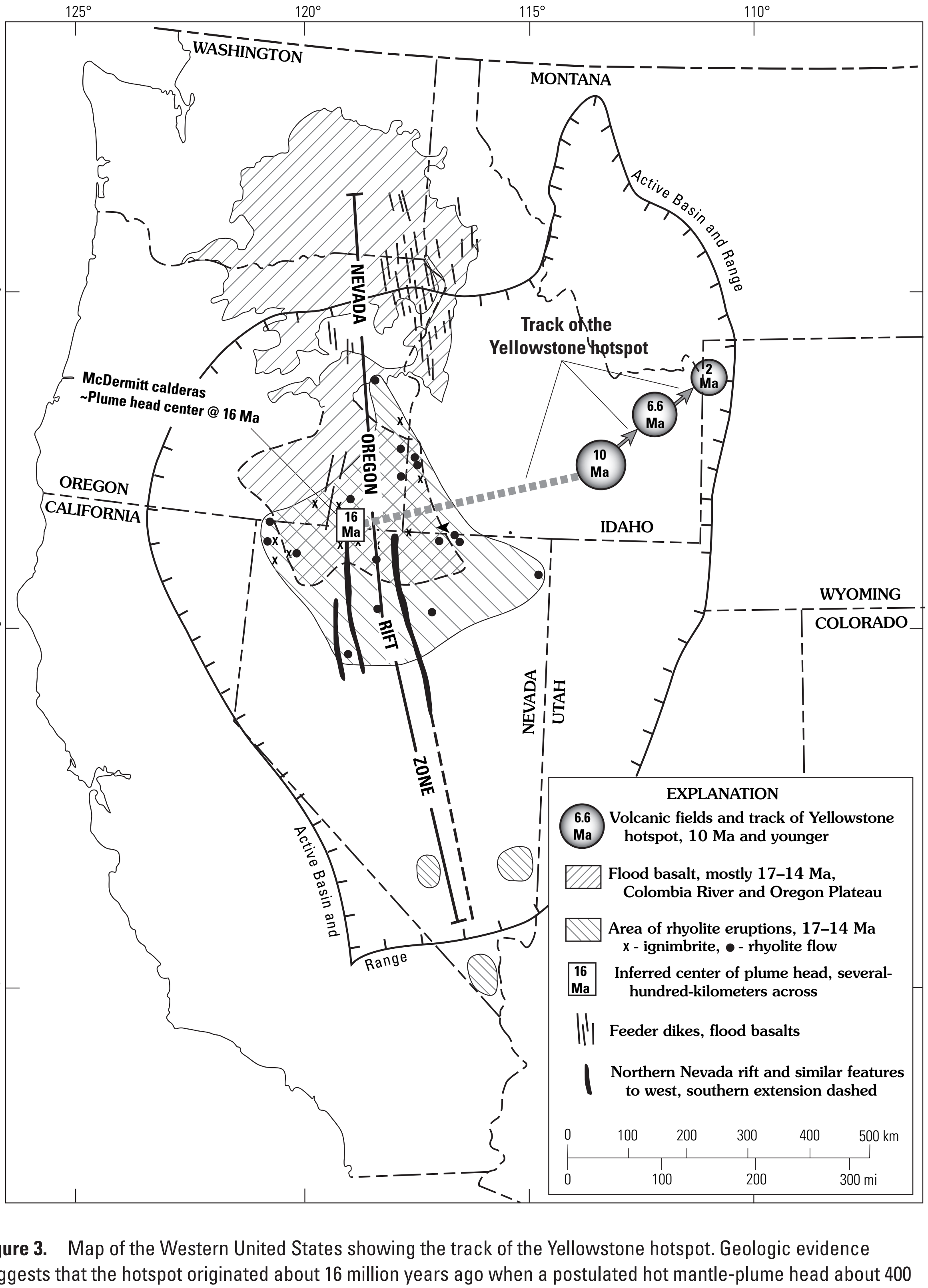
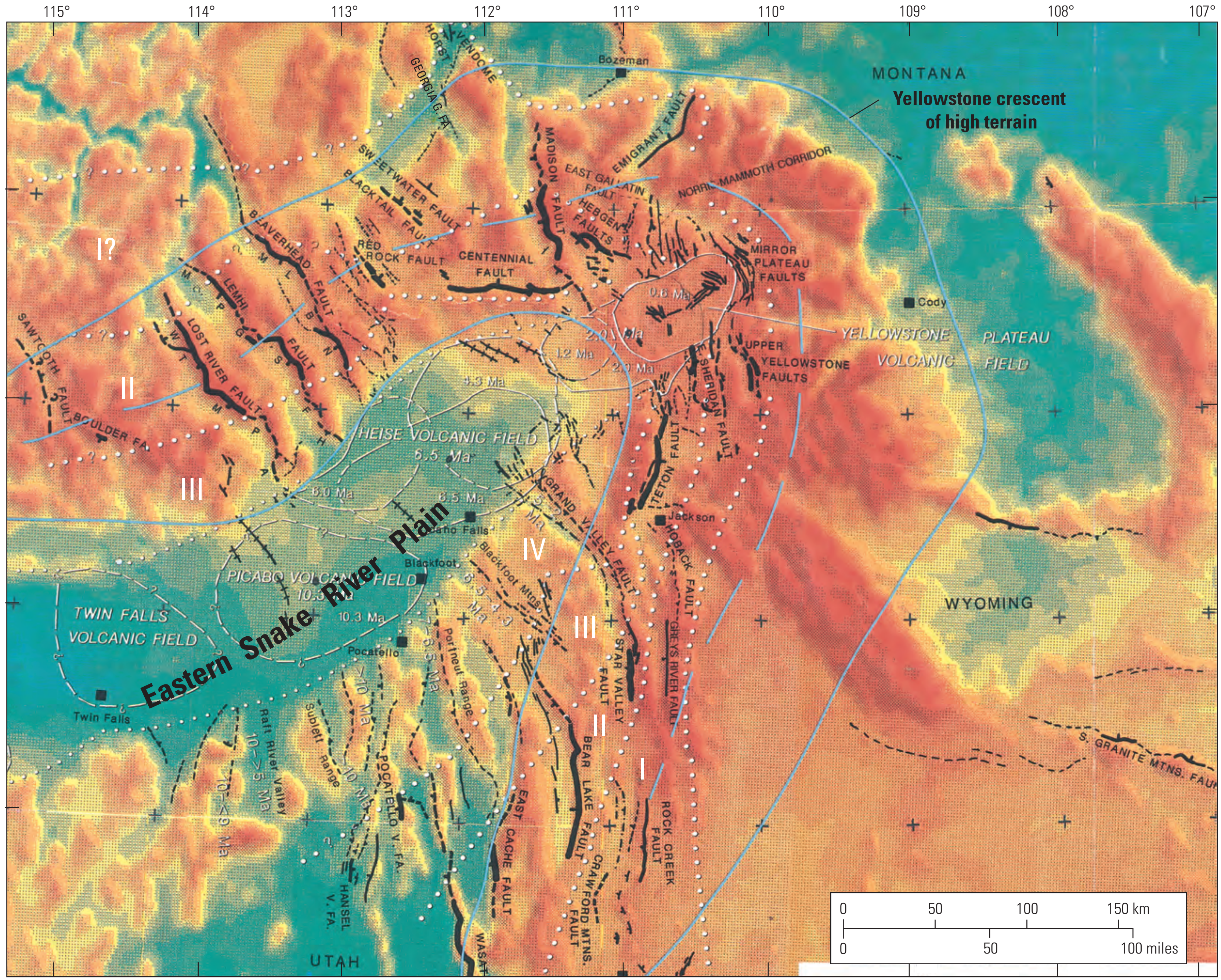


Figure 3. Map of the Western United States showing the track of the Yellowstone hotspot. Geologic evidence suggests that the hotspot originated about 16 million years ago when a postulated hot mantle-plume head about 400 km (250 mi) in diameter, pushed into the base of the North American plate. This plume head centered on the symbol labeled 16 Ma near the Nevada-Oregon border and produced both the flood basalts and rhyolite eruptions (indicated by the two directions of cross-hatching). From 10 to 2 million years ago, the hotspot track became more systematic and left in its wake the trench of the eastern Snake River Plain. The hotspot arrived in the greater Yellowstone area about 2 million years ago. The ages shown for individual volcanic fields refer to time of inception of volcanism.



115°
114°
113°
112°
111°
110°
109°
108°
107°
45°
44°
43°
42°
MONTANA
Yellowstone crescent
of high terrain
Bozeman
Cody
WYOMING
UTAH
EMIGRANT FAULT
MADISON FAULT
EAST GALLATIN FAULT
HEBGEN FAULTS
NORRIS-MAMMOTH CORRIDOR
MIRROR PLATEAU FAULTS
CENTENNIAL FAULT
RED ROCK FAULT
SWEETWATER FAULT
BLACKTAIL FAULT
BEAVERHEAD FAULT
LEMHI FAULT
LOST RIVER FAULT
SAWTOOTH FAULT
BOULDER FA.
GEORGIA G. FA.
HORST
VENDOME
YELLOWSTONE PLATEAU VOLCANIC FIELD
UPPER YELLOWSTONE FAULTS
SHERIDAN FAULT
TETON FAULT
GRAND VALLEY FAULT
HOBACK FAULT
GREYS RIVER FAULT
STAR VALLEY FAULT
BEAR LAKE FAULT
CRAWFORD MTNS. FAULT
ROCK CREEK FAULT
EAST CACHE FAULT
WASATCH
POCATELLO V. FA.
HANSEL V. FA.
S. GRANITE MTNS. FAULT
HEISE VOLCANIC FIELD
PICABO VOLCANIC FIELD
TWIN FALLS VOLCANIC FIELD
Eastern Snake River Plain
Idaho Falls
Blackfoot
Pocatello
Twin Falls
Jackson
Blackfoot Mtns
Portneuf Range
Sublett Range
Raft River Valley
0.6 Ma
1.2 Ma
2.0 Ma
4.3 Ma
6.5 Ma
6.0 Ma
10.3 Ma
I?
I
II
III
IV
0 50 100 150 km
0 50 100 miles

We attribute this linear sequence to a thermal-plume tail (or chimney) phase of the Yellowstone hotspot, which is currently beneath Yellowstone (Pierce and Morgan, 1992).

We use *hotspot* and *hotspot track* to refer to observed features on the surface of the Earth, in particular such Earth-surface features as the volcanic progression, associated fault activity, and young uplift. Driving of such Earth-surface processes by a thermal mantle plume is only one interpretation. However, we prefer the explanation that the hotspot and its track are products of a hot mantle plume rising from perhaps the core-mantle boundary to the base of the overriding North American plate (fig. 5). Two geophysical studies conclude that a thermal mantle plume rises from a depth of 500 km and intercepts the crust beneath Yellowstone (Yean and Dueker, 2005; Waite and others, 2006). This plume rises to the southeast at an angle of~70°, and at a depth 500 km it is under the town of Dillon, Mont.[2] Other geoscientists consider the hotspot and the hotspot track to be the result of "… feedback between upper-mantle convection and regional lithospheric tectonics …" (Christiansen and others, 2002) and mantle upwelling forced by lithospheric extension of the Western U.S. (Humphreys and others, 2000). Whether deep or shallow origin, rising mantle material has generated hot magma.[3]

Figure 4. Track of the Yellowstone hotspot over the last 10 million years from the eastern Snake River Plain to the greater Yellowstone ecosystem. The Yellowstone crescent of high terrain is outlined in blue with a dashed blue line along the crest. The warmer colors indicate higher altitudes. Active faults are shown in black with the heaviest lines for more active faults on major mountain fronts. Dotted white lines denote four belts (I–IV) of faulting with belt II the most prominent. Volcanic fields and their ages are shown in white. Small black letters denote segments of faults described in Pierce and Morgan (1992).

Flared out from the hotspot track like the wake of a boat are two belts of active faulting that extend south and west from Yellowstone National Park and appear to have migrated northeastward with the hotspot (fig. 4) (Anders and others, 1989; Pierce and Morgan, 1992; Anders, 1994). This faulting has created the ecologically important landscape features of linear grassland basins and adjacent forested ranges.

Culminating a little farther to the northeast (or outward) of the active fault belts is the Yellowstone crescent of high terrain (fig. 4). This area appears to be rising and then subsiding like a large bow wave on the leading margin of the track of the Yellowstone hotspot. Pierce and Morgan (1992) estimate about 500–1,000 m (1,500–3,000 ft) of uplift; Smith and Braile (1993) estimate about 600 m (2,000 ft). Humphreys and others (2000) suggest that mantle buoyancy holds the Yellowstone crescent of high terrain (hotspot swell) about 1 km (3,300 ft) higher than would normal mantle. The highest geoid anomaly in the conterminous United States, which coincides with the current position of the Yellowstone hotspot, also suggests ongoing uplift (Milbert, 1991; Smith and Milbert, 1999; Pierce and others, 1992; Smith and Braile, 1993) (see fig. 10 later in this report). The geoid is an imaginary (mathematical) surface that coincides with the mean sea level in the ocean and its extension through the continents. The major United States geoid anomaly that centers on Yellowstone also indicates a deep-seated process beneath the North American plate.

Perhaps the most noteworthy aspect of the volcanism, faulting, and uplift in the GYE is the enormous scale of these processes, as expressed in the following measures. The three cycles of caldera-forming volcanism during the past 2.1 m.y. in the Yellowstone Plateau volcanic field have produced more than 6,500 km^3 (1,500 mi^3) of volcanic material (Christiansen, 1984, 2001). The large calderas formed during these eruptions are large depressions and do not have the conical or shield shape most people associate with volcanoes. The last major caldera formed 640,000 years ago and is a 40- by 65-km (25- by 40-mi) depression flanked by sheets of ash-flow tuff and is largely filled by younger rhyolite lava flows. The level of seismicity in the GYE area is one of the highest in North America, resulting in dozens of moderate to large earthquakes (magnitudes between 5.5 and 7.5) since 1900 (Smith and Arabasz, 1991). Heat flow from the Yellowstone caldera is about 50 times the continental mean. The geologically active Yellowstone Plateau stands more than 1,000 m (3,000 ft) higher than the older hotspot track of the eastern Snake River Plain. Finally, in the Yellowstone area, the crescent of high terrain, which largely coincides with the positive geoid anomaly, is about 400 km (250 mi) across in a northwest-southeast direction (fig. 4) and is quite similar to the dimensions of the GYE. The sheer magnitude of individual processes, as well as their cumulative effect on the

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[2]The following arguments support a deep mantle origin of the Yellowstone hotspot, perhaps from the core-mantle boundary (fig. 5): (1) the broad scale (400 km, 250 mi) of faulting and uplift associated with the hotspot track, (2) $^3He/^4He$ values of 16 from both Yellowstone's thermal waters and rocks along the hotspot track that require a deep mantle source, whereas ratios of 8 are associated with the asthenosphere (soft upper mantle) at plate-spreading centers (Kennedy and others, 1987; Craig, 1990, 1997; Farley and Neroda, 1998), (3) a track defined by migrating volcanism and faulting closely matching motion of the North American plate in both rate and direction, (4) a major positive geoid anomaly that centers on Yellowstone and extends about 200 km (125 mi) "ahead" of Yellowstone, and is about 800 km (500 mi) across at Yellowstone (Smith and Milbert, 1999), reflecting an origin deeper than the crustal processes centered on Yellowstone (see fig. 10), (5) a pattern where uplift occurs well in advance of volcanism, indicating that upwelling is caused by deep-seated processes and is not in response to plate-interaction processes such as faulting, and (6) the start of the hotspot track with an inferred large diameter plume head that implies a deep vertical dimension.

[3]As mantle material (density ~3.3 g/cm^3) rises towards the surface, decompression melting (White and McKenzie, 1989) yields 10 percent or so basaltic magma (density ~3.0 g/cm^3) that ascends into the base of the crust (density <3.0 g/cm^3). As the basaltic magma pushes into the lower crust, heat from the molten basalt melts crustal material to form siliceous magmas, which have a lower melting temperature and density than basaltic magma. Meanwhile, down in the mantle, the material remaining (restite) after the basaltic partial-melt has risen upward also becomes lighter (density also roughly ~3.0 g/cm^3). The resultant hotspot uplift has three possible origins: (1) the higher temperatures, and therefore lower density, of the plume material and the heated crust, (2) the formation of two lower density materials (basalt and restite) from the higher density mantle source, and (3) possible thermal erosion of high-density mantle lithosphere (density ~3.3 g/cm^3) by hotter, lower density mantle material.

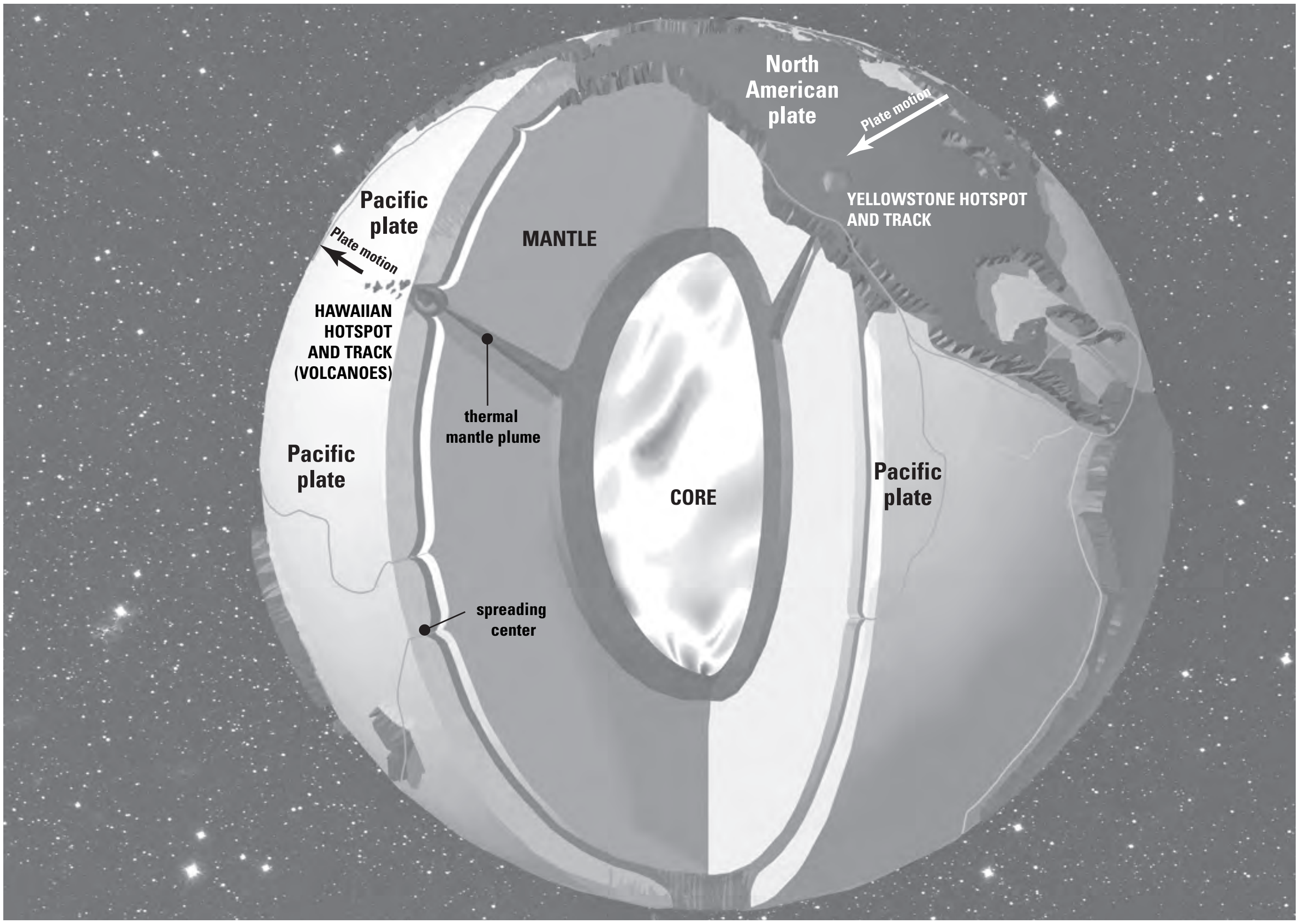

Figure 5. Illustration showing the hypothesis that a deep-seated mantle plume originating from excess heat at the core-mantle boundary drives the Yellowstone hotspot. Some researchers suggest a shallower mantle source with upwelling of the plume from a depth of near 600 km (400 mi) to produce the hotspot track. (From Good and Pierce, 1996.)

scale of hotspot-related geologic features, is an essential argument that a deep-seated geologic process is at work.

The Yellowstone Plateau, at about 2,450 m (8,000 ft) altitude, resulted from hotspot volcanism and probably also hotspot uplift (fig. 4). Key geologic features of the plateau are its rhyolitic lava flows, rhyolite tuffs (ignimbrites), and its famous geysers and hot springs. Both the plateau and surrounding mountains are snow covered much of the year and are too cold for profitable agriculture. For example, at an altitude of 2,750 m (9,000 ft), snow cover lasts three-fourths of the year (Despain, 1990, p. 127).

Some geologists favor shallower processes in the upper mantle to explain the origin and maintenance of the hotspot (see Christiansen, 2002; Humphreys and others, 2000). Although figure 5 is helpful in visualizing the idea of a thermal plume, we do not think that the depth of the thermal upwelling (deep plume, shallow upwelling) driving the hotspot is critical to the topic of this paper. What is important is that Yellowstone hotspot processes, whatever their depths of origin in the mantle, are responsible for the *Earth-surface processes* of volcanism, geothermal activity, faulting, and uplift[4].

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[4]Hotspots, and particularly what drives them, are controversial and actively under investigation. The hotspot idea was introduced by J.T. Wilson (1963) for the Hawaiian Island chain, for which he suggested that the Pacific plate was moving across a stationary heat source in the mantle, later termed a mantle plume. Hotspot tracks define the hotspot reference frame for global plate motions. For the numerous moving plates, this hotspot reference frame has proven quite successful for solving the absolute motion of each plate. This suggests that, to a first approximation, hotspots have a source fixed in the relatively stationary mantle. Duncan and Richards (1991) give a comprehensive overview of hotspots around the world, their origin by mantle plumes, and relationship to flood-basalt volcanism. In his 1997 presidential address to the Geological Society of America, George Thompson (1998) emphasized the importance of hotspots and mantle plumes in the geologic record, including their need to be integrated with the modern plate-tectonic scheme. Norm Sleep (1990, 1997, 2002) concluded that hotspots are driven by deep mantle plumes, and with Thompson and Gibson (1991) noted that the thinner the lithosphere, the higher the rise of plume material and the more decompression melting and magma production occurs. Two recent volumes (Davies, 1999; Jackson, 2000) develop attributes and concepts of deep-mantle plumes.

In the anti-plume camp, Don Anderson (see 1998 and references therein)

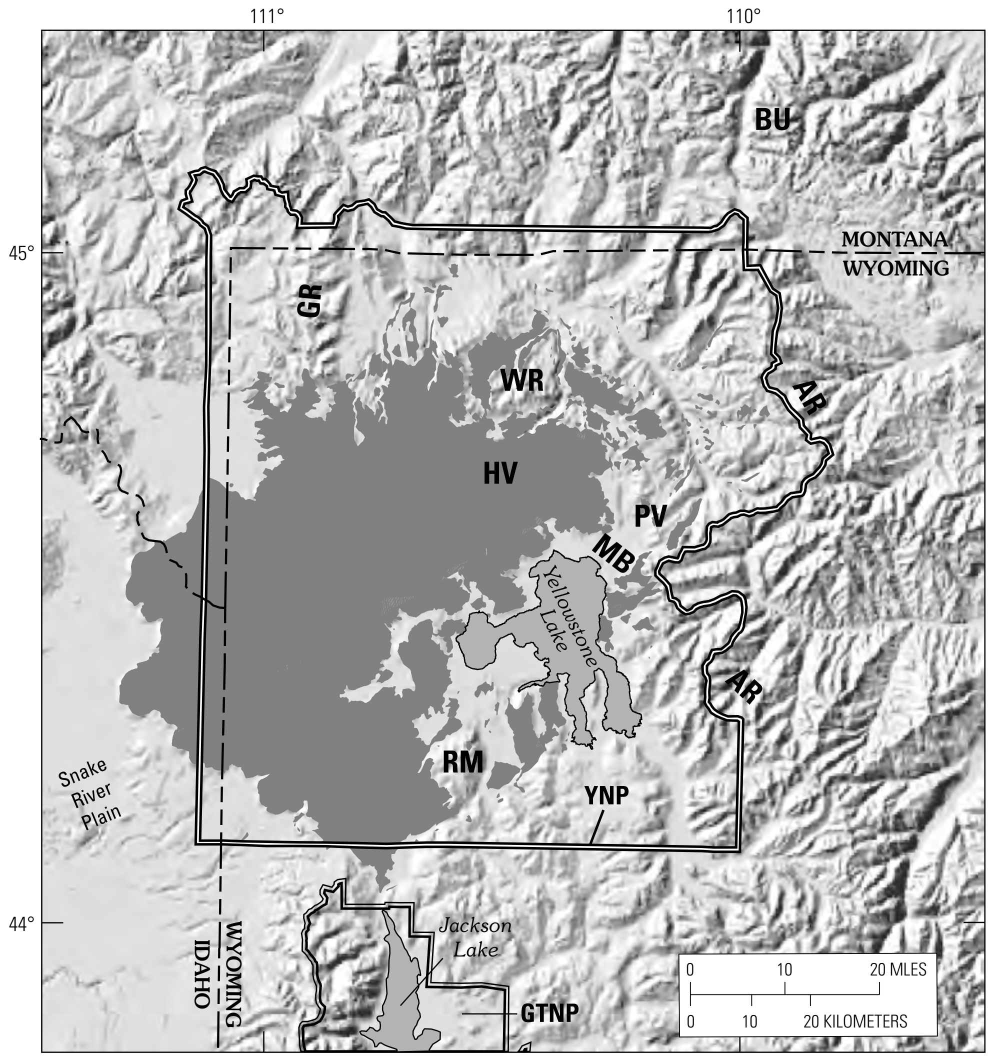


Figure 6. Rhyolite area (darkest shade) that forms the Yellowstone Plateau in the core of the greater Yellowstone ecosystem. Rhyolite has only one-fourth the nutrients of andesite—a volcanic rock intermediate between rhyolite and basalt. Rhyolite forms well-drained sandy soils with snowmelt infiltrating down to several meters. Lodgepole pine is well adapted to grow on the rhyolite soils, whereas spruce fir forests grow on other bedrock types such as (1) andesite in the Washburn Range (WR) and Absaroka Range (AR), (2) mixtures of sedimentary rocks (shale, sandstone, and limestone) in the Gallatin Range (GR) and Red Mountains (RM), (3) a variety of Precambrian rocks in the Beartooth Mountains uplift (BU), and (4) surficial materials from all of the previously mentioned rock types. Other locations on map are Hayden Valley (HV, where lake sediments overlie the rhyolite), Pelican Valley (PV), Mary Bay (MB), Yellowstone National Park (YNP), and Grand Teton National Park (GTNP).

Ecological Effects of the Yellowstone Hotspot

The Yellowstone hotspot theory provides a unifying concept for an understanding of how Earth processes have influenced ecology, human history, and cultural patterns of the greater Yellowstone ecosystem. In the following sections, we discuss how salient aspects of the GYE are related to the hotspot-associated processes of volcanism, active faulting, and uplift. Although we discuss uplift last, it has had the most profound effect on the ecosystem and has been the controlling factor determining human geography.

and Warren Hamilton (2003) have argued strongly against the mantle-plume explanation of hotspots and particularly the idea of deep-seated mantle plumes. Foulger and Natland (2003) question deep mantle plumes and with Don Anderson convened a conference in 2003 looking for non-plume explanations for hotspots (see www.mantleplumes.org).

Recent papers supporting plumes include Courtillot and others (2003), who present evidence for three types and depths of mantle plumes. Using seismological analysis involving new wave-front techniques, Montelli and others (2004) identified more than thirty mantle plumes, about one-third of which are identified as originating at the core-mantle boundary.

Two seismic tomography studies conclude that a thermal mantle plume is inferred inclined to the northwest from Yellowstone at ~20° from vertical and extends to a depth of about 500 km (Yuan and Dueker, 2005; Waite and others, 2006). A relation may exist between the inferred plume and the asymmetric pattern of faulting and uplift. Faulting and uplift associated with the Yellowstone hotspot track flares outward ~1.6 times farther to the south than to the north of the volcanic track (Pierce and Morgan, 2005). Both this asymmetry and the southeast upward rise of the Yellowstone plume might be explained by upper mantle flow (mantle winds) as modeled to the east by Steinberger (2000) or most concordantly to the southeast (Bernhard Steinberger, written commun., 2005, Berkeley model).

Rhyolite, Hotspot, and Lodgepole Pine

At an altitude of about 2,500 m (8,000 ft), the Yellowstone Plateau forms the core area of Yellowstone National Park. The plateau was built up by extrusion of rhyolitic volcanic rocks produced by hotspot volcanism (figs. 6 and 7) (Christiansen, 1984, 2001; U.S. Geological Survey, 1972b). Two distinct types of rhyolite are present: (1) relatively viscous lava flows originally emplaced with an irregular upper surface and steep flow margins 100 m or more high (hundreds of feet) (figs. 7*A*, 7*B*, 7*C*, 7*E*, and 7*F*), and (2) ash-flow tuffs (ignimbrites) emplaced by hot, incandescent, gas-rich, very fluidized pyroclastic flows that came to rest with nearly planar original upper surfaces.

Figure 7. RHYOLITE. Suite of six photographs (figs. 7A–7F) showing landscapes with forests of lodgepole pine developed on hotspot-generated rhyolite of the Yellowstone Plateau and two photographs (figs. 7G and 7H) showing contrasting vegetation in non-rhyolite areas. The rhyolite/lodgepole landscape of the Yellowstone Plateau relates directly to hotspot volcanism. The lodgepole pine forest and its sparse understory are practically an ecological desert that forms most of the central part of Yellowstone. The rhyolite bedrock favors a lodgepole forest because rhyolite is both poor in nutrients and has well-drained sandy soil and sub-soil so that much of the snowmelt infiltrates deeper than 30–50 cm (1–2 ft) and probably much of the snowmelt percolates below root depth.

A, View across the Yellowstone rhyolite plateau built up to an altitude of 2,500 m (8,000 ft) and forested with lodgepole pine.

B, Lodgepole pine forest on rhyolite—an ecologically challenged landscape.

C, Obsidian Cliff. Native Americans extensively quarried this rhyolite flow for obsidian.

D, Lodgepole pine forest that was burned in 1988 on the Obsidian Cliff rhyolite flow.

E, Lewis River incising the hotspot-built constructional Yellowstone rhyolite plateau.

F, Grand Canyon where Yellowstone's largest river has cut deepest into the constructional rhyolite plateau.

The rhyolite plateau is remarkably gently sloping (fig. 7A) except for steep flow fronts and incised scenic canyons. The plateau was built up by volcanic tuffs and lava flows emplaced on top of the original landscape. Streams developed steep gradients where they flowed off the edge of the plateau and cut canyons deep into its edge. The main rivers of Yellowstone have incised canyons deep into the margins of the plateau, creating part of the scenic grandeur of Yellowstone (figs. 7E and 7F). The largest and most powerful river, the Yellowstone, has cut the farthest back into the plateau (30 km, 18 mi) to form Yellowstone's Grand Canyon.

The Yellowstone rhyolite plateau is covered by vast expanses of lodgepole pine forest, which are commonly difficult to walk through because of crisscrossed down timber (figs. 7B and 7D). The lodgepole forests on the nearly flat rhyolitic plateau are considered by many to be the least scenic features of the GYE. The lodgepole forests might be considered ecologically challenged because of their monotonous appearance, low biodiversity, and limited wildlife habitat. C.C. Parry (1874, p. 179), a botanist on the William Jones expedition to northwestern Wyoming in 1873, commented that lodgepole pine forests covered vast expanses of the park and would forever be associated with the monotony of the Yellowstone Plateau:

"Not less than ninety-nine per cent of the pine growth of this district is made up of the single species, *Pinus contorta*…. Mile after mile of continuous forest may be traversed without seeing any other arborescent species, and their tall, straight, uniform trunks and scattering foliage will be always associated with the monotonous and disagreeable features of the park scenery. Only where the blazing campfire sends forth its grateful warmth to relieve the ordinary chill of a night temperature, where the thermometer in August ranges between 36°F. and 14°F., do we realize a manifest utility in this widespread forest production."

In contrast, adjacent areas on basaltic or andesitic volcanic rocks, sedimentary rocks, and Precambrian crystalline rocks have an entirely different vegetation composition and distribution pattern. Such non-rhyolitic rocks support a combination of forest and grassland. Forests are typically of Engleman spruce, subalpine fir, whitebark pine, or Douglas fir and patches of lodgepole pine. Highly productive grasslands, sagebrush steppes, or meadows typically occur on glacial and other fine-grained surficial deposits and form important habitat for elk, bison, deer, and bears. Talus accumulations below cliffs—essential habitat for marmots and pikas, lichen communities, and local congregations of moths eaten by grizzly bears—are also common on the steeply sloped andesite, sandstone, and Precambrian rock areas.

Why does the geologic substrate so markedly delineate species distributions? Soils developed on rhyolite are sandy and contain little clay or nutrients (Trettin, 1986; Rodman and others, 1996). Despain (1990, p. 141) estimates that, overall, soils on rhyolite have only one-fourth the plant nutrients of soils on andesitic volcanic rocks. Lodgepole is well adapted to the very limited nutrients available from rhyolite. It is not, however, very shade tolerant and is easily out-competed by more shade tolerant trees where soil moisture and nutrients are adequate for their growth. Compared to nearly all other bedrock types, soils derived from rhyolite are better drained and retain less water, favoring the growth of lodgepole over other conifers. Because rhyolite soils drain so rapidly, the large amount of water released by melting the thick snowpack on the Yellowstone rhyolite plateau rapidly percolates downward through thin, sandy soil into permeable rhyolite bedrock in which high permeability was developed from fracturing during initial cooling and thermal contraction. For example, the Pitchstone Plateau receives approximately 1.8 m (70 in) of annual precipitation (Farnes, 1977), mostly as snowfall. In spite of this high precipitation, few permanent streams or lakes are present, and a considerable portion of the surface water enters the deep ground-water system and thus becomes unavailable to plants. However, hundreds of feet lower at the base of the rhyolite flows, ground water emerges to form a nearly continuous band of swamps and springs (Benjamin, 2000).

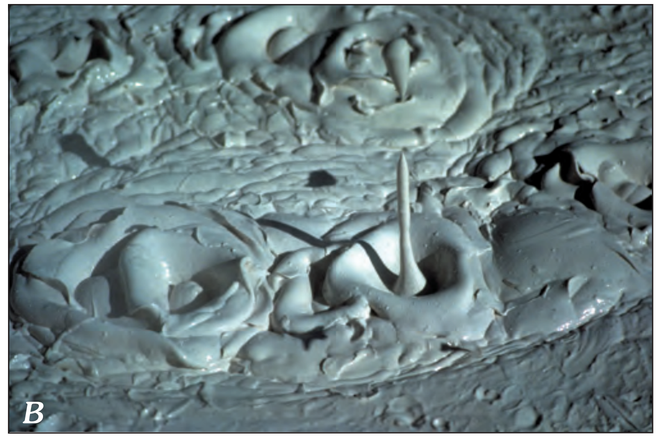
Table 1 shows the three main types of volcanic rocks and their salient attributes including their typical vegetation at the altitude of the Yellowstone Plateau.

G, Hayden Valley—a meadowy enclave on fine-grained lake sediments surrounded by lodgepole forests on rhyolite.

H, Non-rhyolitic area in southern Teton Range with soils that hold moisture well and support lush vegetation.

Figure 8. THERMAL FEATURES. Photographs of hot springs, geysers, and other thermal features driven by hotspot heat, whose abundance, character, and uniqueness were the primary reasons for the establishment of Yellowstone as the world's first national park. Yellowstone is the world's largest and most energetic geothermal field. In photograph credits, NPS is for National Park Service photographs in collection at Yellowstone National Park.

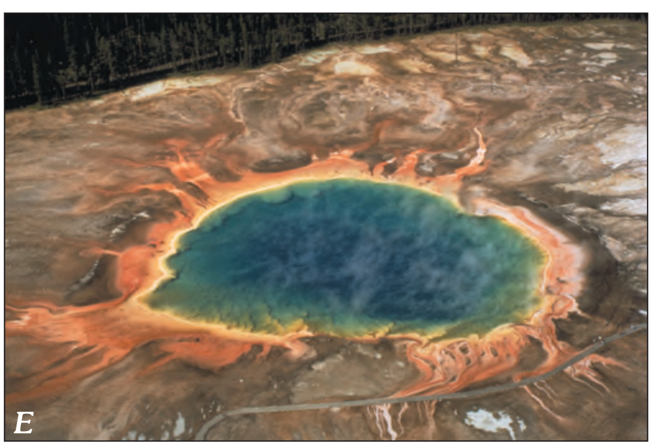
A, Steamboat Geyser in full eruption to a height of about 100 m (300 ft) in Norris Geyser Basin. Photograph from NPS.



B, Mud Pots. Mud is formed by acid alteration of rhyolite. Photograph from NPS

C, Castle Geyser in Upper Geyser Basin. Photograph from NPS.

D, Excelsior Pool in Middle Geyser Basin. Painting by Thomas Moran.



E, Grand Prismatic Spring in Middle Geyser Basin. Note boardwalk for scale. Photograph from NPS.

F, Mary Bay of Yellowstone Lake, formed by hydrothermal explosion(s). W.H. Jackson photograph (1871).

Table 1. Characteristics of the three main types of volcanic rocks found in the greater Yellowstone ecosystem.

Attribute	Rhyolite	Andesite	Basalt
Color	Light colored, pastels; local black obsidian	Medium colors; weathers brown	Dark gray, weathers reddish brown
Chemistry	Rich in silica; nutrient poor	Intermediate; nutrient rich	Rich in iron and magnesium; nutrient rich
Vegetation	Lodgepole forest, sparse understory	Mixed conifer forest and meadows	Mixed conifer forest and meadows
Geological setting	Melting of crust; hotspots(?)	Above subduction zones	Derived from partial melting of mantle

As the summer progresses, the upland rhyolite areas and their lodgepole forests become generally dry earlier than adjacent areas on non-rhyolite substrates where soils are deeper and contain more fine-grained materials (silt, clay, and organic matter). However, because lodgepole forests on rhyolite have little or no understory of spruce and fir, the return interval for fires in lodgepole is 350–400 years, longer than for lodgepole on andesite (Despain, 1990). Only an unusual combination of conditions leads to spectacular, crown-transmitted forest fires. Conditions necessary for extensive crown fires in lodgepole forests on the rhyolite plateau include (1) mature lodgepole forests, (2) development of local understory, (3) an extended period of drought, (4) ignition by lightening or human, and (5) perhaps most important, strong, persistent winds. This combination of conditions occurred in 1988 when fires burned a third of the Park during a hot, dry summer with strong, persistent winds (fig. 7D). The main difference between fires in lodgepole on rhyolite and other forest fires is this long return interval.

Hayden and Pelican Valleys are highly productive meadow communities, yet they lie within the Yellowstone rhyolite plateau (fig. 6). Even though these two valleys are flanked by rhyolite flows, the floors of the valleys consist of a thick blanket of fine-grained glacial lake and other sediments (U.S. Geological Survey, 1972a) that have sufficient water-holding capacity and nutrients so to favor herbaceous meadowlands. During Pleistocene glacial buildup and recession, damming by glaciers created lakes in which fine sediment relatively rich in nutrients was deposited. Bison, elk, grizzly bears, and trumpeter swans inhabit these valleys and thrive on this diverse and productive plant community. Whereas on the surrounding rhyolite bedrock, abundant wildlife cannot be sustained by the lodgepole pine forest growing in the sandy, well-drained and nutrient-poor rhyolite. But red squirrels, pine martins, and chickadees may be present.

Although limited in vegetative diversity, the rhyolite plateau was important to Native Americans because it provided high quality obsidian for tool making. Located between Mammoth and Norris Junction, Wyo., the Obsidian Cliff and nearby Spring Creek rhyolite flows supplied an essentially inexhaustible supply of high-quality obsidian to Native Americans (fig. 7C) (Davis and others, 1995). Locally the top of this flow is blanketed with a layer of obsidian chips produced centuries ago as Native American craftsmen prepared chunks of obsidian called bifaces for transport and trade out of the area. This obsidian was traded across North America; 15-cm (6-in) ceremonial blades from Obsidian Cliff have been identified in the mound builder culture in the State of Ohio (Griffin and others, 1969).

G, Mammoth Hot Springs with "terraces" of travertine (calcium carbonate). W.H. Jackson photograph (1871).

H, Site of geothermal well, across Yellowstone River from La Duke Hot Spring (in foreground).

[5]Some of the thermal waters of Yellowstone have exceptionally high values of $^3He/^4He$, commonly expressed as multiples compared to this ratio in the atmosphere. Values of about 16 times the atmospheric ratio have been obtained from thermal springs in Yellowstone (Kennedy and others, 1987; Craig, 1997). These high values contrast with maximum values of about 8 that are typical of mid-ocean spreading centers between tectonic plates where the helium source is in the upper mantle (Craig, 1990; Farley and Neroda, 1998) and support a deep-mantle-plume origin of the Yellowstone hotspot.

Thermal Features and Associated Ecosystems

The most dramatic and directly observable manifestations of the Yellowstone hotspot are Yellowstone's hot springs and geysers (fig. 8) (Fournier, 1989), whose attractiveness and uniqueness were the primary reasons for the establishment of Yellowstone as the world's first national park. Helium isotope studies suggest these geothermal features are driven from a heat source deep in the Earth's mantle.[5]

Almost all the active thermal areas lie within or near the margin of the 640,000-year-old Yellowstone caldera, which is 70 by 45 km (45 by 25 mi) in area (fig. 4, white ellipse at NE. end) (Christiansen, 1984, p. 92; Christiansen, 2001; Fournier, 1989). The main exception is the Norris-Mammoth corridor (White and others, 1988), which extends from the northern caldera margin near Norris 27 km (17 mi) north to Mammoth Hot Springs (fig. 8G) and perhaps 10 km (6 mi) farther north to La Duke Hot Springs along the Yellowstone River (fig. 8H).

The heat flow from the area underlain by the Yellowstone caldera is about 50 times greater than the continental mean.[6] Heat from deep magma, associated hot fluids, and hot rock drives the many geothermal features of Yellowstone, the world's largest and most energetic geothermal field.

Heat is also an essential component of hydrothermal explosions that have left craters surrounded by aprons of ejected material. Along the north shore of Yellowstone Lake (fig. 6), Mary Bay is a depression 3.5-km (2-mi) across formed by one or more large hydrothermal explosions with a main one erupting about 13,000 years ago (fig. 8F) (Pierce and others, 2002, this volume; Morgan and others, 1998). Smaller hydrothermal explosions are common in the geyser basins. In 1989, an explosion of Pork Chop Geyser blew out the upper part of the geyser system and hurled blocks of hydrothermal material (siliceous sinter) 60 m (200 ft). Such explosions probably formed deep, funnel-shaped pools such as Morning Glory Pool in Upper Geyser Basin (see fig. 18I later in this report) and Excelsior in the Middle Geyser Basin (fig. 8D). The hydrothermal-explosion craters now commonly form lakes or wetlands in steep-sided, protected basins that create warm niches for waterfowl and other organisms.

Yellowstone's thermal features provide habitat for a group of amazing organisms that were relatively unappreciated until life was discovered in thermal vents along the mid-ocean ridges, and a closer look at thermal microorganisms was undertaken (see Varley, 1993). This led to discovery of bacteria from Yellowstone hot springs that made possible the polymerase chain reaction (PCR)—the process used to identify DNA material. PCR subsequently revolutionized the study of biology, because it makes possible the rapid multiplication of genetic material so it can be analyzed. PCR also made possible a new look at the molecular level of living organisms, and thereby helped to restructure what is known about the Earth's earliest life and subsequent evolution. Significantly, many of the species that inhabit the thermal waters of the Park are close relatives of those first living organisms (Woese and others, 1990; Pace, 1991).

A thermal zonation follows the temperature gradient downflow from the thermal springs and pools, creating much of the vivid sequence of colors that enliven the outflow channels. The extreme thermophiles, including white bacteria, are nearest the vent at temperatures that are at or near the boiling point of water at this altitude. As the water cools, the white bacteria give way to yellow or orange microorganisms that, in turn, yield to green algal-bacterial mats. Whole miniature ecosystems occur along these channels. Mats of algae and bacteria form organic mats that are fed on by other organisms, including fly larvae. Spiders, predatory flies, and other predators feed on the larvae and adult flies (Brock and Brock, 1971). Nutrient-rich runoff from hot springs keeps some streams, such as the Madison River, warmer year-round and enhances the fishery. In addition to the algae and bacteria, large animals such as elk and bison inhabit the thermal areas in winter where the snowpack is thin or absent. Massive bison skulls in remote thermal areas mark the winterkill of some bison.

Fault Valleys and Adjacent Mountains Associated with Hotspot Faulting

Basin-and-range faulting has accompanied migration of the hotspot to Yellowstone and has formed the linear mountains and valleys that flank the north and east sides of the hotspot track delimited by the eastern Snake River Plain (figs. 1 and 4). The most active faults generally form the most prominent ranges and valleys; they define belt II that extends both southward and westward from Yellowstone (fig. 4, belt II). During the last 10 million years, as the hotspot migrated to the northeast, the most active faults were immediately adjacent to the caldera-forming hotspot volcanism. As the hotspot activity migrated farther northeast, the locus of faulting migrated in a bow-wave fashion farther outward from the hotspot track to form the present two belts that extend south and west from Yellowstone (Anders and others, 1989; Pierce and Morgan, 1992; Smith and Braile, 1993; Anders, 1994). The GYE includes only a small part of the basin-and-range, but along the hotspot track, high rates of basin-and-range faulting accompany the northeast migration of hotspot volcanism to its present position (Anders and others, 1989; Pierce and Morgan, 1992; Anders, 1994).

The western band of faulting (fig. 4) includes the 1959 Hebgen Lake earthquake (fig. 9B, magnitude 7.5) and the 1983 Borah Peak earthquake (fig. 9G, magnitude 7.3). Repeated such earthquakes and associated offsets have resulted in lowering the valleys and uplifting the adjacent ranges to form, respectively, the West Yellowstone Basin

[6]Irving Friedman (oral commun., 1999, and this volume) concluded that convective heat flow from Yellowstone to be 4.9×10^{16} cal/yr, as determined by the chloride content of rivers flowing from Yellowstone. This value is 22 percent higher than the 4.0×10^{16} cal/yr previously estimated (Fournier, 1989). Friedman's value converts to a heat flow of about 2,900 mW/m^2 for the 2,500-km^2 area of the Yellowstone caldera. The Yellowstone caldera's heat flow of 2,900 mW/m^2 is 51.2 times the continental mean of 56.6 mW/m^2 (Turcotte and Schubert, 1982).

and Madison Range, and the Thousand Springs Valley and the adjacent Lost River Range. The southern band of faulting extends south from Yellowstone toward the Wasatch fault near Salt Lake City, Utah, and includes the coupled basin-and-range faulting of Jackson Hole-Teton Range just south of Yellowstone (fig. 9A). Within Yellowstone National Park, this southern band includes the basin-and-range faulting between Heart Lake and Red Mountains (fig. 9E and 9F), where postglacial fault scarps are 25-m (90-ft) high (Pierce, 1979; structure number 766 in Machette and others, 2001). At any position along faults in the most active parts of these two belts, major offsets and associated earthquakes occur about every several thousand years.

In summary, basin-and-range faulting associated spatially and temporally with the Yellowstone hotspot forms distinctive landscapes within the GYE, with characteristic linear, rugged, forested ranges and adjacent flat-floored, grassy valleys. The valleys are the sites of accumulation of sediment, including glacial outwash gravels and alluvial fans. The adjacent mountains are characterized by steep slopes that are eroding by slope wash and mass wasting. To the west from Yellowstone are the following basins and ranges in the GYE: southern Madison Range/West Yellowstone basin (fig. 9B), Madison Range/Madison Valley (fig. 9D), Centennial Range/Centennial Valley (fig. 9C), and Lemhi Range/Little Lost River valley (fig. 9G). To the south are Mount Sheridan/Heart Lake (figs. 9E and 9F), Teton Range/Jackson Hole (fig. 9A), and Snake-Salt River Ranges/Star and Grand Valleys. The large difference of altitudes present in the basins and adjacent ranges is integral to the subsequent ecosystem that developed here providing a year-round environment for elk, bison, and other animals through annual migrations. The valleys provide nearly snow-free winter ranges with dried grasses in winter and lush green grass in spring, whereas the ranges provide lush grass all summer.

Cold, Snowy Climate and Rugged Mountains Enhanced by Hotspot Uplift

The most important effect of the Yellowstone hotspot on the GYE has been the consequence of uplift on altitude, climate, topography, ecology, and human geography. Deep winter snows, steep mountain slopes, lush mountain meadows, cool trout streams, and shady coniferous forests are characteristic of the GYE (fig. 10).

Uplift is a difficult geologic process to prove. The idea of geologic uplift in various parts of the world in the last few millions or tens of millions of years has been challenged by Molnar and England (1990) on the basis that such rapid changes in the isostatic balance of the lithospheric plate (crust plus mantle lithosphere) are geophysically unreasonable unless there is a clear driver for such lithospheric modification. They argue that evidence for uplift such as valley incision may be caused by accelerated stream erosion produced by Pleistocene glacial and climatic conditions. While this may hold true for many young mountains and plateaus elsewhere in the world, numerous indicators suggest that geologic uplift in Yellowstone is a very recent phenomenon, is ongoing, and is driven by a deep-seated process of probable mantle origin.

Pierce and Morgan (1992, p. 19–30) discuss in detail the following factors that support the argument for uplift of the GYE:

1. The present Yellowstone crescent of high terrain (fig. 4).
2. Evidence for uplift in swells associated with other hotspots, particularly oceanic ones where anomalies in sea-floor altitude can be estimated.
3. The present altitude of rhyolite tuffs (ignimbrites) from the Yellowstone Group in the crescent of high terrain a thousand meters (thousands of feet) above the altitude of their source calderas.
4. Historic uplift measured along level lines across the Yellowstone crescent of high terrain.
5. High, rugged mountains formed from easily erodible rocks such as the Absaroka Volcanic Group and Mesozoic sandstones and shales (figs. 10B and 10D).
6. Basalt flows dated at 3 Ma on high upland erosion surfaces incised by young, steep-sided stream valleys 1,000-m (3,000-ft) deep (fig. 10C).
7. Ratios of the lengths of glaciers during the last glaciation compared to those of the next-to-last glaciation suggesting uplift on the leading margin of the Yellowstone crescent of high terrain, and subsidence on the trailing margin during the last 140,000 years.
8. Tilting of stream terraces away from Yellowstone (fig. 11, after Jaworowski, 1994).
9. Lateral migration of stream courses away from Yellowstone.
10. On the leading margin of the Yellowstone hotspot, migration of inflection points between convergent/divergent terraces at a rate similar to the hotspot migration rate.
11. Calcic soils apparently uplifted above their present altitude of formation.
12. Perhaps most important, the major positive North America geoid anomaly that centers on Yellowstone (fig. 12) (Milbert, 1991; Smith and Milbert, 1999) indicates that a deep-seated process beneath the GYE is responsible for the scale, amplitude, and uplift of the Yellowstone crescent of high terrain.[7]

[7]This geoid anomaly is comparable to that of oceanic hotspots in amplitude and breadth (Pierce and Morgan, 1992; Pierce and others, 1992; Smith and Braille, 1993). The compensation depth for the geoid is deeper than that for the regional topography or the associated Bouguer gravity (geoid, approximately 100(?) km; Bouguer gravity and regional topography, approximately 30–40 km).

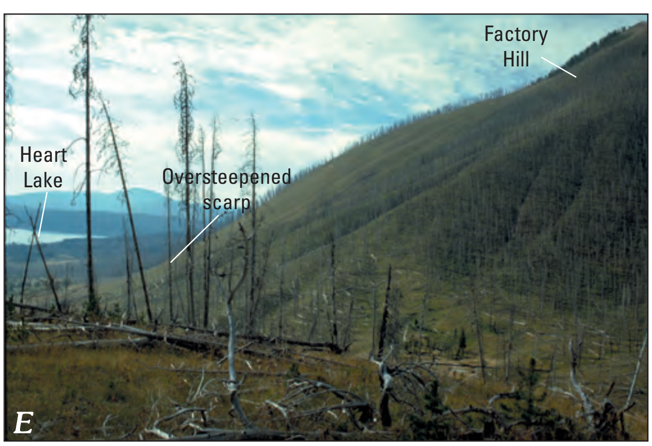
Figure 9. FAULTING. Active faulting associated with the Yellowstone hotspot created basins and ranges. The ranges have high mountains with steep valley walls, and are covered by a mosaic of forests, meadows, and sparsely vegetated talus below rocky cliffs. The basins have flat floors underlain mostly by gravel and other surficial deposits and form grasslands.

A, Teton fault scarp near foot of Teton Range. Postglacial offset is 18 m (60 ft).

B, Hebgen Lake fault scarp partly formed during the 1959 earthquake.

C, Oversteepened slopes on the Centennial fault that created the Centennial Range and Centennial Valley.

D, The Madison Valley (foreground) and Madison Range (distance) were formed by offset on the range-front fault.



E, Faulting on the East Sheridan fault has oversteepened the lower part of Factory Hill and formed the Heart Lake basin.

F, Fissure Group hot springs are aligned along the East Sheridan fault that offsets postglacial deposits 9.6 m (32 ft).

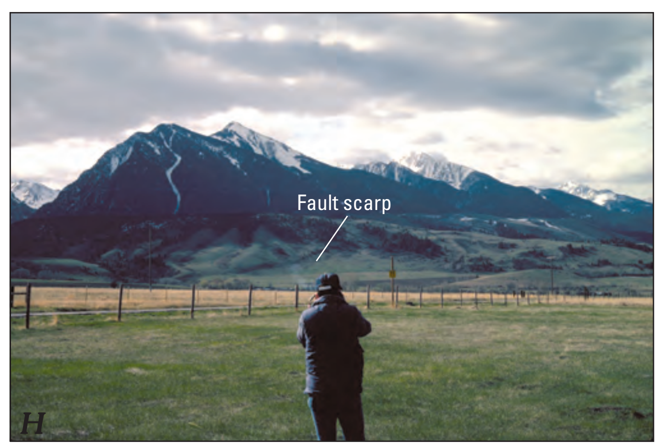
The GYE forms the headwaters of 25 rivers and large drainages, and the Continental Divide traverses the GYE. This topography gives further support to the idea that the GYE is a topographic culmination (see fig. 19 later in this report; table 2). Studies of leaf morphology of a 45-million-year-old site (Eocene) within the GYE indicate the area has been uplifted by about 900 m (3,000 ft) since Eocene time (Wolf and others, 1998). Based on identification of white mangrove (*Terminalia*) and red mangrove (*Rizopora*) pollen or leaves in Eocene rocks (Fritz, 1980; Bill Fritz, written commun., 1999), the lowest parts of the Yellowstone area 45 million years ago *may* have been in salty water at sea level after the Laramide orogeny affected the area.[8] If so, uplift to the present altitude of more than 2,500 m (8,000 ft) has occurred since 45 million years ago, with perhaps about 900 m (3,000 ft) of this uplift associated with the Yellowstone hotspot.

Many salient ecological characteristics of the GYE relate to and are enhanced by this hotspot-induced uplift. Uplift of lower, more subdued pre-hotspot terrain has produced the moderate to high altitudes and associated cool temperatures, deep snowfall, and cool summers. The projection of a large mountain mass into the atmosphere intercepts moisture and creates cooler air temperatures and a markedly snowier climate. If this uplift had not occurred, mountains such as the present Beartooth uplift might look more like the Black Hills do today; the present Absaroka Range might look more like a dry, short-grass prairie like eastern Montana and Wyoming. Instead, the Yellowstone Plateau and the surrounding mountains are covered with forests of Douglas fir, lodgepole pine, Engleman spruce, subalpine fir, and whitebark pine, adapted to higher and wetter environments. Interspersed in the forests are mountain meadows of Idaho fescue, bearded wheatgrass and other grasses, and wildflowers (Despain, 1990). This

Table 2. Rivers and other large drainages that head in the greater Yellowstone ecosystem, listed clockwise from the Yellowstone River (fig. 19).

River	Towns associated with drainage
Yellowstone River	Gardiner, Livingston, Big Timber, Columbus, Laurel, Billings
Lamar River	–
Boulder River	Big Timber
Stillwater River	Nye, Columbus
Rosebud Creek	Absarokee
Rock Creek	Red Lodge
Clarks Fork	Clark, Bridger, Laurel
Shoshone River	Cody, Powell, Lovell
Greybull River	Meeteetse, Greybull
Wind River-Bighorn River	Dubois, Riverton, Thermopolis,
Owl Creek	Thermopolis
Green River	Big Piney, Green River (south of fig. 19)
Gros Ventre River	Kelly, Jackson (near)
Buffalo Fork	–
Snake River	Moran, Wilson, Idaho Falls
Hoback River	Bondurant
Greys River	–
Salt River	Afton
Teton River	Driggs, Rexburg (near)
Falls River	Ashton (near)
Henrys Fork	Macks Inn, Ashton (near), St. Anthony
Camas Creek	Kilgore
Red Rock River	Lakeview (near)
Madison River	West Yellowstone (near), Ennis, Three Forks
Gallatin River	Gallatin Gateway, Bozeman (near), Three Forks

G, Scarp formed by 1983 Borah Peak earthquake (magnitude 7.3). Such faulting eventually created a basin (left) and range (right).

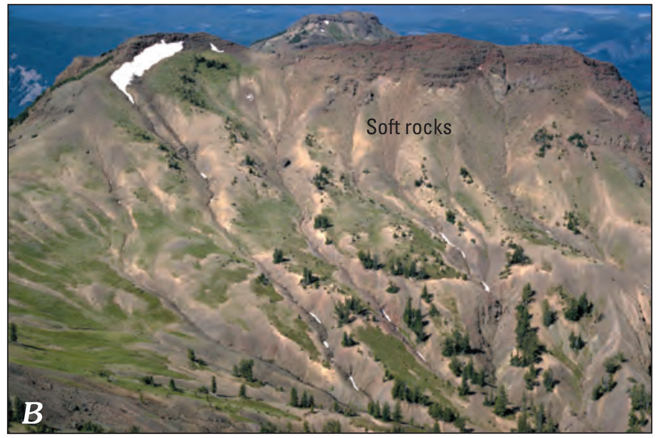


H, Range-front fault downdropping the Paradise Valley (foreground) and uplifting the Beartooth uplift (distance).

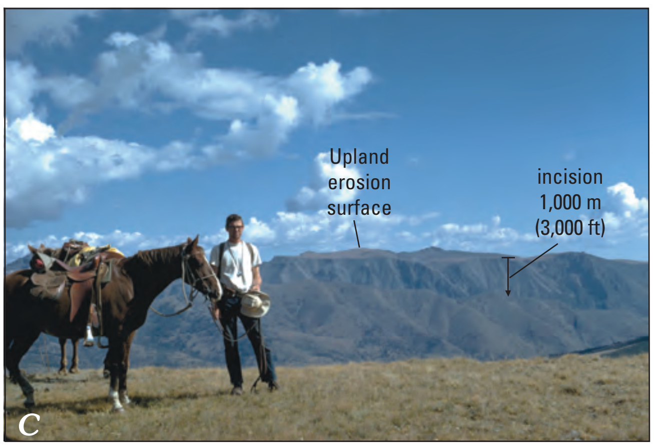
[8]Such uplift would have occurred after the Laramide orogeny, which climaxed about 70–50 million years ago, had produced uplifts such as the Beartooth Mountains and Wind River Range, and these uplifts had been eroded to more subdued mountains. Locally in the GYE, these Eocene Absaroka Volcanic Supergroup rocks were deposited across these Laramide thrusts and not subsequently offset by faulting. The possibility of mangrove trees in this region needs further study. For example, Scott Wing (written commun., 1999) has reservations about both the mangrove identification and consequently the sea-level altitudes in the Yellowstone area.

Figure 10. UPLIFT. High, eroding mountains of the Yellowstone crescent of high terrain are related to hotspot uplift. Uplift accompanied by erosion has carved deep valleys with steep valley walls. These steep slopes are subject to high rates of erosion, especially in readily erodible rocks such as the volcanic rocks of the Absaroka Volcanic Supergroup along the eastern Yellowstone boundary and in Mesozoic sandstones and shales south of the eastern part of Yellowstone.

A, Deep snows in the greater Yellowstone area along the Beartooth highway. Photograph from NPS.



B, High mountains formed by readily erodible rocks of the Absaroka Volcanic Supergroup along Yellowstone's eastern boundary.



C, Upland erosion surface (foreground and distance) incised by valleys 1,000 m (3,000 ft) deep in the volcanic rocks of the Absaroka Volcanic Supergroup.

D, Soft, easily erodible Cretaceous shale and sandstone uplifted to form high terrain (3,000 m; 10,000 ft) in southern Yellowstone.

E, High, steep valley walls in the southern Gallatin Range. Spruce fir forest broken by meadows and avalanche chutes.

F, Prickly pear cactus flower near Gardiner, Mont., in deep, dry valley eroded by glacial and stream processes.

vegetation mix provides summer pasture for herds of ungulates and their young that thrive on the grasses flourishing in the cool, moist meadows. The winter snows feed clear, cold streams where abundant algae feed numerous species of insect larvae that feed large populations of trout. These animals and numerous smaller mammal species provide food for grizzly bears, black bears, coyotes, wolves, mountain lions, bald eagles, golden eagles, osprey, and a host of other predators and scavengers.

Without the hotspot-related uplift and the lowland hotspot track of the eastern Snake River Plain, the GYE would be drier, lower, and warmer, but many of the species noted above might well be present but in lesser numbers and on a lower, drier landscape. Yellowstone was designated a national park because of its hotspot-related thermal features. As a result, its ecosystem has been protected and has remained largely intact, and the public now values Yellowstone's wildlife as much as its geothermal features.

Ongoing uplift followed by erosion has created valleys 1 km deep (thousands of feet) (fig. 10C). Pleistocene glaciations have modified these valleys to form the characteristic U-shaped glacial form. Stream and glacial processes have deepened valleys to produce high, steep valley walls, a landscape feature common over much of the GYE. These steep valleys generate debris flows, particularly after forest fires, that move sediment out of the mountains to the valley floors of the GYE (Meyer and others, 1995) (fig. 10H).

Modern and Pleistocene Snows Greatly Enhanced by Yellowstone Hotspot Geography

Figure 13 shows contours on annual precipitation for Yellowstone National Park. The important topographic features enhancing snowfall in the GYE are the hotspot track of the topographically low eastern Snake River Plain, the Yellowstone Plateau, and the Yellowstone crescent of high terrain (fig. 4). Geophysical surveys of the eastern Snake River Plain show a significant thickening of dense material at mid-crustal depths—that together with the massive volume of material erupted, the large size of calderas, and cooling following passage of the hotspot—all contribute to the present-day topographic low of the plain.

Topography shaped by the Yellowstone hotspot (fig. 4) creates a mountain-induced (orographic) weather pattern as moisture-laden air rises up across mountain barriers and then descends into basins (figs. 13 and 14).

1. Winter moisture from the northern Pacific Ocean moves eastward and becomes channeled well inland by the eastern Snake River Plain, a trough created by the hotspot track.

2. The upper end of the Snake River Plain is a cul-de-sac, and the moist air mass then must rise above orographic (mountain) barriers including the Yellowstone Plateau (altitude about 2,500 m; 8,000 ft) where the resulting orographic rise produces deep snowfall.

3. Storms continue moving east and rise up and over the Yellowstone crescent of high terrain, between 2,700- and 3,300-m (9,000- and 11,000-ft) altitude, extracting additional orographic snowfall.

4. The eastward-moving storms descend and warm as they traverse the east side of the crescent of high terrain, causing the air to become dryer and leading to a snow shadow (precipitation shadow) along the east side of the GYE in the Cody, Wyo., area.

Figure 15 shows the snowpack (April 1) at a constant altitude of 2,450 m (8,000 ft) along latitude 44.5°N. from the Pacific Ocean, through the Oregon Cascades, through the mountains of central Idaho, then across Yellowstone and to the Bighorn Mountains. The eastern Snake River Plain is just south of this transect. The overall pattern shows decreasing snowpack inland, but at Yellowstone a major reversal occurs—Yellowstone has more snowpack at 2,440 m (8,000 ft) than the central Idaho area, even though central Idaho is nearer to the

G, Landslide west of Gardiner, Mont., in incompetent, muddy sediments beneath slopes oversteepened by glacial erosion.

H, Debris flow into the Gibbon River resulting from rain on steep slopes burned in the 1988 fires.

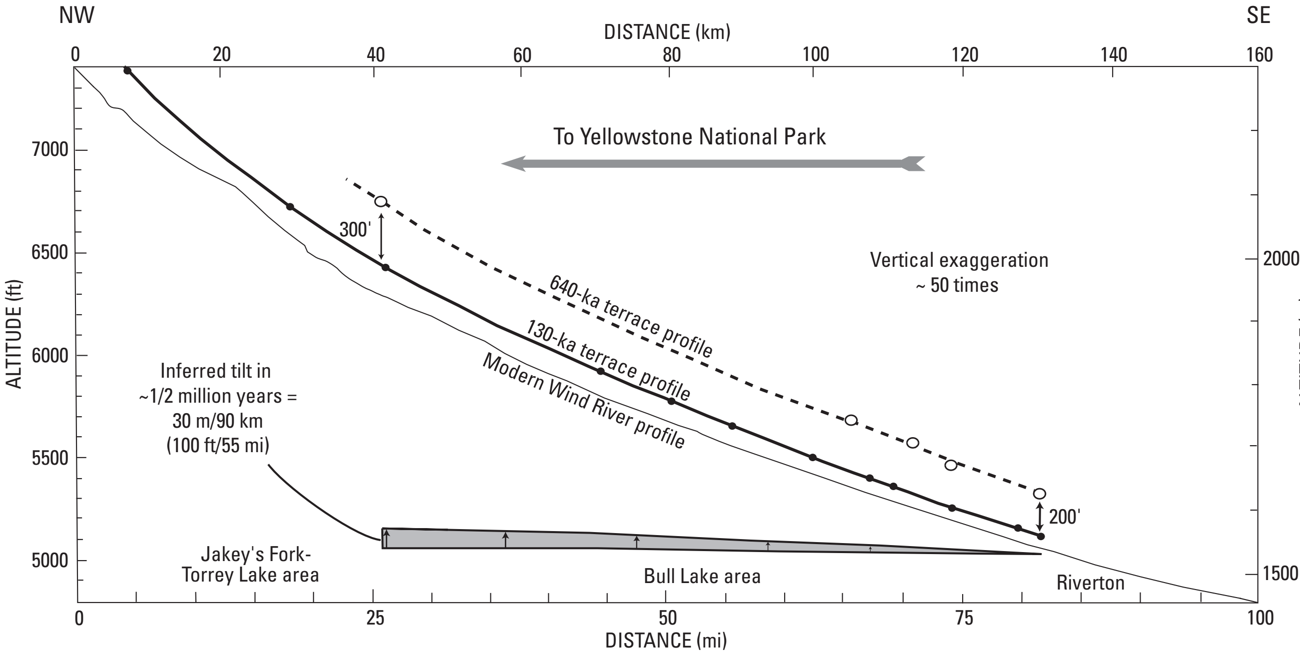


Figure 11. Diagram illustrating tilting of Wind River terraces away from the Yellowstone hotspot (modified from Jaworowski, 1994). The difference in terrace profiles suggests that in the 500,000 years between deposition of the upper terrace and the lower terrace, the upper terrace has been tilted away from the Yellowstone area about 30 m over a distance of 90 km (100 ft over 55 mi). Extrapolation of this inferred tilting over a distance of 200 km (125 mi) and to a time interval of 8 million years would yield uplift at the hotspot center of about 1,056 m (3,500 ft). This amount is somewhat larger than the uplift estimated to be associated with the Yellowstone hotspot of 0.5–1 km (1,600–3,300 ft) suggested by Pierce and Morgan (1992), and 600 m (2,000 ft) suggested by Smith and Braile (1993).

Pacific Ocean moisture source. East of Yellowstone, near Cody, Wyo., and farther east in the Bighorn Mountains, water in the snowpack at 2,440 m is 5 to 10 times less than it is on western Yellowstone Plateau.

The vegetation and ecology of the GYE is strongly influenced by this altitude and dry-wet-dry precipitation progression that results from hotspot-related topographic features. The increase in altitude at the upper end of the Snake River Plain produces deep snows that recharge the soil moisture in the vegetation root zone, and, consequently, this area supports lush vegetation (fig. 7H). A notable exception is the Yellowstone rhyolite plateau where low water-holding capacity, high permeability, and low nutrients in the soil produce a lodgepole forest with little understory (discussed earlier; figs. 6 and 7). Eastward from the crest of the Absaroka Range, annual precipitation decreases rapidly down the altitudinal gradient; Douglas-fir-dominated forests grow higher up the mountain sides, limber pine is a more common forest component, and lower timberline is about 450–600 m (1,500–2,000 ft) higher than on the western slope of the GYE. In addition, this precipitation shadow helps to produce vegetation adapted to arid conditions in much of the Big Horn Basin that is more like the vegetation in the Great Basin deserts than the Great Plains semiarid grasslands just 150 km (100 mi) to the north.

Another effect of increased altitude is the expression of different seasonal precipitation maximums (Despain, 1987, 1990; Porter and others, 1983; Whitlock and Bartlein, 1993). Mountain barriers intercept winter moisture (storm tracks) from the Pacific Ocean to the west and have a precipitation peak from November through March with annual snow accumulations of 100–150 cm (40–60 in) of water equivalent. Lower altitude areas, such as the Lamar Valley and the Mammoth, Wyo. and Gardiner, Mont. areas, receive a much lower total annual precipitation (fig. 13). Their basin topography prevents extraction of winter snows by orographic rise, and their main moisture is received during the more regional patterns of spring precipitation similar to that in the basal plains both east and north of the GYE, such as the Bighorn Basin and Gallatin Valley (Despain, 1990).

Pleistocene Glaciation and Its Effects Enhanced by the Yellowstone Hotspot

During the Pleistocene, both deep snowfall facilitated by the lowland hotspot track and cold temperatures resulting from hotspot uplift combined to generate glaciers that covered essentially all of Yellowstone National Park and much of the GYE (fig. 16). The glaciation of Yellowstone had two modes (Pierce, 1979; Sturchio and others, 1994; Pierce and Good, 1998): (1) a mode during both the early and late part of a glacial cycle when glaciers formed and flowed down valleys from the mountains surrounding the Yellowstone Plateau, and (2) a climax mode when a large ice cap built up on the Yellowstone Plateau to a thickness of more than 1,000 m (3,000 ft) and dominated the glacial flow from the surrounding mountains. With buildup of glacial ice on the plateau, either by glaciers flowing from the adjacent mountains or ice

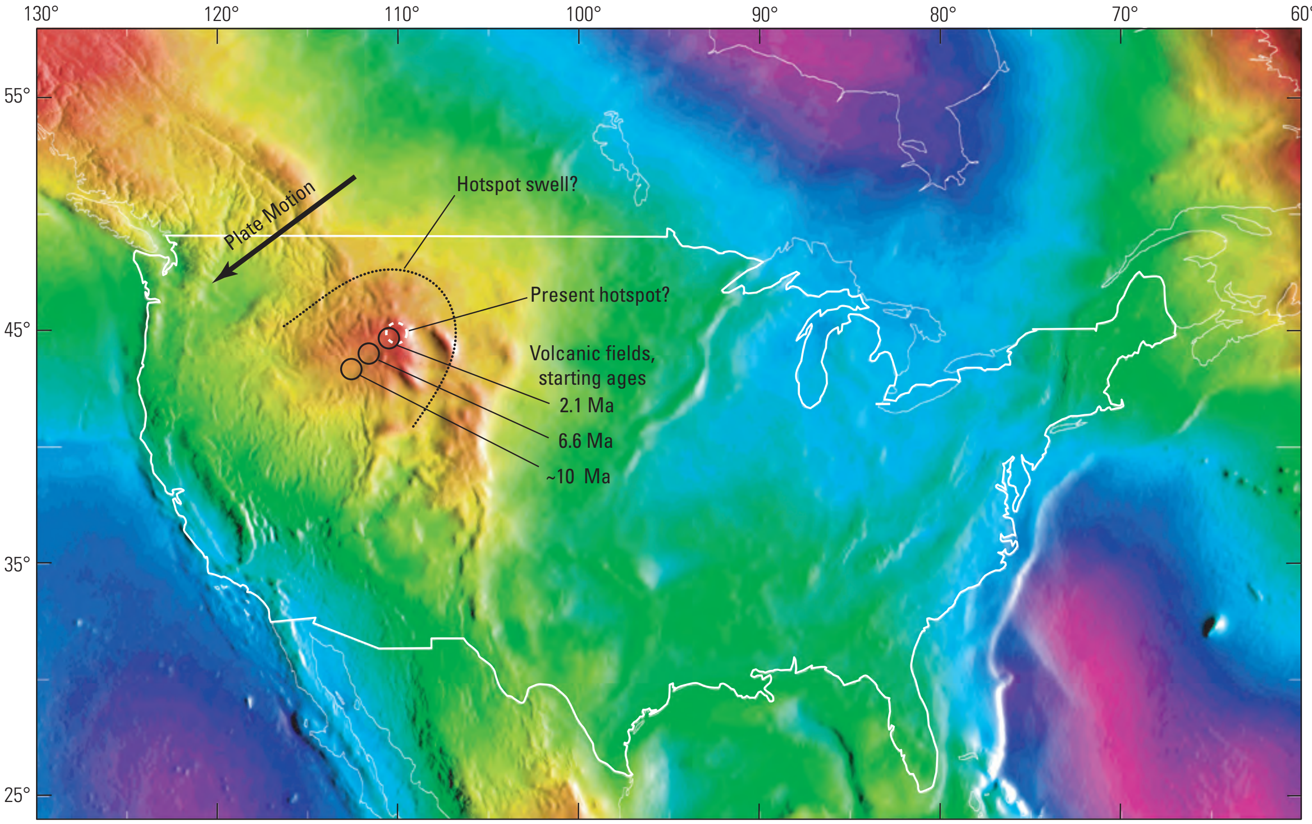


Figure 12. Map showing that the major geoid anomaly in the Western United States centers on the present Yellowstone hotspot. The warmer colors indicate higher altitude anomalies on the geoid, including the culmination in red at Yellowstone. Volcanic fields (circles) along the hotspot track are shown along with their starting ages. The dashed white circle shows the inferred position of the present hotspot based on a rate of plate movement of 25 km/m.y. The dotted line shows the inferred margin of the Yellowstone-hotspot swell, which is comparable in size to swells associated with oceanic hotspots. This major geoid anomaly suggests that the greater Yellowstone ecosystem stands high due to processes in the mantle.

formation on the plateau itself, the altitude of the plateau's surface increased so that orographic extraction of snow from storms channeled by the eastern Snake River Plain became self-amplifying. This positive-feedback loop resulted in an even more pronounced accumulation of snow and glacial ice on the plateau. Such unusual two-mode glacial behavior conforms elegantly to the hotspot-produced geography beyond the eastern end of the eastern Snake River Plain. Early and late in a cycle, glacial snows accumulated only on the Yellowstone crescent of high terrain; whereas, during full-glacial (climax) conditions, the rise of more than 1,500 m (5,000 ft) from the Snake River Plain (altitude 1,800 m, 6,000 ft) to the ice-cap crest (altitude 3,350 m, 11,000 ft) produced deep orographic snows on the Yellowstone Plateau itself (Pierce, 1979; Pierce and Good, 1998).

Glaciation sculpted the landscape of the GYE and older soils were scraped away. Deposits of glacial moraines, outwash gravels and sands, lake sediments, and thin glacial tills have greatly influenced soil and landscape development (fig. 17) (Rodman and others, 1996; Trettin, 1986). Soils on both glacially eroded areas as well as on glacial deposits formed in originally unweathered material in the relatively short interval of about 15,000–12,000 years since glaciation (fig. 17H). Many of the meadow areas of Yellowstone are fine-textured glacial deposits (figs. 17C and 7G). In northern Yellowstone near Gardiner, Mont., thick glacial ice converged to form a large outlet glacier that flowed north 65 km (40 mi) down the Yellowstone Valley to where it deposited extensive end moraines—beyond which a large, glacial-meltwater river deposited thick outwash gravels (figs.17A and 17B). Glacial flow was northward across the Washburn Range, where it overrode the highest peaks in the range (fig. 17D) and rounded the range into a smoothed form (fig. 17E) that is dramatically different from the rock pillars (hoodoos) and cliffs formed by similar bedrock in the unglaciated and drier terrain west of Cody, Wyo.

Jackson Lake and Jenny Lake in Grand Teton National Park were formed by Pleistocene glaciations (figs. 16, 17F, and 17G), as was the accumulation of lake sediments in Hayden and Pelican Valleys (located on fig. 6). Many of the topographic elements on a scale of 0.5 to 30 m (1 to 100 ft) in the GYE within the area covered by Pleistocene glaciations (fig. 16) are the result of glacial erosion and deposition. The topographic surface left by this glacial erosion and deposition is the "canvas" upon which the GYE vegetation was "painted" using a palette of vegetation types that provided the plant diversity upon which a broad range of biotic communities have developed.

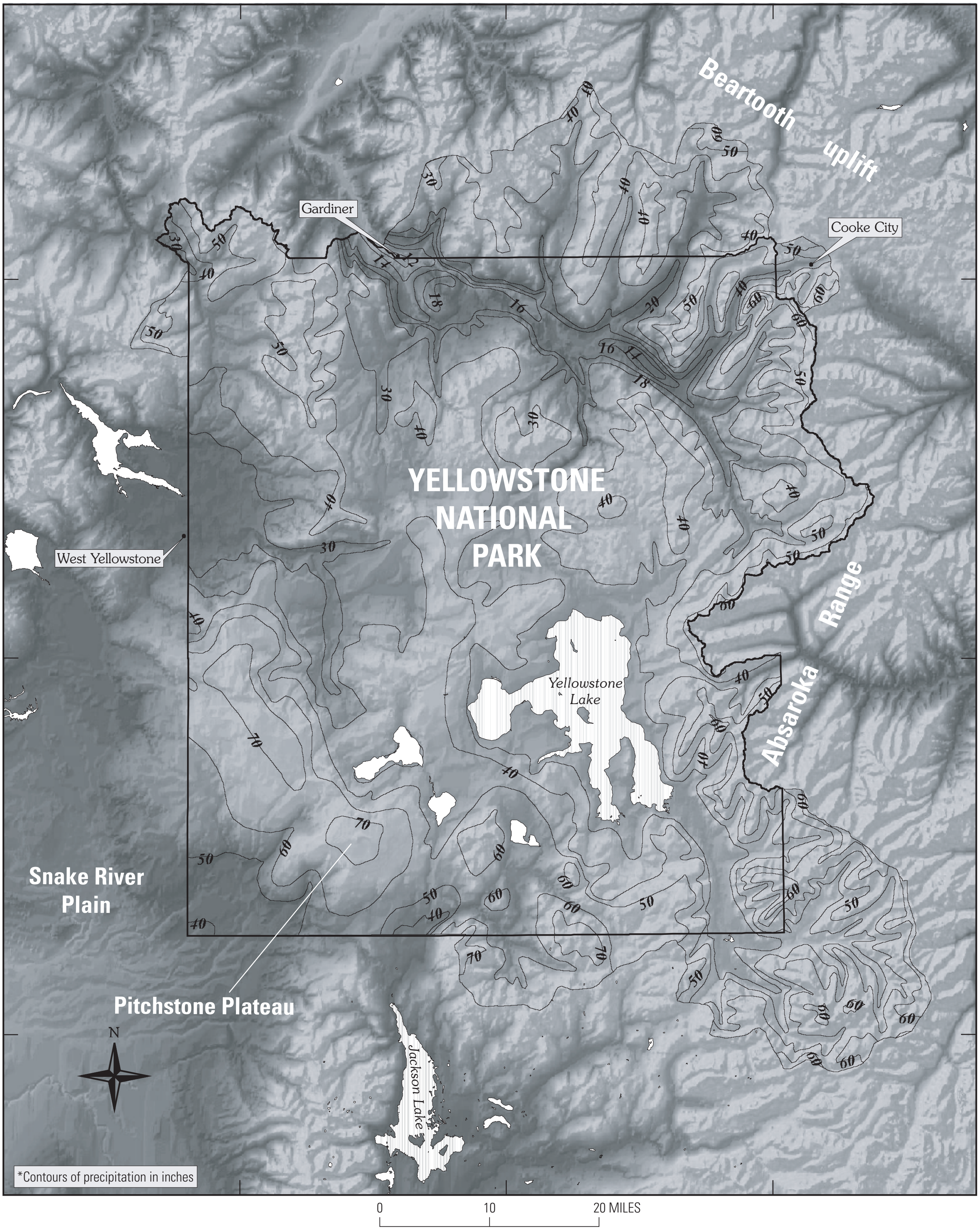


Figure 13. Map showing average annual precipitation (in inches) in Yellowstone National Park and the nearby drainage areas (modified from Farnes, 1997). Note that the precipitation shows a maximum of more than 180 cm (70 in) on the west side of the Yellowstone Plateau, where the altitudes reach only about 2,600 m (8,500 ft), and high but lesser values in the Absaroka Range along the east side of Yellowstone, where altitudes are about 1,000 m (2,000–3,000 ft) higher.

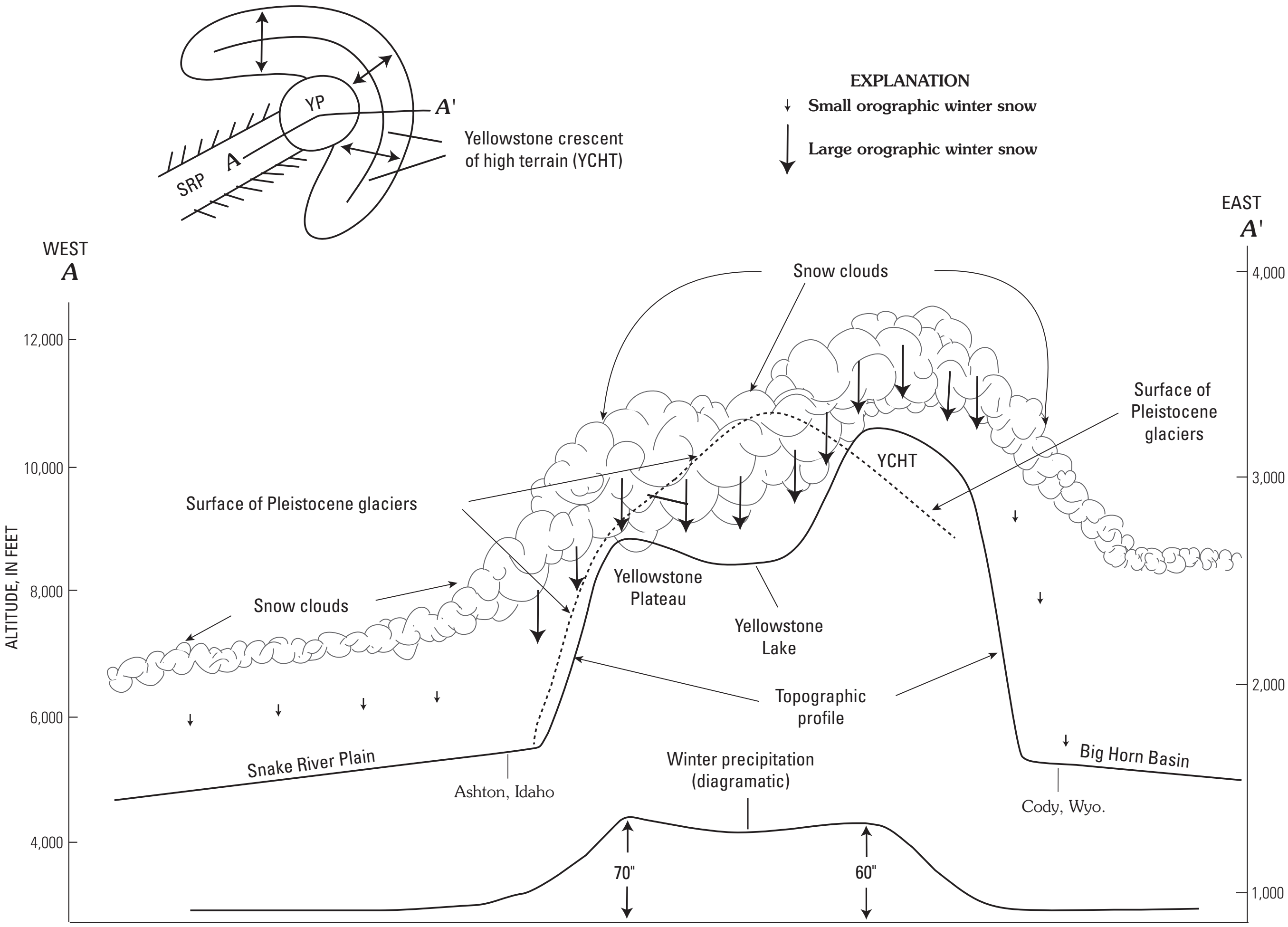


Figure 14. Profile illustrating orographic snowfall across Yellowstone. Storms first rise up from the Snake River Plain onto the Yellowstone Plateau, then ascend higher across the Absaroka Range crest, and then descend towards Cody, Wyo. Inset is schematic diagram of major topographic elements showing location of topographic section A–A' (fig. 1). Abbreviations are SRP, Snake River Plain; YP, Yellowstone Plateau; and YCHT, axis of the Yellowstone crescent of high terrain. Length of vertical arrows diagrammatically indicates the relative amount of winter snow extracted from the west-to-east moving air mass. The increasing amount of snow clouds diagrammatically shows increasing amounts of orographic snowfall.

Human Experience and Human Geography of the GYE as Influenced by the Yellowstone Hotspot

> *The geographic environment is a mould into which the human race has been poured and the history of the race has been shaped by that mould (A.E. Parkins, 1934, p. 224).*

This paper concerns the relation between geology and ecology, and this final section concerns geology as applied to human geography or human ecology. The distinctive attributes of the landscapes of the GYE are critical to how people have experienced and used the GYE. In this section, we first portray the human experience in the GYE and then show how some salient aspects of human geography relate to hotspot-related processes.

Several Native-American origin myths are thought to refer to Yellowstone Lake and its outlet at Fishing Bridge (Reeve, 1989; Nabokov and Loendorf, 2002). Kiowa (Mooney 1979), Appachean (Gunnerson and Gunnerson, 1971; Perry, 1980), and Shoshonean (Dominick, 1964) myths and ethnohistories refer to Yellowstone Lake and its outlet at Fishing Bridge. Native Americans entered the GYE apparently not long after they entered North America, as indicated by early Paleoindian Clovis and Folsom projectile points dating from about 13,500–12,800 years ago (ages given here are in corrected radiocarbon ages). Sites on the shores of Yellowstone and Jackson Lake have abundant Cody Complex points indicating occupation there by 10,600–9,800 years ago. Native Americans were present in the GYE much of the time from then up to historic times, although probably only at times and in places where snows were not too deep. Although Native Americans regarded Yellowstone and its thermal features as sacred, Euro-Americans are responsible for

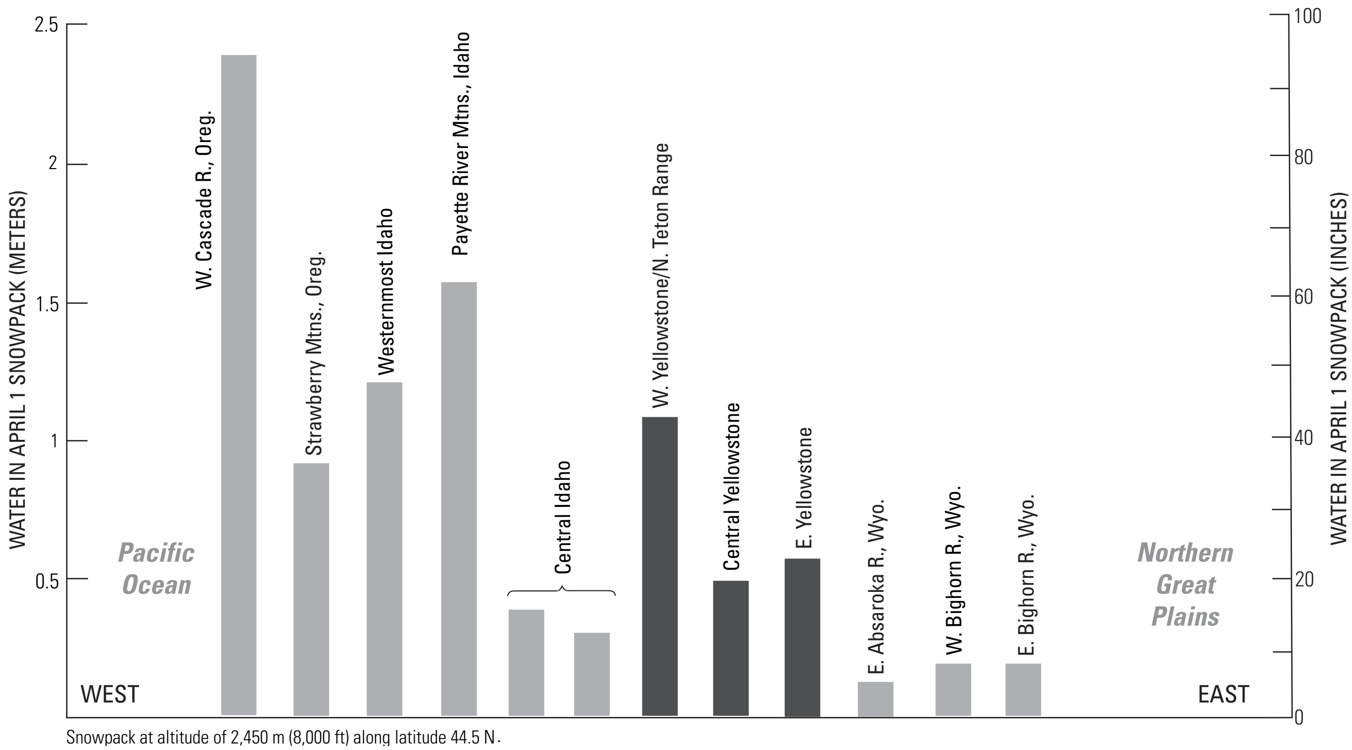


Figure 15. Plot of snowpack from the Pacific Ocean through Yellowstone to the Big Horn Mountains. The plot is along a latitudinal transect and normalized to 2,450-m (8,000-ft) altitude to isolate snowpack anomalies. Note major increase from central Idaho eastward to the Yellowstone Plateau. Storms moving northeast along the Snake River Plain are intercepted by mountains around the cul-de-sac at upper end of the plain; here moisture-laden air rises first up onto the Yellowstone Plateau resulting in a large orographic extraction of snow, and rise subsequently higher across the Yellowstone crescent of high terrain where additional snow is extracted. Farther east to the Cody, Wyo., area, the descending air becomes drying and snowfall decreases dramatically.

the myth that Native Americans were afraid of Yellowstone (Weixelman, 2001).

Ever since French and American fur trappers reported the amazing features of Yellowstone (fig. 18) in the early 1800s, the GYE has assumed almost mythical properties. Its geysers and hot springs suggest powers deep in the Earth. The human experience in the GYE is strongly related to the landscape, vegetation patterns, and climate that, in turn, are direct or indirect results of hotspot processes (fig. 18). Yellowstone is the best-known natural thermal feature in the world and, as such, attracts millions of visitors each year. It is the subject of many TV broadcasts and is the topic of many environmental concerns. Despite more than 3 million visitors annually from throughout the world, Yellowstone and vicinity remain the largest intact ecosystem in temperate North America (Reese, 1984).

The mountainous areas of the ecosystem have been a significant factor in human use of the region for the last 10,000 years or more. As the lower elevations dried out and game animals migrated to higher elevations for their summer range, hunter-gatherer groups also went to the moister, cooler mountains and gathered plant materials as they ripened or became ready for harvest (Wright, 1984). Seasonal plant maturation also migrated upslope reaching the proper growth or ripening (phenological) stage later than those lower down in the valleys. This hunter-gatherer culture lasted until the last vestiges of Native Americans were moved from Yellowstone National Park to a reservation in central Wyoming shortly after the Park was established in 1872.

Patterns of human settlement and political organization are elements in the study of human geography and are often governed by major landscape features. In the historical geography of Europe, the high Alps acted as a sparsely populated highland barrier, partitioning the human history, political associations, and commerce on the different sides of the mountains (Pounds, 1990). Similarly, the mountainous, snowy GYE remained a highland of mystery in the heart of expanding western development. Wagon roads were established to supply the gold camps of Montana, and settlements evolved to provide a closer supply. These wagon roads skirted the GYE uplands, avoiding steep grades. Native Americans attempted to protect their prairie hunting grounds from this encroachment on the north and east side of the GYE. Forts were constructed to guard incoming settlers. This state of affairs in American history provided many of the plots for the “westerns” that dominated the movie and TV industry for decades. Fort Ellis, established in 1867 near Bozeman, Mont. (established in 1864), was the jumping-off place for Yellowstone’s early explorers. As the Native Americans were removed and the

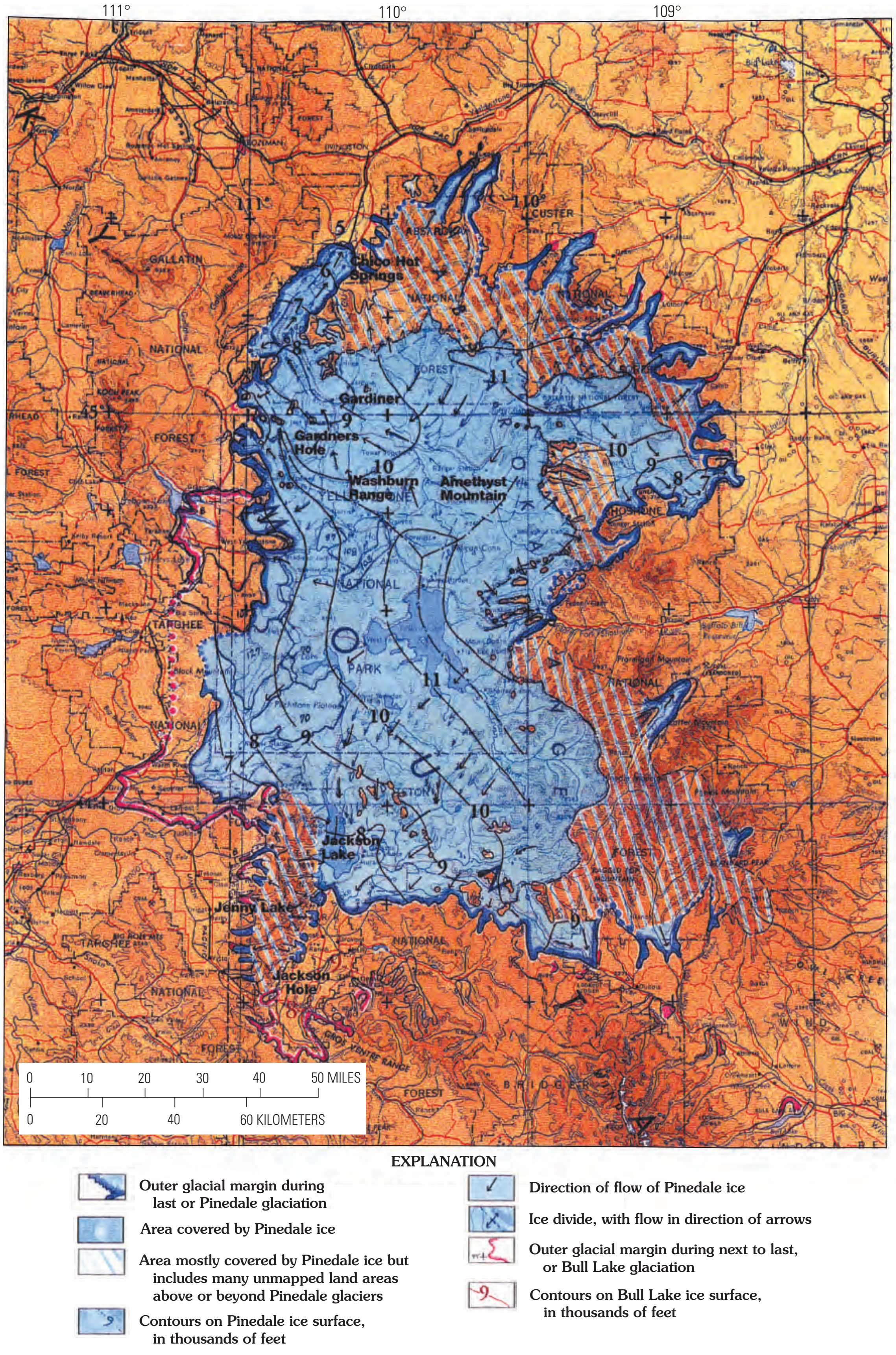
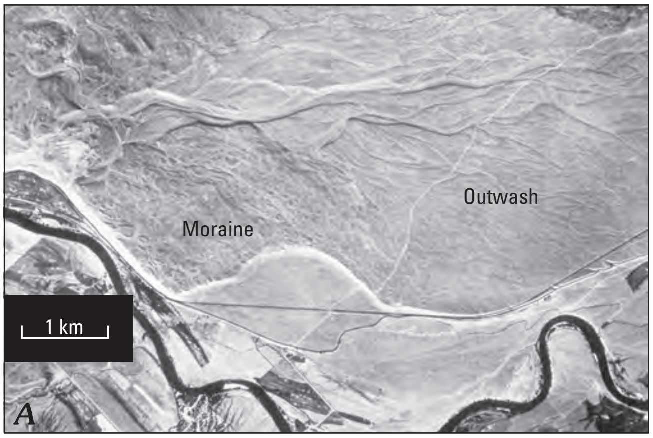


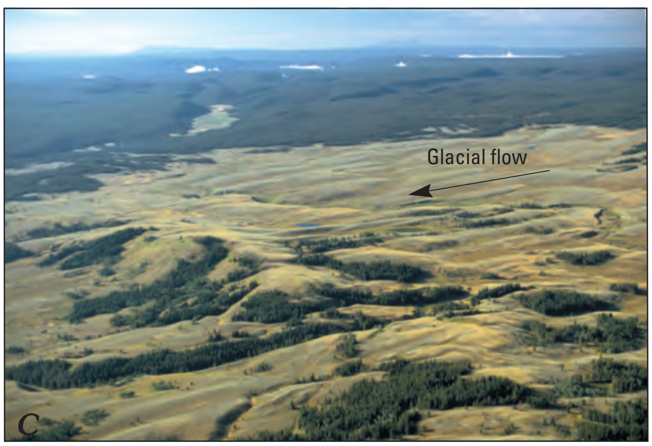
Figure 16. Map showing extensive glacial cover of the Yellowstone area about 17,000 years ago. Only the glaciers that were contiguous with those in Yellowstone are shown. Nearly all of Yellowstone Park was covered with glacial ice that was enhanced by three hotspot-related features: (1) the storm conduit of the eastern Snake River Plain, (2) the buildup of rhyolite to form Yellowstone Plateau, and (3) uplift to form the Yellowstone crescent of high terrain.

Figure 17. GLACIATION. Glacial erosion and deposition have greatly modified the landscape and soil of the greater Yellowstone ecosystem (GYE). Most of the soil in which GYE vegetation grows has formed only since the last glaciation and is weakly developed. Soils commonly are formed either in different-textured glacial deposits (till, gravel, and lake sediment) or on bedrock scraped clean during glaciation and, consequently, are very thin.

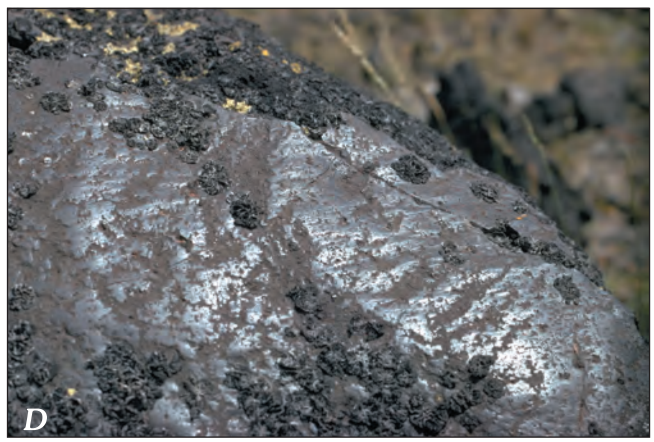


A, Glacial outwash plain (channel patterns) and moraines (left side of photograph) of the northern Yellowstone outlet glacier.

B, Glacial molding of landscape by right-to-left glacial flow 1,100 m (3,300 ft) thick above Gardiner, Mont.

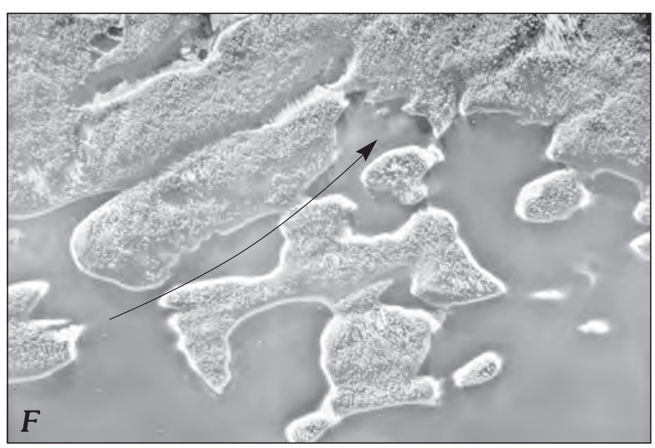


C, Gardners Hole consists of glacial deposits molded by glacial flow (fig. 16). Meadow is on glacial deposits; lodgepole forest is on rhyolite.



D, Glacial striations on the crest of the Washburn Range.

E, Washburn Range was smoothed and rounded by overriding ice.



F, Glacial sculpting along east side of Jackson Lake by a thick glacier flowing south from Yellowstone.

railroads expanded from the east through Bozeman in 1883 and from the south into the Snake River Plain, the settlements rapidly expanded. Fingers of settlement reached into the GYE as pioneering ranchers settled the isolated lower valleys along major streams. Following construction of the railroad spur from Livingston, Mont., to Yellowstone National Park in the late 1800s, railroads brought ever-increasing numbers of tourists to the heart of the GYE, and the patterns of use that exist today were solidified. People visited Yellowstone during the summer but few could negotiate the deep snows of winter.

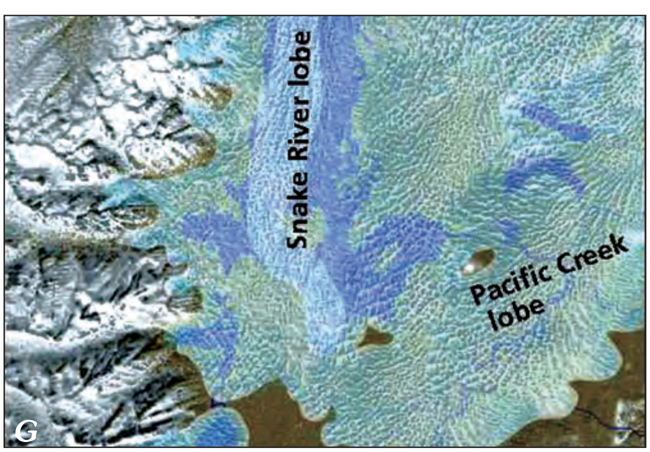
A similar “in-and-out” pattern of use by many animals was underway by about 15,000 years ago when Yellowstone was emerging from the most recent ice age. Then, vegetation was in a state of flux as stream valleys and snow-free mountain ridges opened dynamic ecological niches as climate warmed. From studies of pollen in cores from lakes, Whitlock (1993) documented the following vegetation changes. As the ice retreated, plants adapted to tundra conditions occupied the newly exposed ground. From about 13,200 to 12,200 years ago (carbon-14 ages are corrected to calendar years), climate continued to ameliorate, enabling whitebark pine, Englemann spruce, and subalpine fir to colonize the richer soils on the non-rhyolitic areas. The central rhyolite plateau with its infertile, well-drained soils, remained treeless about 1,000 years longer—until about 11,200 years ago when it became covered with lodgepole pine. Continued warming first brought the vegetation similar to today’s, but warming culminated about 8,000 years ago with Douglas fir growing higher up the mountains than it does today. Subsequent cooling about 5,000 years ago led to several glacial oscillations, the youngest of which was the Little Ice Age that culminated in about A.D. 1850, or perhaps as recently as 1920. Subsequently, the climate has been warming and vegetation readjusting (Meagher and Houston, 1998).

Elk, bison, and deer moved into Yellowstone with spring green-up and were driven out by winter snows. Wolves and coyote movements mirrored migration patterns of the ungulates. Native Americans hunted in Yellowstone’s plateaus, mountains, and valleys for thousands of years and mined obsidian for trade; trappers harvested beaver, and all left with autumnal storms.

The core of the GYE is a mountainous area along the Continental Divide that is the headwaters of 25 rivers and other large drainages that flow radially outward (fig. 19). The map pattern might be idealized as shown in figure 20 to that of a domal highland. The results of human activities—such as towns, roads, irrigation systems, ranches, and farms—are concentrated along the river valleys (table 2), and most commerce occurred within these valleys or across lower divides; however very little commerce was conducted across the rugged, mountainous core of the GYE.

The downstream parts of drainages shown in figure 19 became corridors for settlement and transportation by European settlers with the building of irrigation canals, roads, towns, and railroads. Each drainage has its key towns (table 2). The GYE includes 21 counties. This central highland “vacant hub” with its radially flowing streams helps explain a geographic political segmentation of the GYE—each river valley had its own associations and was separated from other valleys by barriers ranging from rugged, forested mountains across the upper parts of drainages to more open and arid divides farther down these drainages. More recently, with enhanced communication, media coverage, transportation, and organization of interest groups, strong differences and polarities for the management of the GYE are manifest from competing interest groups within the valleys, within the GYE, and within the Nation.

Because of its remote highland setting centering on the Continental Divide, the GYE contains the boundaries of many National, State, and local governmental jurisdictions (fig. 1; table 3). In large part because of its location at drainage headwaters, the GYE contains the boundaries of (1) Yellowstone and Grand Teton National Parks, (2) three National Forest regions and seven National Forests (Gallatin, Custer, Shoshone, Bridger-Teton, Caribou, Targhee, and Beaverhead), (3) the States of Wyoming, Montana, and Idaho, and (4) 21 counties (table 3). Collaborative decision-making within the GYE is hampered because of its many jurisdictions.



G, Reconstruction showing the glacier that flowed south from the Yellowstone Plateau and excavated Jackson Lake.

H, Glaciation of the GYE left fresh stony soils such as these on top of Amethyst Mountain.

Figure 18. HUMAN EXPERIENCE. Human experience in the greater Yellowstone ecosystem (GYE) related to the Yellowstone hotspot. The Yellowstone hotspot has created or enhanced the main features that attract people to the GYE: its thermal features, wildlife, mountain character, and scenic vistas. (YNP, Yellowstone National Park.)

A, Shoshone Native-American family in Yellowstone area. Photograph by W.H. Jackson in 1871.

B, Fire pits on Jackson Lake paleobeach. Surface hearth above deeper, buried hearth—both are about 2,000 years old.

C, Trapper painted in 1837. Photograph from YNP collection (no. 2901).

D, Geologist F.V. Hayden in camp. Photograph by W.H. Jackson in 1871.

E, Tower Falls as painted by Thomas Moran. Photograph from YNP collection (no. 3096).

F, Old tour bus at West Thumb in 1917. Photograph from YNP collection (no. 10,518).

G, Fishing Bridge in the early 1900s. Photograph from YNP collection (number not known).

H, Tourists at Mammoth Hot Springs. Photograph from YNP collection (no. 2863).

I, Morning Glory Pool in Upper Geyser Basin. Photograph from YNP collection (no. 5710).

J, Teton Range as viewed across Jackson Lake. Photograph from YNP collection (no. 4519).

K, Old Faithful. Photograph from YNP collection (no. 5205).

L, Grizzly bears dining at Trout Creek dump in 1970. Photograph from YNP collection (no.11,678).

Table 3. Governmental jurisdictions in the greater Yellowstone ecosystem (GYE).

Federal		
National Parks (2): Grand Teton Yellowstone	National Forests (7): Region 1: Custer, Gallatin, and Deer Lodge Region 2: Shoshone Region 4: Bridge-Teton, Caribou, and Targhee	Bureau of Land Management (many districts)
States (3) and counties (21)		
Montana (7): Beaverhead, Carbon, Gallatin, Sweet Grass, Madison, Park, and Stillwater	Wyoming (6): Fremont, Hot Springs, Lincoln, Park, Sublette, and Teton	Idaho (8): Bear, Bingham, Bonneville, Caribou, Clark, Fremont, Madison, and Teton
Indian reservations		
Wind River Indian Reservation Just beyond GYE (fig. 1) are the Fort Hall (Idaho) and Crow (Montana) Indian Reservations		

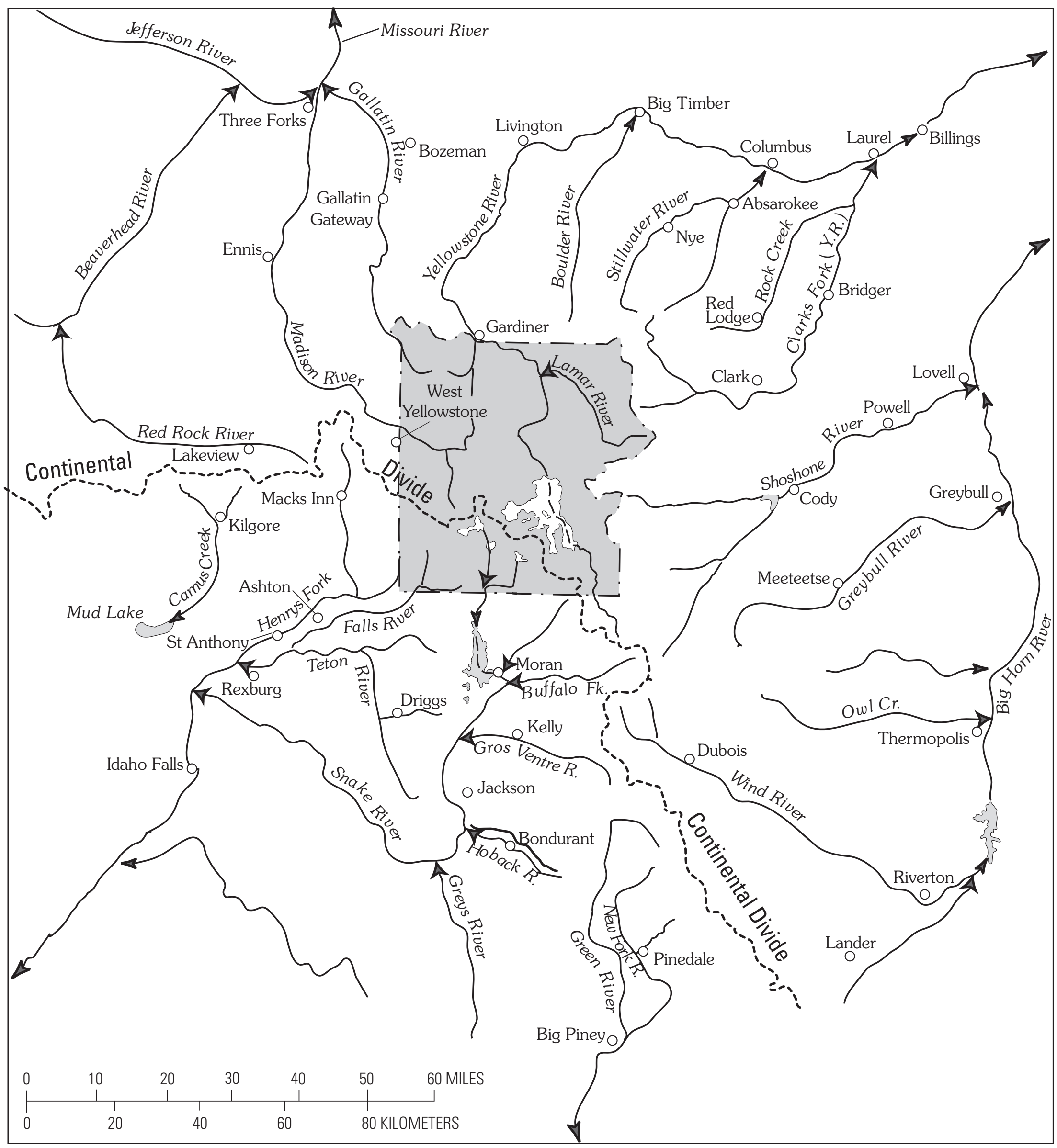


Figure 19. Sketch map showing radial pattern of major rivers of the greater Yellowstone ecosystem (GYE). The GYE is a mountainous area along the Continental Divide. From the central highland “hub” of the GYE, the headwaters of about 25 drainages (table 2) flow radially outward. This high, “mother of waters,” location explains why Yellowstone was relatively late to be explored by Euro-Americans and even now is difficult to traverse in winter. This central highland “hub” also helps explain the political segmentation of the GYE; each river valley has its own human association and is separated from adjacent rivers by mountainous divides.

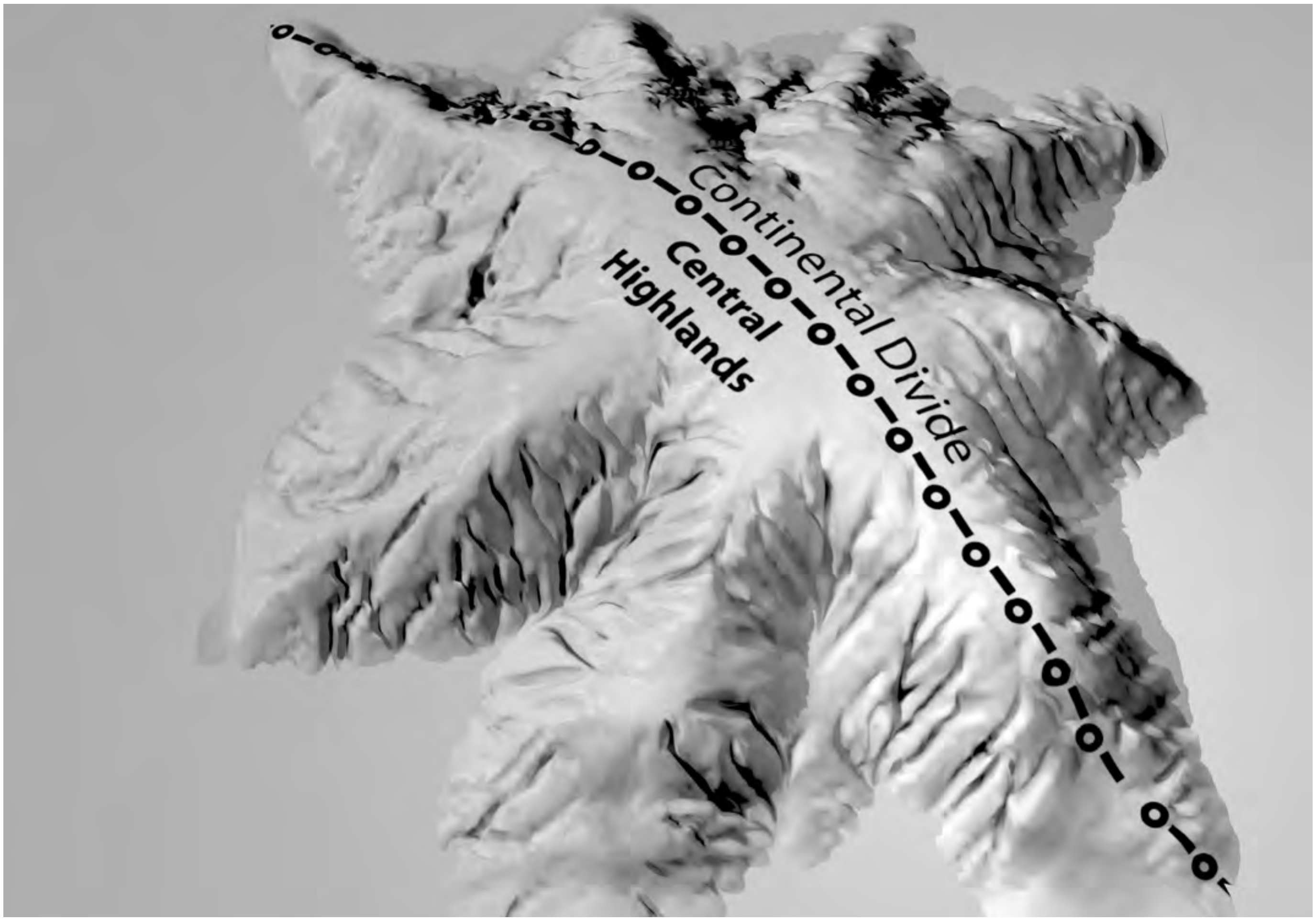


Figure 20. Cartoon showing central highland and idealized radial drainage pattern. Nature is more complicated than this simplified pattern, and the greater Yellowstone ecosystem has a geologic heritage older than the 2-million-year-old Yellowstone Plateau volcanic field, such as the topography produced by Laramide-age uplifts about 60 million years ago. In addition, rather than a dome, which would suggest static plate motion, the uplift appears to have a crescent pattern associated with the relatively stationary Yellowstone hotspot interacting with the southwest-moving North American plate.

Today, the historic "in-and-out" annual use pattern characteristic of Yellowstone National Park is blurred, but it truly extends over larger parts of the GYE. Air transport moves people quickly from anywhere in the world to communities near the GYE, and over-snow vehicles carry them swiftly to Old Faithful itself. Where ranchers once toughed out winters in near isolation, second homes and subdivisions dot the landscape. Human-use patterns have expanded; ungulate-use patterns have been truncated (which has also circumscribed predator migration patterns). Major ski resorts occupy snowy mountains once considered barriers to development. Improved transportation, affluence, and winter sports are increasing winter use in parts of the GYE, but Yellowstone, and its surrounding mountains and villages, is still visited by far more people during the summer months.

We have shown how the Yellowstone hotspot and associated geologic processes of volcanism, faulting, and uplift have shaped patterns of habitation and land-use in the GYE, even though many visitors to Yellowstone are unaware of the connection. The skier busting through powder snow above Teton Village in Jackson Hole, Wyo., or Big Sky, Mont., the photographer too close to a grizzly in the Park's Gallatin Range, or the summer resident enjoying her sunset from her new home above the Madison River may never ask, "Why these mountains, these animals, or these geysers and hot springs?" They could be surprised to learn that the driving force behind these scenic landscapes lies deep beneath their feet and that this long-lived source of energy has raised the mountains and high plateaus of Yellowstone; it has powered Yellowstone's famous thermal features; and it has been active for the last 16 million years. Without the hotspot, much of Yellowstone would resemble the dusty, dry landscape that surrounds it. Although there would have still been mountains, they would have been lower and drier than the present landscape. Precipitation would be much less than it is today, and grasslands would be less luxuriant. Without the hotspot, rivers would be smaller and there would be no geysers—the Yellowstone that we know today would have been very different indeed.

References Cited

Anders, M.H., 1994, Constraints on North American plate velocity from Yellowstone hotspot deformation field: Nature, v. 369, p. 53–55.

Anders, M.H., Geissman, J.W., Piety, L.A., and Sullivan, J.T., 1989, Parabolic distribution of circum-eastern Snake River Plain seismicity and latest Quaternary faulting—Migratory pattern and association with the Yellowstone hot spot: Journal of Geophysical Research, v. 94, no. B2, p. 1,589–1,621.

Anderson, D.L., 1998, The edges of the mantle, *in* Gurnis, Michael, Wysession, M.E., Kittle, Elise, and Buffett, B.A., eds., The core-mantle boundary region: American Geophysical Union, Geodynamics Series, v. 28, p. 255–271.

Benjamin, Lyn, 2000, Groundwater hydrology of the Henry's Fork springs: Intermountain Journal of Sciences, v. 6, no. 3, p. 119–142.

Brock, T.D., and Brock, M.L., 1971, Life in the geyser basins—Yellowstone National Park: Yellowstone Library and Museum Association, 32 p.

Camp, V.E., 1995, Mid-Miocene propagation of the Yellowstone mantle plume head beneath the Columbia River Basalt source region: Geology, v. 23, no. 5, p. 435–438.

Camp, V.E., and Ross, M.E., 2004, Mantle dynamics and genesis of mafic magmatism in the intermontane Pacific Northwest: Journal of Geophysical Research, v. 109, B08204, 14 p.

Christiansen, R.L., 1984, Yellowstone magmatic evolution—Its bearing on understanding large-volume explosive volcanism, *in* Explosive volcanism—Inception, evolution, and hazards; studies in geophysics: Washington, D.C., National Academy Press, p. 84–95.

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., Foulger, G.A., and Evans, J.R., 2002, Upper mantle origin of the Yellowstone hotspot: Geological Society of America Bulletin, v. 2004, p. 1,245–1,526.

Coffin, M.F., and Eldholm, Olav, 1994, Large igneous provinces: Crustal structure, dimensions, and external consequences: Reviews of Geophysics, v. 32, p. 1–36.

Courtillot, Vincent, Davaille, Anne, Besse, Jean, and Stock, Joann, 2003, Three distinct types of hotspots in the Earth's mantle: Earth and Planetary Science Letters, v. 205, p. 295–308.

Craig, Harmon, 1990, Helium isotope distribution in mantle hotspots: EOS, Transactions of the American Geophysical Union , v. 71, p. 1,669.

Craig, Harmon, 1997, Helium isotope ratios in Yellowstone Park and along the Snake River Plain: Backtracking the Yellowstone hotspot: EOS, Transactions of the American Geophysical Union, v. 78, p. F801.

Daubenmire, Rexford, 1943, Vegetational zonation in the Rocky Mountains: Botanical Review, v. 9, p. 325–393.

Davies, G.F., 1999, Dynamic Earth—Plates, plumes, and mantle convection: Cambridge, England, Cambridge University Press, 470 p.

Davis, L.B., Aaberg, S.A., Schmitt, J.G., and Johnson, A.M., 1995, The Obsidian Cliff plateau prehistoric lithic source, Yellowstone National Park, Wyoming: Selections from the Division of Cultural Resources, Rocky Mountain Region, National Park Service, no. 6, 164 p.

Despain, D.G., 1987, The two climates of Yellowstone National Park: Proceedings of Montana Academy of Science, v. 47, p. 11–19.

Despain, Don G., 1990, Yellowstone vegetation—Consequences of environment and history in a natural setting: Boulder, Colo., Roberts Rinehart Publishers, 239 p.

Dominick, D., 1964, The Sheepeater: Annals of Wyoming, v. 36, p. 131–168.

Draper, D.S., 1991, Late Cenozoic bimodal magmatism in the northern Basin and Range Province of southeastern Oregon: Journal of Volcanology and Geothermal Research, v. 47, p. 299–328.

Duncan, R.A., and Richards, M.A., 1991, Hotspots, mantle plumes, flood basalts, and true polar wander: Reviews in Geophysics, v. 29, p. 31–50.

Eversman, Sharon, and Carr, Mary, 1992, Yellowstone ecology—A road guide: Missoula, Montana Press Publishing Company, 242 p.

Farley, K.A., and Neroda, E., 1998, Noble gases in the Earth's mantle: Annual Review of Earth and Planetary Sciences, v. 26, p. 189–218.

Farnes, Phil, 1997, The snows of Yellowstone: Yellowstone Science, v. 5, no. 2, p. 8–11.

Fee, David, and Dueker, Ken, 2004, Thermal structure of the transition zone beneath Yellowstone as revealed by receiver function imaging [abs.]: Geological Society of America Abstracts with Programs, v. 36, no. 4, p. 94.

Foulger, G.R., and Natland, J.H., 2003, Is "hotspot" volcanism a consequence of plate tectonics?: Science, v. 300, p. 921-922.

Fournier, R.O., 1989, Geochemistry and dynamics of the Yellowstone National Park hydrothermal system: Annual Reviews of the Earth and Planetary Sciences, v. 17, p. 13–53.

Fritz, W.J., 1980, Reinterpretation of the depositional environment of the Yellowstone “fossil forests”: Geology, v. 8, p. 309–313.

Good, J.M., and Pierce, K.L., 1996, Interpreting the landscapes of Grand Teton and Yellowstone National Parks, recent and ongoing geology: Grand Teton National History Association, 58 p.

Griffin, J.B., Gordus, A.A., and Wright, G.A., 1969, Identification and sources of Hopewellian obsidian in the middle west: American Antiquity, v. 34, p. 1–13.

Glick, Dennis, Carr, Mary, Harting, Bert, and others, 1991, An environmental profile of the greater Yellowstone ecosystem: Bozeman, Mont., Greater Yellowstone Coalition, map.

Hamilton, W.B., 2003, An alternative Earth: GSA Today, v. 13, no. 11, p. 4–12.

Hooper, P.R., 1997, The Columbia River flood basalt province—Current status, *in* Mahoney, J.J., and Coffin, M.F., eds., Large igneous provinces—Continental, oceanic, and planetary flood volcanism: American Geophysical Union Monograph 100, p. 1–27.

Humphreys, E.D., Dueker, K.G., Schutt, D.L., and Smith, R.B., 2000, Beneath Yellowstone—Evaluating plume and nonplume models using teleseismic images of the upper mantle: GSA Today, v. 10., no. 12, p. 1–7.

Jackson, Ian, ed., 2000, The Earth’s mantle—Composition, structure, and evolution: Cambridge, England, Cambridge University Press, 592 p.

Jaworowski, Sheryl, 1994, Geologic implications of Quaternary tephra localities in the western Wind River Basin, Wyoming: Friends of the Pleistocene, Rocky Mountain Field Trip, August 13–14, 1994.

Kennedy, B.M., Reynolds, J.H., Smith, S.P., and Truesdell, A.H., 1987, Helium isotopes—Lower Geyser Basin, Yellowstone National Park: Journal of Geophysical Research, v. 92, p. 12,477–12,489.

Lanphere, M.A., Champion, D.E., Christiansen, R.L., Izett, G.A., and Obradovich, J.D., 2002, Revised ages for tuffs of the Yellowstone Plateau volcanic field—Assignment of the Huckleberry Ridge Tuff to a new geomagnetic polarity event: Geological Society of America Bulletin, v. 114, p. 559–568.

Li, Xueqing, Kind, Ranier, Yuan, Xiaohui, Wolbern, Ingo, and Hanka, Winfried, 2004, Rejuvenation of the lithosphere by the Hawaiian plume: Nature, v. 427, p. 827–829.

Love, J.D., Reed, J.C., Jr., and Pierce, K.L., 2003, Creation of the Teton landscape—A geological chronicle of Jackson Hole and the Teton Range: Moose, Wyo., Grand Teton Natural History Association, 132 p.

Machette, M.N., Pierce, K.L., McCalpin, J.P., Haller, K.M., and Dart, R.L., 2001, Map and data for Quaternary faults and folds in Wyoming: U.S. Geological Survey Open-File Report 01-461, scale 1:500,000, 155 p.

Malde, H.E., 1991, Quaternary geology and structural history of the Snake River Plain, Idaho and Oregon, *in* Morrison, R.B., ed., Quaternary nonglacial history of the conterminous U.S.: Geological Society of America, The Geology of North America, v. K-2, ch. 4, p. 251–282.

Marston, R.A., and Anderson, J.E., 1991, Watersheds and vegetation of the greater Yellowstone ecosystem: Conservation Biology, v. 5, no. 3, p. 338–346.

Meagher, Mary, and Houston, Doug, 1998, Yellowstone and the biology of time: Norman, University of Oklahoma Press, 287 p.

Meyer, G.A., Wells, S.G., and Jull, A.J.T., 1995, Fire and alluvial chronology in Yellowstone National Park—Climatic and intrinsic controls on Holocene geomorphic processes: Geological Society of America Bulletin, v. 107, p. 1,211–1,230.

Milbert, D.G., 1991, GEOID90—A high-resolution geoid for the United States: EOS, Transactions of the American Geophysical Union, v. 72, p. 545–554.

Molnar, Peter, and England, Philip, 1990, Late Cenozoic uplift of mountain ranges and global climate change—Chicken or egg?: Nature, v. 346, p. 29–34.

Montelli, Raffaella, Nolet, Guust, Dahlen, F.A., Masters, Guy, Engdahl, G.E., and Hung, Shu-Huei, 2004, Finite-frequency tomography reveals a variety of plumes in the mantle: Science, v. 303, p. 338—343.

Mooney, J., 1979, Calender history of the Kiowa Indians: Washington, D.C., Smithsonian University Press.

Morgan, J.P., Morgan, W.J., and Price, Evelyn, 1995, Hotspot melting generates both hotspot volcanism and a hotspot swell?: Journal of Geophysical Research, v. 100, p. 8,045–8,062.

Morgan, L.A., and McIntosh, W.C., 2005, Timing and development of the Heise volcanic field, Snake River Plain, Idaho, Western U.S.A., Geological Society of America Bulletin, v. 117, p. 288–306.

Morgan, L.A., McIntosh, W.C., and Pierce, K.L., 1997, Inferences for changes in plume dynamics from stratigraphic framework studies of ignimbrites, central Snake River Plain, Idaho [abs.]: Geological Society of America Abstracts with Programs, v. 29, no. 6, p. A-299.

Morgan, L.A., Pierce, K.L., and McIntosh, W.C., 1999, $^{40}Ar/^{39}Ar$ ages of silicic volcanic rocks in the Snake River Plain—Timing of volcanism and tectonism along the track of the Yellowstone hotspot [abs.]: Geological Society of America, Abstracts with Programs, v. 31, no. 4, p. A-49.

Morgan, L.A., Shanks, W.C., Pierce, K.L., Rye, R., and Meeker, G.P., 1998, Hydrothermal explosion deposits in Yellowstone National Park—Links to hydrothermal processes: EOS, Transactions of the American Geophysical Union, v. 79, no. 45, p. F964.

Nabokov, Peter, and Loendorf, Lawrence, 2002, American Indians and Yellowstone National Park—A documentary overview, Yellowstone National Park, Wyo.: National Park Service, Yellowstone Center for Resources, 367 p.

Pace, N.R., 1991, Origin of life—Facing up to the physical setting: Cell, v. 65, p. 531–533.

Parkins, A.E., 1934, The geography of American geographers: Journal of Geography, v. 33, p. 221–230.

Parry, C.C., 1874, Botanical observations in western Wyoming: American Naturalist, v. 8, no. 3, p. 175–180.

Parsons, Tom, Thompson, G.A., and Sleep, N.H., 1994, Mantle plume influence on the Neogene uplift and extension of the U.S. western Cordillera?: Geology, v. 22, p. 83–86.

Patton, D.T., 1963, Vegetational pattern in relation to environments in the Madison Range, Montana: Ecological Monographs, v. 33, p. 375–406.

Perry, R.J., 1980, The Appachean transition from the subarctic to the southwest: Plains Anthropologist, v. 25(90), p. 79–296.

Pierce, K.L., 1979, History and dynamics of glaciation in the northern Yellowstone National Park area: U.S. Geological Survey Professional Paper 729-F, 91 p., 4 pl.

Pierce, K.L., Despain, D.G., Whitlock, Cathy, Cannon, K.P., Meyer, Grant, Morgan, Lisa, and Licciardi, J.M., 2003, Quaternary geology and ecology of the greater Yellowstone area, *in* Easterbrook, D.J., ed., Quaternary Geology of the United States, INQUA 2003 Field Guide Volume: Reno, Nev., Desert Research Institute, p. 313–344.

Pierce, K.L., and Good, J.M., 1998, Pleistocene glaciations of the greater Yellowstone geo-ecosystem: Yellowstone Science, v. 6, no. 2, Spring Supplement, p. 44.

Pierce, K.L., Milbert, D.G, and Saltus, R.W., 1992, Geoid dome culminates on Yellowstone: Yellowstone hotspot fed by a thermal mantle plume?: EOS, Transactions of the American Geophysical Union, v. 73, p. 284.

Pierce, K.L., and Morgan, L.A., 1992, The track of the Yellowstone hot spot—Volcanism, faulting, and uplift, *in* Link, P.K., Kuntz, M.A., and Platt, L.B., eds., Regional geology of eastern Idaho and western Wyoming: Geological Society of America Memoir 179, p. 1–53.

Pierce, K.L., and Morgan, L.A., 2005, Asymmetrical features across the Yellowstone hotspot track and the northwest inclination of the Yellowstone plume [abs.]: Geological Society of America Abstracts with Programs, v. 37, no. 7, p. 127.

Pierce, K.L., Morgan, L.A., and Saltus, R.N., 2000, Yellowstone plume head—Postulated tectonic relations to the Vancouver slab, continental boundaries, and climate: U.S. Geological Survey Open-File Report 00-498, 39 p.

Pierce, K.L., Morgan, L.A., and Saltus, R.N., 2003, Yellowstone plume head—Postulated tectonic relations to the Vancouver slab, continental boundaries, and climate, *in* Bonnichsen, Bill, White, C.M., and McCurry, Michael, eds., Tectonic and magmatic evolution of the Snake River Plain volcanic province: Idaho Geological Survey Bulletin 30, p. 5–33.

Porter, S.C., Pierce, K.L., and Hamilton, T.D., 1983, Late Pleistocene glaciation in the Western United States, *in* Porter, S.C., ed., The late Pleistocene, v.1, of Wright, H.E., Jr., ed., Late Quaternary environments of the United States: Minneapolis, Minn., University of Minnesota Press, p. 71–111.

Pounds, N.J. 1990, An historical geography of Europe: Cambridge, England, Cambridge University Press, 484 p.

Reese, Rick, 1984, Greater Yellowstone—The national park and adjacent wildlands: Helena, Mont., Montana Magazine, Inc., 104 p.

Richards, M.A., Duncan, R.A., and Courtillot, V.E., 1989, Flood basalts and hot spot tracks—Plume heads and tails: Science, v. 246, p. 103–107.

Rodgers, D.W., Hackett, W.R., and Ore, H.T., 1990, Extension of the Yellowstone Plateau, eastern Snake River Plain, and Owyhee Plateau: Geology, v. 18, p. 1,138–1,141.

Rodman, Ann, Schovic, H.F., and Thomas, David, 1996, Soils of Yellowstone National Park: Yellowstone Center for Resources, Yellowstone National Park, Wyoming, YCR-NRSR-96-2, 324 p.

Sleep, N.H., 1990, Hotspots and mantle plumes—Some phenomenology: Journal of Geophysical Research, v. 95, no. B5, p. 6,715–6,736.

Sleep, N.H., 1997, Lateral flow and ponding of starting plume material: Journal of Geophysical Research, v. 102, no. B5, p. 10,001–10,012.

Sleep, N.H., 2002, Ridge-crossing mantle plumes and gaps in tracks: Geochemistry, Geophysics, Geosystems (G^3), v. 3, (2001GC000290), 33 p.

Smith, D.A., and Milbert, D.G., 1999, The GEOID96 high-resolution geoid height model for the United States: Journal of Geodesy, v. 73, no. 5, p. 219–236.

Smith, R.B., and Arabasz, W.J., 1991, Seismicity of the intermountain seismic belt, *in* Slemmons, D.B., Engdahl, E.R., Zoback, M.M., and Blackwell, D.D., eds., Neotectonics of North America: Boulder, Colo., Geological Society of America, Decade Map, v. 1, p. 185–228.

Smith, R.B., and Braile, L.W., 1993, Topographic signature, space-time evolution, and physical properties of the Yellowstone-Snake River Plain volcanic system——The Yellowstone hotspot, *in* Snoke, A.W., Steidtmann, J.R., and Roberts, S.M., eds., Geology of Wyoming: Geological Survey of Wyoming Memoir No. 5, p. 694–754.

Smith, R.B., and Siegel, L.J., 2000, Windows into the Earth—The geologic story of Yellowstone and Grand Teton National Parks: Oxford, Oxford University Press, 242 p.

Steinberger, B., 2000, Plumes in a convecting mantle: Models and observations for individual hotspots: Journal of Geophysical Research, v. 105, no. B5, p. 11,127–11,152.

Sturchio, N.C., Pierce, K.L., Morrell, M.T., and Sorey, M.L., 1994, Uranium-series ages of travertines and timing of the last glaciation in the northern Yellowstone area, Wyoming-Montana: Quaternary Research, v. 41, p. 265–277.

Thompson, G.A., 1998, Deep mantle plumes and geoscience vision, Geological Society of America, and presidential address: GSA Today, April 1996, p. 17–25.

Thompson, R.N., and Gibson, S.A., 1991, Subcontinental mantle plumes, hotspots, and pre-existing thinspots: London, Journal of the Geological Society, v. 148, p. 973–977.

Trettin, C.C., 1986, Characterization of soils in Yellowstone National Park—Final project report: Contract no. CX-1200-1-B027, L'Anse, Michigan, Michigan Technological University, Ford Forestry Center, 33 p. and appendixes, 153 p.

Turcotte, D.L., and Schubert, G., 1982, Geodynamics applications of continuum physics to geological problems: New York, Wiley, 450 p.

U.S. National Park Service and U.S. Forest Service, 1979, Greater Yellowstone cooperative regional transportation study—Regional assessment environmental report: Denver, Colo., National Park Service, many pages with maps.

U.S. Geological Survey, 1972a, Surficial geologic map of Yellowstone National Park: U.S. Geological Survey Miscellaneous Investigations Series Map I-710, scale 1:125,000.

U.S. Geological Survey, 1972b, Bedrock geologic map of Yellowstone National Park: U.S. Geological Survey Miscellaneous Geologic Investigations Series Map I-711, scale 1:125,000.

Varley, John, 1993, Saving the parts: Yellowstone Science, v. 1, no. 4, p. 13–16.

Waite, G.P., Smith, R.L., and Allen, R.L., 2006, VP and VS structure of the Yellowstone hotspot upper mantle from teleseismic tomography: Evidence for an upper mantle plume: Journal of Geophysical Research, v. 111, B04303, doi: 1029/2005JB003867.

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.

White, R.S., and McKenzie, D.P., 1989, Magmatism at rift zones—The generation of volcanic continental margins and flood basalts: Journal of Geophysical Research, v. 94, no. B6, p. 7,685–7,729.

Whitlock, Cathy, 1993, Postglacial vegetation and climate of Grand Teton and southern Yellowstone National Parks: Ecological Monographs, v. 63, no. 2, p. 173–198.

Whitlock, Cathy, and Bartlein, P.J., 1993, Spatial variations of Holocene climatic change in the Yellowstone region: Quaternary Research, v. 39, p. 231–238.

Wilson, J.T., 1963, A possible origin for the Hawaiian Islands: Canadian Journal of Physics, v. 41, p. 863–870.

Woese, C.R., Kandler, Otto, and Wheelis, M.L., 1990, Towards a natural system of organisms—Proposal for the domains Archaea, Bacteria, and Eucarya: Proceedings of the National Academy of Science, v. 87, p. 4,576–4,579.

Wolfe, J.A., Forest, C.E., and Molnar, Peter, 1998, Paleobotanical evidence on Eocene and Oligocene paleoaltitudes in mid-latitude western North America: Geological Society of America Bulletin, v. 110, p. 664–678.

Wright, G.A., 1984, People of the high country, Jackson Hole before the settlers: American University Studies, ser. XI, Anthropology/Sociology, v. 7, 181 p.

Yuan, H., and Dueker, K., 2005, Teleseismic P-wave tomogram of the Yellowstone plume: Geophysical Research Letters, v. 32, doi: 10.1029/2004GL022056.

Zoback, M.L., and Thompson, G.A., 1978, Basin and range rifting in northern Nevada—Clues from mid-Miocene rift and its subsequent offsets: Geology, v. 6, p. 111–116.