

Excursion guide 12: Yellowstone

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The National Park at Yellowstone contains more than half the world's active geysers. Lying mostly in Wyoming, its host of geothermal features and fresh volcanic rocks offers an incomparable experience for any visiting geologist.

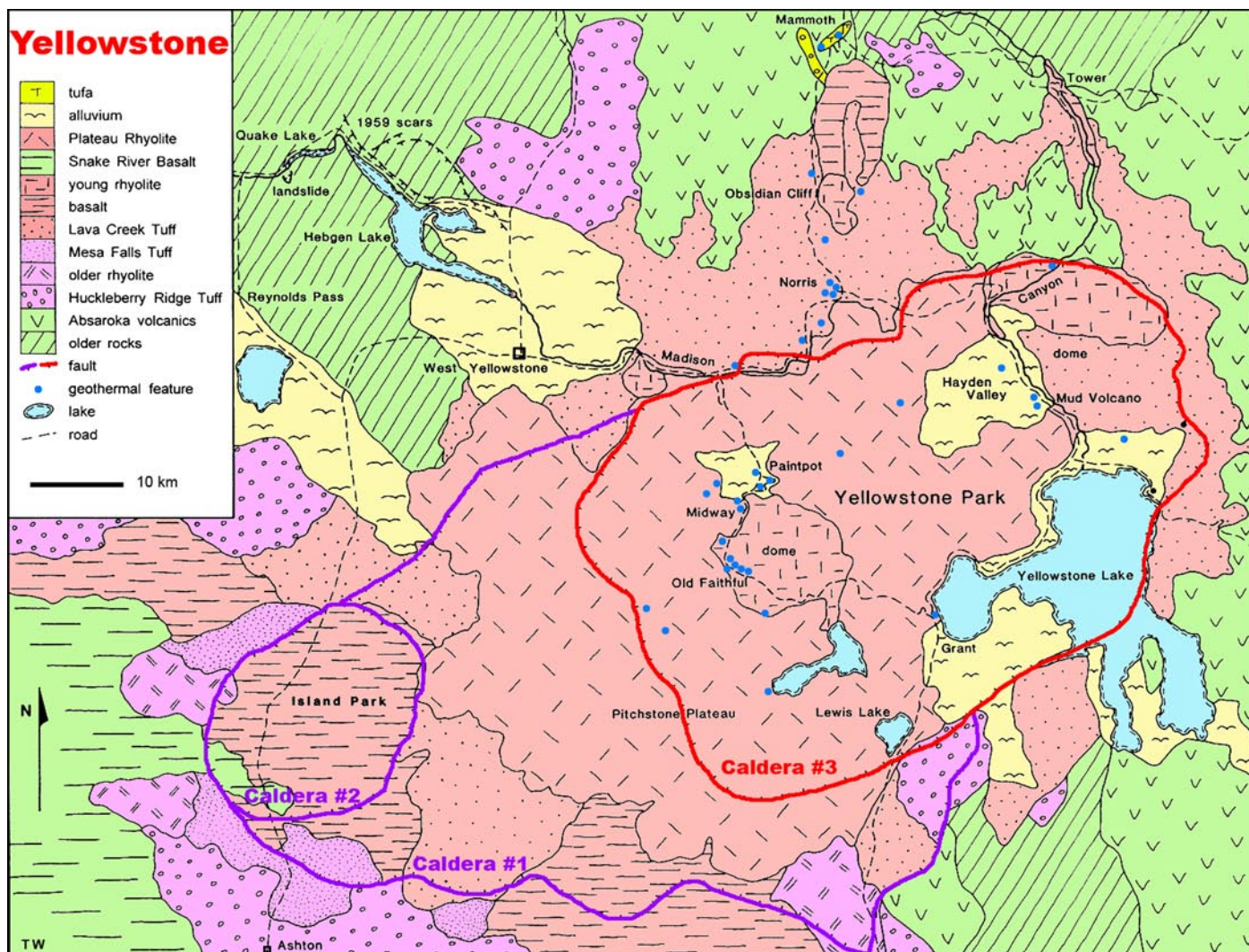
Astride America's continental divide in the Wyoming Rockies, Yellowstone is a magnificent park, seething with elk, moose, buffalo and many other wild animals. It also contains the world's largest concentration of active geothermal features, including 200 erupting geysers. Even though it was only fully explored by the Hayden expedition as late as 1871, it is now a major tourist attraction and a highlight of American's beloved 'great outdoors'. Wildlife, wilderness and geological marvels are wrapped in lovely pine forest; the fires of 1988 took out great swathes of trees, but regrowth is now well established, and many of the geological features are

more clearly seen where dramatic, skeletal trunks obscure less than did dense foliage. Excellent roads, boardwalk trails, lodges and all conceivable facilities make everything so very accessible, and any geologist will find a visit totally enthralling.

The geological setting

Yellowstone Park occupies a broken plateau composed of the eroded remains of three main cycles of dominantly rhyolitic volcanism. Each cycle went through a similar sequence of phases. For over 100 000 years, rhyolite lavas emerged from frac-

Fig. 1. Outline geological map of Yellowstone.



tures over a growing magma chamber. There was then a violent, explosive eruption, producing hundreds of cubic kilometres of rhyolite tuff within a few days, followed immediately by a caldera collapse. Lesser rhyolite eruptions continued for another 100 000 years, and there were minor episodes of basalts and rhyolites between times.

Each of the three cycles was centred on its own caldera, offset from its predecessors (Fig. 1). The large ancestral caldera collapsed about two million years ago, when the 2400 km³ of Huckleberry Ridge Tuff was produced. The smaller Island Park caldera and the 270 km³ of Mesa Falls Tuff date from 1.3 million years ago. The Yellowstone caldera and the 980 km³ of Lava Creek Tuff are only about 610 000 years old. The climactic explosive eruptions of the pyroclastic flows which deposited the thick tuffs and ignimbrites must have been awesome; contrast their volumes with the 25 km³ of tuff ejected at Katmai, Alaska, in 1912. Subsequent volcanism has produced the Plateau Rhyolite lavas from fissures within the last caldera; these erupted in three episodes peaking around 150, 110 and 70 thousand years ago. The West Thumb arm of Yellowstone Lake may occupy a small fourth caldera, which collapsed when the earliest of these phases of rhyolites were extruded. Only fragments of the calderas' walls can be recognized in today's topography – where they have not been buried by later tuffs or lavas.

The background to Yellowstone's volcanic activity lies with the subducting margin of the Pacific and its associated, smaller, oceanic plates. The convergence zone is distinguished by the rapid westward advance of the American plate, which appears to have overrun the less powerful divergence zone of the East Pacific Rise, whose main output is basaltic material despatched westwards as the Pacific Ocean floor. Further north, the rapid westward advance of the American plate has overrun a rising mantle plume which produced the Columbia basalts. The trailing plume tail produced volcanism on a declining scale, represented by the Snake River basalts, as the earlier flood basalts moved west on the American plate. The explosive andesitic volcanics of Yellowstone were then produced from within the continental crust by heat energy from the remains of the underlying mantle hotspot. This broad concept is attractive, although it may be rather simplistic.

Hot springs and geysers

The hydrothermal activity, which continues today, lies mainly along fracture zones both inside and outside the third caldera, where descending groundwater, derived from rainfall, is heated at depth. Most hot water emerges at steady springs; some emerges from geysers with intermittent eruptions. Siliceous rhyolite and calcareous limestone are dissolved in the hydrothermal systems at depth. Silica is then redeposited (owing to temperature and pressure decline) as vein infillings underground and as subaerial geyserite (sinter) round many springs. Carbonate is deposited as travertine by a few springs, owing to carbon dioxide loss at the surface. Some hot springs emerge through alluvial clays, and therefore form boiling mud pools; almost none of the

clay is primary material from hydrothermal alteration of feldspars. Other systems are rich in sulphur derived from deep volcanic sources, although the Park does lack solfataras with pneumatolytic sulphur crystals.

Geysers are fed from deep reservoirs, overpressured in rock with restricted permeability. Water at about 200 °C rises into fissure system reservoirs, at depths of about 300 m, and then upwards again to a surface discharge at about 90 °C. The water cools by conduction to rock near the surface, but where the heat flow is high at depth the temperature rises to boiling. Where this boiling water produces steam bubbles, the water column in the conduit is shortened, so reducing the hydrostatic pressure in the lower sections of the reservoir; and the boiling temperature is lower at lower pressure. Flash boiling of much more water therefore occurs in a chain reaction; this expansion drives a geyser eruption by ejecting overlying water within the upper conduit out of the vent (Fig. 2). The cycle ends when the system has temporarily lost too much water and heat. An imminent eruption can often be recognized when hot water starts to overflow the lip of the vent.

The geothermal features of Yellowstone are largely grouped into a handful of quite small areas, each of which has been developed as a visitor site. Trail guides and signposts make it easy to find most features. A visiting geologist does well to visit all the main sites, and there are a few noteworthy geological gems along the connecting roads. Other sites include Eocene fossil forests and smaller geyser basins, but are only reached by back-country hiking. Conditions at the geothermal sites do vary as their hydraulic conduits become choked or enlarged, and many features also changed their eruptive styles after the 1959 earthquake focused at Hebgen Lake, just west of the Park.



Fig. 2. Boiling water and steam ejected from inside the geyserite rim at Castle Geyser. (All photographs are by the author.)

Upper Geyser Basin

In the heart of the Yellowstone caldera, the valley of the Firehole River lies over a fracture zone between two plateaus of young rhyolite, and contains three separate geothermal basins. The Upper Geyser Basin is the largest and most spectacular; nowhere else in the world has so many geysers within sight of each other, and with such regular eruptions that the visitor is never disappointed. Old Faithful is just the most regular and most famous of an amazing cluster of over 30 geysers, and the Upper Basin also has a host of hot pools and splendid deposits of siliceous geyserite; there is no mud or travertine in the basin.

Old Faithful is at the crest of a low geyserite dome now surrounded by rows of viewing benches. It erupts to about 40 m high for 2–5 min, usually at intervals of 45–100 min, and its powerful jet is singularly beautiful. All the other geysers are a few minutes walk down the valley. Grand Geyser has multiple eruptions each lasting 10 min and reaching 50 m high, about every 10 h. It is now the largest because Giant Geyser has been dead since 1955. Castle Geyser (Fig. 2) has a distinctive geyserite cone and erupts to 20 m high every 11 h. Grotto Geyser is much smaller and emerges from weirdly shaped sinter deposits over some dead tree trunks. Riverside Geyser (Fig. 3) is a bit different; it erupts about every 6 h (after an hour when water spills from its mouth) to hurl its water 20 m high obliquely out over the river.

Justifiably most famous of the boiling springs, the deep pool of Morning Glory is coloured by bands of temperature-dependent algae; sadly its temperature gradient and therefore its colour banding have been rather reduced by the junk thrown in by past generations of thoughtless visitors. Nearer to Old Faithful, Geyser Hill is a steam-



Fig. 4. The boiling pool of Punch Bowl Spring, with a siliceous geyserite rim nearly a metre high.

ing mound of geyserite with a trail past Doublet and many other beautiful hot pools of clear water decorated by their silica deposits. Crested Pool and Punch Bowl Spring (Fig. 4) are both notable for their raised geyserite rims. Beyond the latter, Black Sand Basin is worth the longer walk, as it has fewer visitors and contains the magnificent Emerald Pool coloured by green algae. Unusual tabular deposits of geyserite gave the name to Biscuit Basin, but this site is less appealing since the springs were damaged and left inactive by an earthquake in 1959.

North of Upper Basin is Midway Geyser Basin (Fig. 5). Before 1888, Excelsior Geyser regularly erupted to heights of 100 m, and blasted out a huge crater. This is now occupied by the Grand Prismatic Spring, which yields 15 m³ of boiling water per minute, but there has been only one eruption of the geyser in the last 110 years. Next to it, Grand Prismatic Spring is a hot pool 100 m across surrounded by geyserite slopes and algal mats with the most beautiful colouring. In the Lower Geyser Basin, Fountain Paint Pot is a spectacular pool of boiling mud, with steam bubbling through alluvial clay coloured by iron oxides; its performances vary with the rainwater conditions. The main basin is crossed by a boardwalk loop trail past many small geysers, including Clepsydra, which spouts continuously. The adjacent Firehole Lake Drive passes the rimstone terraces of Great Fountain Geyser, which erupts to 40 m for about 1 h, usually twice a day.

North of Lower Basin, the Firehole Canyon loop road should not be missed, preferably in afternoon sunlight. It has an excellent roadside cliff exposure of the brecciated front of a flow-banded rhyolite lava which emerged onto the caldera floor about 150 000 years ago.

Norris Geyser Basin

Steam reservoirs at about 270 °C underlie this geothermal zone within the Lava Creek Tuff, where loop trails reach round two spectacular geyser basins. Porcelain Basin has extensive and very beautiful white terraces of siliceous sinter, most of which is precipitated from neutral water that emerges at many small geysers in almost continuous eruption. Some of the white material is tuff leached by separate highly acidic waters, and may be recognized by its surviving quartz phenocrysts.

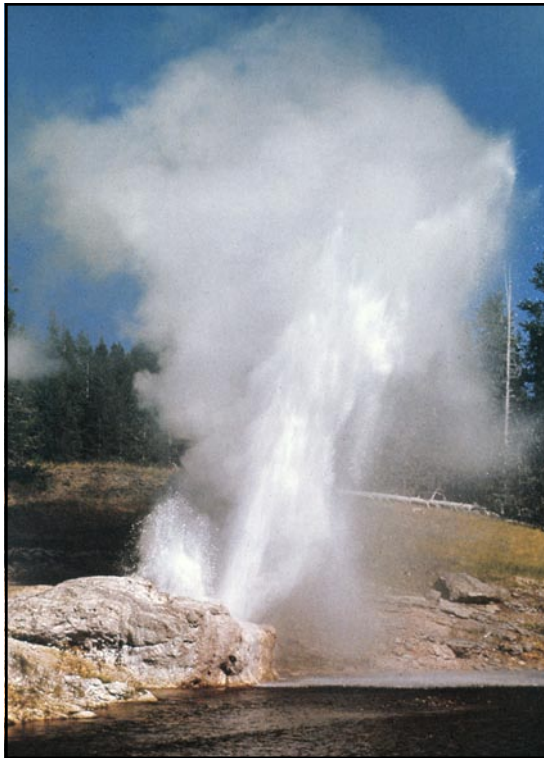


Fig. 3. Riverside Geyser hurling water out over the Firehole River.



Fig. 5. Steam clouds produced by the many boiling springs in the Midway Basin.

The adjacent Back Basin has a series of isolated pools and geysers in the forest. Emerald Pool has water 8 m deep at over 90 °C, with sulphur deposits at the edge; its colour is again due to green algae in acidic water. Steamboat Geyser erupts to over 100 m high, but only rarely and unpredictably. Echinus Geyser is notable because it displays its full eruption cycle so clearly, about every 75 min. Water level in the vent conduit is normally low, but rises for 20 min to reach its overflow level just before each eruption; this is due to the steam expansion at depth. The reduction of pressure within the conduit, due to the overflow loss of water, then allows flash boiling, and an eruption 15 m high lasts about 5 min. This dies down when the heat is lost from the system, and water then drains back into the cooled vent. The basin has had one less geyser since 1989, when Porkchop Geyser blew up and ruptured its plumbing system; its final water column hit 30 m high, before it blew out rocks of up to 2 tonnes each. Broken geyserite still lies around the peaceful boiling spring which remains.

South of the Norris Basin, a short and easy trail leads to Artist's Paintpot with its strongly coloured hot spring pools and a very fine basin of boiling mud. On the opposite side of the Gibbon Canyon, a steep trail takes energetic hikers up to the Monument Basin; there the fumaroles have built splendid geyserite columns 2 m high, which pour forth steam like chimney stacks (Fig. 6).



Fig. 6. Steam emerging from the top of a narrow geyserite tower on one of the fumaroles in the Monument Basin.

Mammoth Hot Springs

Well outside the Yellowstone calderas, this northernmost geothermal area has no geysers but is distinguished by its massive terraced deposits of travertine, which is essentially calcareous geyserite. Geothermal water circulates through subsurface reservoirs within Palaeozoic and Mesozoic limestones, where it becomes saturated with carbonate. It then rises on deep fractures, and emerges at temperatures around 70 °C, where it loses carbon dioxide by diffusion to the atmosphere, and so has to precipitate the carbonate. Travertine deposition is most rapid where thin films of water flow over ridges, so rimstone accumulates round self-damming pools, to create the terraced profiles with their endless variation of detail (Fig. 7). It is estimated that Mammoth now grows by deposition of about 2 m³ of new travertine per year.

Massive travertine deposits extend north-eastwards from the main hot springs which are high in the forest, down beneath the Mammoth Inn and visitor centre, and onward to the river, but only the central area is currently active. Just above the main road, Jupiter and Minerva Springs are beautifully terraced and are coloured by iron oxides and various algae. Boardwalks lead past the best of the sights, and on to the top of the main terraces, where Canary Spring is now very active (Fig. 8). A road loops round the highest terraces, which until the 1930s were the main attraction at Mammoth; but groundwater patterns are continually changing and the upper area now has little fresh deposition. Just north of Minerva, the Palette terraces are now some of the most beautiful; below them, Liberty Cap is a tower of travertine 12 m tall built around a geothermal spring, before its activity ceased when the emergent water found an alternative and lower exit. Opal Terrace, just across the road, has been formed by renewed deposition which only started in 1926.

The road south from Mammoth to Norris passes a few notable features. The Hoodoos are landslide blocks of old, grey travertine which have come down from the west, and the Golden Gate gorge has a high road-cutting which exposes thick, welded Huckleberry Ridge Tuff of the ancestral caldera stage. Looming over the road, Obsidian Cliff is formed by the chilled margin of a rhyolite flow which occupies a palaeovalley. The obsidian is banded with dark glass and white devitrified lava, and also by sheets of devitrification spherulites; small white lithophysae are crystal linings in gas bubbles. It was worked by the local Indians for stone tools, and it is easily seen (but not collected) in the cliff-foot screes. Just to the south, Roaring Mountain was named after noisy fumaroles, but has been silent since a terminal crescendo in 1902.

Yellowstone Canyon

The canyon of the Yellowstone River has a late Pleistocene history of fluvial erosion, which was interrupted by periodic growth of the volcano, caldera collapse, repeated filling by tuffs, and glacial occupation.

In Stage 1, a large valley was cut into Eocene Absaroka volcanics on the flank of a Pleistocene



Fig. 7. Travertine terraces at the Mammoth Hot Springs.

volcanic pile outside the caldera, whose lake was then draining the opposite way, out to the south. It was then filled by lavas (including the Canyon rhyolite) and glacial sediments, and re-excavated to smaller dimensions.

Around 150 000 years ago, and towards the end of an Illinoian (Wolstonian) ice maximum, the caldera's drainage outlet was blocked by new rhyolite lavas. In Stage 2 of the Canyon, this new overflow crossed the caldera rim and fed into the older and lower section of the canyon. The first stage of the upper canyon (between the modern waterfalls and the caldera rim) was a narrow incision into a linear zone of hydrothermal alteration within the Canyon rhyolite. It was subsequently filled with fluvial sediments; the floor of these survives at Red Rock, 100 m below the rim and 130 m above the present canyon floor.

In Stage 3, the modern canyon was offset from its Red Rock line either by its clastic fill or by ice. Though cut largely during the Devensian cold phase, it is a fluvial feature. It was filled and overrun by the Pinedale (late Devensian) ice sheet, but

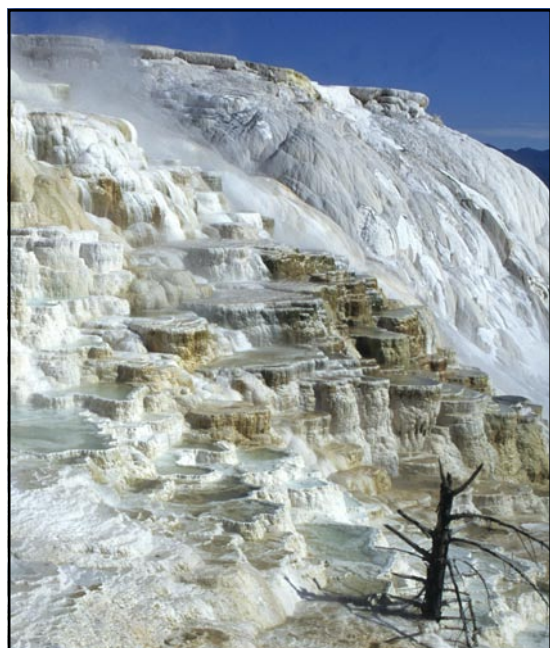


Fig. 8. A cascade of travertine terraces which has almost engulfed a tree stump below the Canary Spring.

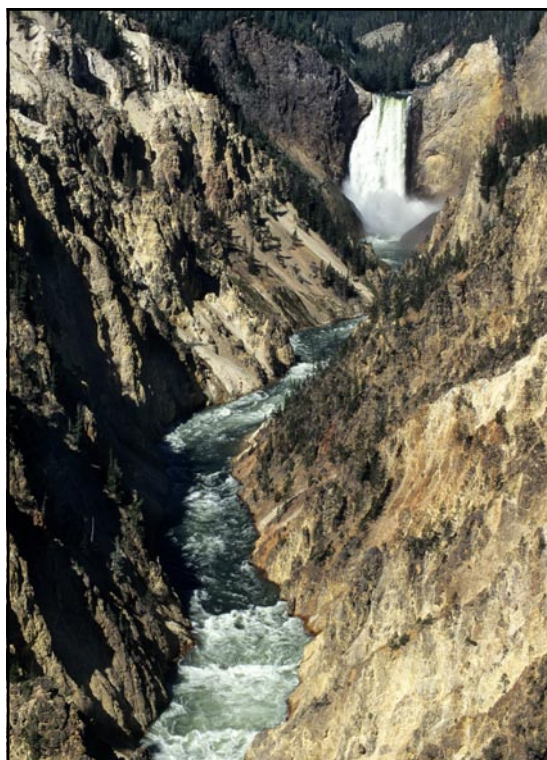
there was no significant glacial erosion so close to the ice source area. The two waterfalls were created where the river cascades across the strong unaltered margin of the Canyon rhyolite.

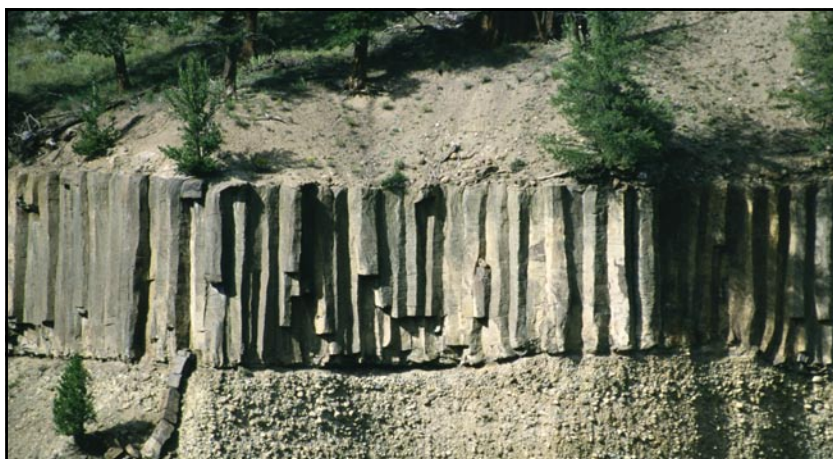
The trail along the northern rim of the canyon is well worth walking, especially for the 2 km from Grandview to the Upper Falls. Lookout Point has the best view of the Lower Falls; a steep band of unaltered rhyolite forms the lip of the waterfall, with the softer, altered core of the Canyon flow exposed below a dipping boundary. Red Rock Point is below the rim, and both it and the intervening gully are in a remnant of sand fill within Stage 1 palaeocanyon. A side trail descends 150 m past exposures of Canyon rhyolite, to the brink of the Lower Falls, for spectacular views down the water and across to a nearly vertical margin of the rhyolite; the river flows from soft tuffs, over the hard marginal zone of rhyolite at the falls lip, and cascades into the soft altered core of the Canyon lava. Around Cascade Creek, a flow front of the Canyon rhyolite has boulders contained in a white matrix of reworked tuff. The rim trail continues to the brink of the Upper Falls, which are over the hard margin of the Canyon rhyolite.

On the south side of the canyon, Artist Point provides an excellent viewpoint. Downstream, the V-profile is cut into both the brightly coloured, hydrothermally altered and oxidized Canyon rhyolite and the overlying, nearly indistinguishable Sulphur Creek tuff; upstream, the Lower Falls drop 94 m at the head of the deepest section of canyon (Fig. 9). A separate viewpoint overlooks the Upper Falls; these descend 33 m off the edge of the Canyon rhyolite into a plunge pool cut in the soft younger tuffs and sediments which formed in a lake against the flow margin.

The lower end of the canyon is of totally different character, and can be seen around the Tower

Fig. 9. The Yellowstone River canyon, cut into altered rhyolite, seen from Artist Point looking towards the Lower falls.





Fall visitor site. The waterfall on Tower Creek drops 40 m beneath towers which are eroded in coarse Lava Creek Tuff. The creek's outlet is into a late Stage 1 Yellowstone Canyon excavated in the fill of gravels and basalts inside the earlier Pleistocene valley. There is no correlation of beds across the canyon, because lavas filled successive trenches in the gravels, so that each subsequent trench was offset away from the resistant lava. Just north of Tower, the road follows undercuts in gravel beneath overhangs of columnar basalt; columns of different diameters grew from both top and floor until they met in the middle of the single flow, and the baked mud beneath the lava flow is clearly exposed. Viewpoints overlook The Narrows, where the Yellowstone River lies in a trench around the edge of a large remnant of the Pleistocene valley fill. The canyon walls expose Pleistocene lavas of columnar basalt (Fig. 10) between beds of glaciofluvial gravel, with classic earth pillars eroded out of the weathered Absaroka volcanics beneath. Hot spring deposits in the canyon floor are travertine.

A spur road just west of Tower reaches to the Petrified Tree. It is a silicified Eocene redwood 1 m in diameter which has 6 m of its trunk, upright and in position of growth, exhumed from the Absaroka volcanics which entombed it.

Mud Volcano

This geothermal area is on the western flank of the Sour Creek dome, beneath which molten rock appears to lie at the shallowest depth within the Park. It is distinguished by water sources which have large contents of clay, derived mainly from the sediment fill of the Hayden Valley. There is also an excess of sulphur, creating hydrogen sulphide, sulphuric acid and sulphur dioxide. The Sour Creek dome is currently rising at 15 mm per year, and is distinguished by a negative gravity anomaly and a zone of low seismic velocities; it is probably underlain by partially molten rock at a depth of about 3000 m. After a modest earthquake swarm in 1978, some sites changed considerably, and there was an overall decrease in heat flow and vent activity.

A loop trail provides easy access to all the features. The Dragon's Mouth and Mud Volcano each have violent steam fumaroles breaching water and mud in their surface pools. Grizzly Fumarole is either a mesmerizing mudpot (Fig. 11) or a group

Fig. 10. Columnar basalt of a lava flow between the gravels, exposed in the Narrows of the Yellowstone River.

of dry steam vents, depending on the amount of recent rainfall infiltration to the ground. Sour Lake produces acidic steam which kills off the nearby trees. Black Dragon's Cauldron only started activity in 1948, and has since migrated to the south; steam almost explodes through its pool, which has faded from black to grey in recent years. The Churning Cauldron is now the most active of the steam-churned pools, but the Mud Geyser has not erupted since 1871. Across the road, Sulphur Cauldron is yellow with sulphur and clay, and a vent in the carpark has yielded steam ever since the road was cracked during the changes wrought by the 1979 earthquake.

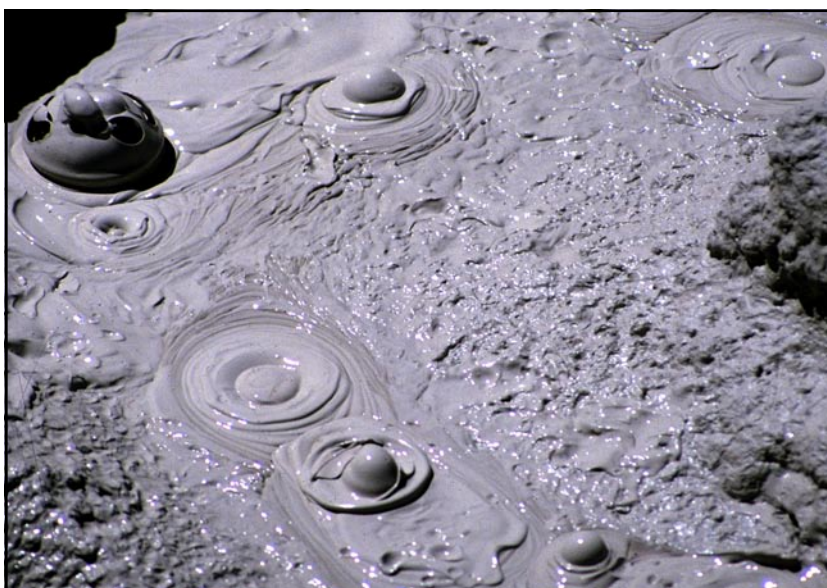
Immediately north-west of Mud Volcano, Hayden Valley is floored by lacustrine silts, whose terraces mark incision stages of the outlets from the Pleistocene caldera lake. The open grassland is often the best place in the Park to see buffalo, elk, moose and the occasional bear. East of the Sour Creek dome, the Pelican Creek basin has been heating up since 1990, and one fumarole has evolved into a very active mud volcano which has even extruded long flows of hot mud; it is only reached by a long back-country hike.

Access to Yellowstone Park

As the centrepiece of the American National Park system, Yellowstone is very easy to visit. Roads and facilities are excellent, and boardwalks provide access to all the geothermal features – across ground which is potentially dangerous where thin geyserite crusts overlie hot mud and boiling water. At both the Old Faithful and Norris visitor centres, display boards predict approximate times for the next eruptions of the larger active geysers.

The mountain weather limits the tourist season to the six months of May to October, but there is also a winter season of three months starting at Christmas, when the Park roads can be traversed by snowmobiles. Accommodation within the Park is not expensive, but does require advance booking; it is worth some effort to reserve a room for a night at the magnificent Old Faithful Inn. There

Fig. 11. Boiling mud at Mud Volcano.



Geological visitors to Yellowstone should also take in some notable features outside the Park. The landslide and fault scarps of the 1959 earthquake at Hebgen Lake are just north of West Yellowstone (Fig. 1). South of the Park, the fault block of the Grand Tetons lies in another National Park with some fine granites, moraines and terraces, and the 1925 Gros Ventre landslide is just outside its south-eastern boundary. And every visitor is recommended to make one early morning start while at Yellowstone – to walk or drive to Old Faithful, and then take a stroll around the Upper Geyser Basin; this can be truly magical when the steam is at a maximum in cool dawn air, especially if there is a morning mist which clears in patches over the warmer ground.

Suggestions for further reading

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- Good, J.M. & Pierce, K.L. 1996. *Interpreting the Landscapes of Grand Teton and Yellowstone National Parks*. Grand Teton Natural History Association, 58pp.
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left: Old Faithful geyser in winter.
below left: Morning Glory pool.
below: Grand Geyser in eruption.

