

Figure 1. Location of the Panther Creek volcano and Swan Lake Flat basalt between Mammoth and Norris Junction. (Box indicates the area covered in Figure 6.)

Panther Creek Volcano

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MANY PEOPLE MAY NOT REALIZE that the volcanoes we see on the Earth's surface have a variety of sizes and shapes. Volcanoes are some of the world's most spectacular phenomena. During an eruption, molten rock (magma) accumulates in the form of lava flows and pyroclastic material to form a volcano. The nature of an eruption is controlled by many factors, including the temperature, gas content, and composition of the magma. Higher-temperature basaltic magma may erupt quietly to form broad shield volcanoes similar to those on the island of Hawaii, or may erupt explosively to produce cinder cones like those at Craters of the Moon National Monument, Idaho. Lower-temperature rhyolitic magma may produce lava domes and flows or generate explosive eruptions that in extreme cases may result in ash-flow tuffs and caldera formation (a supervolcano). Volcanoes are complex features that develop over time by means of different types of eruptions. If conditions change during an eruption,

the nature of the volcano may change. Even smaller volcanoes can be quite complex and be formed in a series of phases. One of the main goals of volcanology is to unravel this complexity and determine the geologic history of volcanoes.

Yellowstone National Park is a natural laboratory for the study of volcanoes. In the park, the most famous volcano is the Yellowstone Caldera, or supervolcano. Additionally, but less well-known, are numerous rhyolite domes and flows, and basaltic shields and cinder cones. This paper focuses on the geologic history of the Panther Creek basalt volcano, which we discovered during our mapping just west of the Norris-to-Mammoth road. This volcano is the source of the basalt at Sheepeater Cliff. Also discussed are other basalt volcanoes located north of the Yellowstone Caldera between Norris Junction and Mammoth Hot Springs, and especially on basalt exposures near Swan Lake Flat (Figure 1).

Background

The area between Norris Junction and Mammoth Hot Springs is well known for geyser basins and hot springs. This corridor also contains numerous rhyolite and basalt flows and volcanoes. The best place to see a rhyolite flow in this area is at Obsidian Cliff. The glassy rhyolite obsidian observed here covers an area of about five square kilometers and erupted 106,000 years ago. Rhyolite usually rises from magma chambers deep in the crust (1 km or more) to the surface through narrow linear fissures or semi-circular conduits. It is likely that most of the Obsidian Cliff rhyolite erupted to the surface and little remains underground.

The majority of the basalt in the corridor predates eruption of the Obsidian Cliff rhyolite (Spell et al. 2004). Basalt mainly occurs as flows and broad lava shields of the Swan Lake Flat basalt (Christiansen 2001). Swan Lake Flat basalt can be easily seen at the Sheepeater Cliff roadside exhibit, where lava flows display spectacular columnar jointing. The volcanoes, lava flows, and thermal areas of the Norris-to-Mammoth corridor lie to the north of the Yellowstone supervolcano, a caldera that erupted the widespread Lava Creek tuff about 640,000 years ago (Christiansen 2001).

Basaltic volcanism is relatively rare in Yellowstone National Park (YNP), but very common to the west, in the Snake River Plain. The reason for this is unclear, but the Snake River Plain follows an ancient boundary between blocks of crust of different ages. Perhaps basalt was able to rise more easily to the surface through this boundary zone. In YNP and adjacent areas, basaltic volcanism younger than the Lava Creek tuff began about 588,000 years ago, with the eruption of the Undine Falls basalt. This was followed by basalt eruptions in the western part of the park along the Madison River 355,000 years ago. Finally, Swan Lake Flat and Osprey basalt erupted in the Norris-to-Mammoth corridor between 350,000 and 209,000 years ago (Bennett and Smith 2004; Smith and Bennett 2004; Spell et al. 2004).

Basalt and rhyolite volcanism are closely related. In the early 1980s, Wes Hildreth of the U.S. Geological Survey suggested that basalt magma was “fundamental” in the production of rhyolitic magma, the type that might result in explosive volcanic eruptions and caldera formation (Hildreth 1981). In his model, basalt is the fuel that runs the magma engine: as it rises from its place of origin in the mantle, basalt magma carries heat from the mantle into the crust. This heat causes melting of crustal rock, producing rhyolitic magmas. If enough rhyolite magma is created, it may coalesce into a large magma chamber.

Magma and rock density control how close to the surface magma can rise. Magma rises because it is less dense than the confining rock. Because rhyolite magma is less dense than basaltic magma, rising basalt magma stalls beneath low density barriers produced by pooled rhyolitic magma. The stalled

Glossary

Two of the best places to find definitions of volcanology terms are the U.S. Geological Survey Photo Glossary of volcanology terms, <<http://volcanoes.usgs.gov/Products/Pglossary/pglossary.html>>, and the Volcano World web page produced by the University of North Dakota, <<http://volcano.und.nodak.edu/vwdocs/glossary.html>>.

Common terms used in the paper, modified from the Volcano World web page:

Agglutinated scoria: A pyroclastic deposit consisting of an accumulation of originally plastic and partially molten ejecta and formed by the sticking together of the fragments upon solidification.

Ash-flow tuff: A turbulent mixture of gas and rock fragments, most of which are ash-sized particles, ejected violently during a caldera-forming eruption. The mass of pyroclastic material is normally of very high temperature and moves rapidly down the slopes or even along a level surface.

Basalt: Dark-colored volcanic rock (or lava) that contains 45–54% silica, and generally is rich in iron and magnesium.

Block: Angular chunk of solid rock ejected during an eruption.

Bomb: Fragment of molten or semi-molten rock, 2½ inches-to-many feet in diameter, which is blown out during an eruption. Because of their plastic condition, bombs take on aerodynamic shapes during their flight or upon impact.

Caldera: The Spanish word for cauldron, a basin-shaped volcanic depression; by definition, at least a mile in diameter. Such large depressions are typically formed by the evacuation of a magma chamber. Ash-flow tuffs are commonly related to the formation of calderas.

Cinder cone: A volcanic cone built of loose, fragmented pyroclastic material, scoria, and agglutinated scoria. Cinder cones may have a summit lava lake. Lava flows commonly erupt from the base of cinder cones.

Crust: Solid, outer layers of the Earth, including the rocks of the continents.

Crater: A steep-sided, usually circular depression formed by either explosion or collapse at a volcanic vent.

Dike: A sheet-like body of igneous rock that cuts across layering or contacts in the rock into which it intrudes.

Dome: A steep-sided mass of viscous (doughy) lava extruded from a volcanic vent (often circular in aerial view) and spiny, rounded, or flat on top. Its surface is often rough and blocky as a result of fragmentation of the cooler, outer crust during growth of the dome. Rhyolite magma commonly forms domes. Rhyolite along the margins of domes is glassy and forms obsidian. Banding in the rhyolite (called flow banding) reflects the flow patterns of

lava in the dome.

Fault: A fracture in the Earth's surface along which movement occurs. Movement along the fault can cause earthquakes.

Fault scarp: A steep slope or cliff formed directly by movement along a fault and representing the exposed surface of the fault before modification by erosion and weathering.

Fissures: Elongated fractures or cracks on the slopes of a volcano. Fissure eruptions typically produce liquid flows, but pyroclastics may also be ejected.

Lava: Magma that has reached the surface through a volcanic eruption. The term is most commonly applied to streams of liquid rock that flow from a crater or fissure. It also refers to cooled and solidified rock.

Lava flow: An outpouring of lava onto the land surface from a vent or fissure. Also, a solidified, tongue-like or sheet-like body formed by outpouring lava.

Magma: Molten rock beneath the surface of the earth.

Magma chamber: The subterranean cavity containing the gas-rich liquid magma that feeds a volcano.

Mantle: The zone of the Earth below the crust and above the core.

Obsidian: A black or dark-colored rhyolitic volcanic glass.

Pyroclastic: Pertaining to fragmented (clastic) rock material formed by a volcanic explosion or ejection from a volcanic vent.

Rhyolite: Volcanic rock (or lava) that characteristically is light in color, contains 69% silica or more, and is rich in potassium and sodium.

Scoria: A bomb-sized (> 64 mm) pyroclast that is irregular in form and generally vesicular. It is usually heavier, darker, and more crystalline than pumice (light-colored, frothy volcanic rock, usually of dacite or rhyolite composition, formed by the expansion of gas in erupting lava).

Shield volcano: A gently sloping volcano in the shape of a flattened dome and built almost exclusively of lava flows.

Vesicle: A small air pocket or cavity formed in volcanic rock during solidification.

Volcano: A vent in the surface of the Earth through which magma and associated gases and ash erupt; also, the form or structure (usually conical) that is produced by the ejected material.

basaltic magma acts like a burner on a stove and continuously heats the overlying pool of rhyolitic magma. In this way, rhyolitic magma bodies can grow in size and may survive in the upper part of the crust for long periods of time (20,000 years for small volumes of rhyolitic magma and up to one million years for large volumes). Eruptions from this magma chamber produce domes of rhyolite and ash-flow tuffs, and may result in caldera formation.

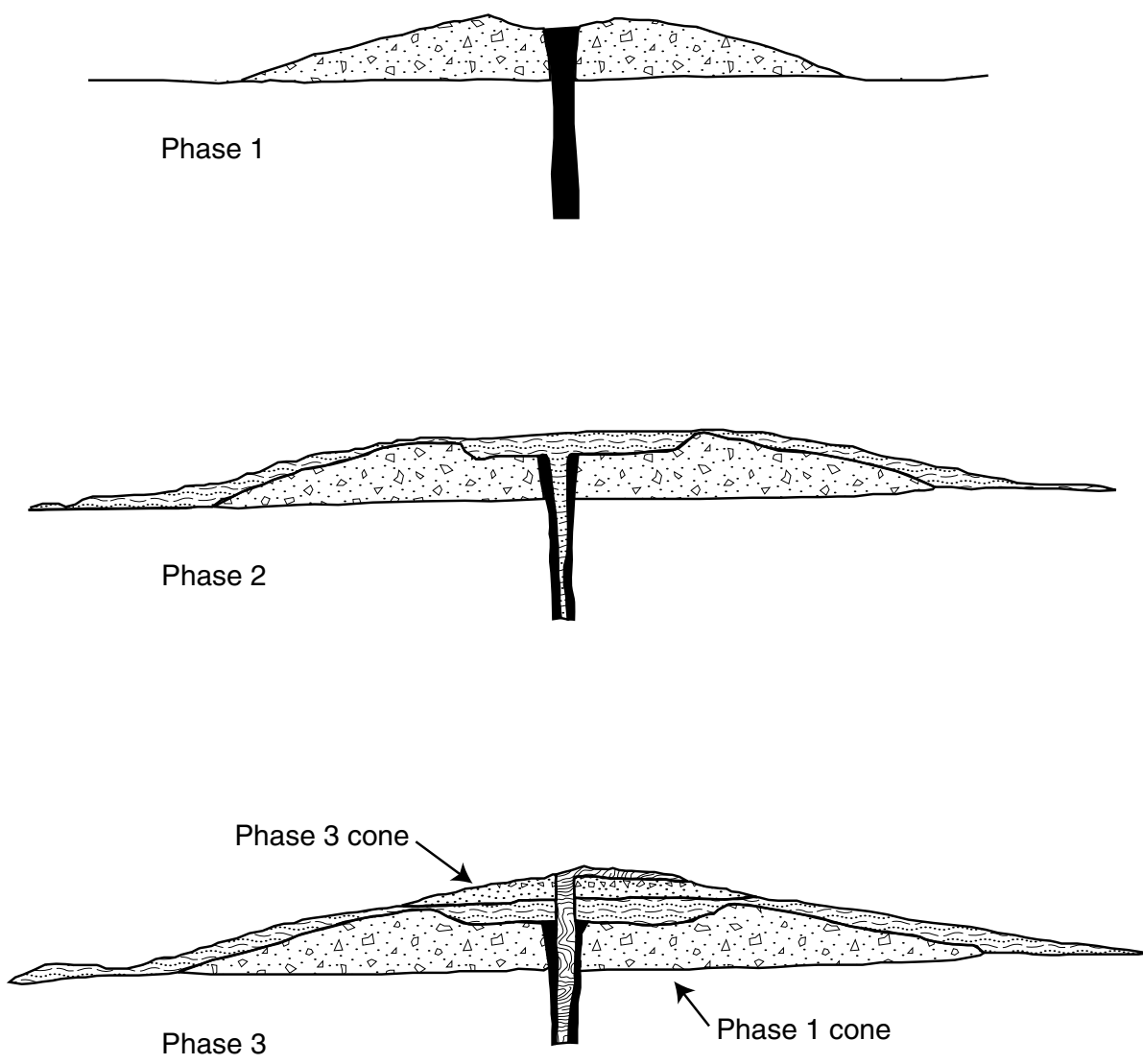
Volcanism in the Yellowstone area occurs at two scales. On one level are the huge eruptions that formed the Yellowstone supervolcanoes. Over the past 2.3 million years, three major eruptions produced three large calderas. The last of these produced the Yellowstone Caldera 640,000 years ago. On the other end of the scale are smaller eruptions that produce rhyolite domes and flows and basalt cinder cones and shield volcanoes. The two types of eruptions may be related. The smaller eruptions may either represent the last phase of a supervolcano eruption or, more ominously, the initial phase of a new supervolcano. Our study suggests that the basalt and rhyolite eruptions in the Norris-to-Mammoth corridor may represent the beginning of a new caldera cycle and perhaps the formation of a new supervolcano. This large event will probably not occur in the near future, but it is likely that smaller eruptions like those that have taken place over the past 500,000 years may become more likely.

Panther Creek Volcano

Mapping the Panther Creek volcano was difficult because of extensive vegetation cover and beveling of the volcano by glaciation. Erosion, however, has exposed the interior of the cone on its east side, allowing for a comprehensive study of its eruptive history. We know that the volcano was glaciated because boulders (erratics) of Precambrian metamorphic rock



The Panther Creek volcano, looking to the northwest. The prominent cliff on the south (left) side of the volcano is a lava flow formed during phase 2. The peak is formed by the phase-3 scoria cone.



Explanation






-  Phase 1 scoria cone
-  Phase 1 dike
-  Phase 2 lava-lake basalt, lava flows, and inner part of dike
-  Phase 3 scoria cone
-  Phase 3 lava flow and dike

Figure 2. Generalized eruptive history of the Panther Creek volcano. (Sketches are not to scale.)

sit directly on top of it. These erratics were probably carried from the nearby Gallatin Range and left on the volcano by retreating glaciers.

The Panther Creek volcano is perched on the edge of an east-facing cliff that may be an eroded fault scarp. This geologic structure is part of a broad, north-trending fault zone that extends the length of the Norris-to-Mammoth corridor. The fault zone probably provided a pathway for magma to reach the surface and controlled the location of the volcano. The Panther Creek volcano is about 0.75 km in diameter, and erupted lava flows that cover an area of approximately 6 km². Because Pleistocene glaciation has eroded the cone, it is impossible to determine its original height, but at present it is about 50 meters high.

The Panther Creek volcano formed in at least three stages, or phases (Figure 2). During the first phase, partially molten, reddish-brown scoria and bombs produced a broad cinder cone with a summit crater. At this point in its history, the volcano may have resembled one of the cinder cones at Craters of the Moon National Monument. Because fragments ejected during the eruption were hot, they welded together, forming agglutinated scoria. This type of eruption is commonly referred to as Strombolian (named for the volcanic activity on the island of Stromboli, Italy), and is characterized by episodic eruptions of cinder and scoria, commonly producing a cinder cone and associated lava flows. Incorporated in the scoria deposits are volcanic bombs, some of which are cored with partially melted “granitic” blocks (Figure 3). These blocks probably represent Precambrian crystalline rock that was incorporated in the rising magma and carried to the surface. Because the temperature of the basaltic magma is so much higher than the melting temperature of the granitic blocks (1,200°C vs. 700°C), the granitic blocks partially melted, producing a dark volcanic glass (obsidian).

The second eruptive phase produced a lava lake within the summit crater. Remnants of the lava lake are exposed near the summit of the cone as a one-meter-thick, massive basalt exposure that overlies the deposits of agglutinated scoria. The lava-lake basalt has subtle banding identified by alternating light and dark gray streaks (Figure 4). Besides differing in color, these light and dark streaks differ in mineral abundance and composition. The

light gray bands contain rectangular plagioclase crystals about 0.5 mm in size, and rare magnetite grains. The dark gray bands contain fewer, and smaller (<0.2 mm) plagioclase crystals, and larger and more abundant magnetite grains. This streaking and mineral zonation may reflect the mode of eruption of the lava-lake basalt. The summit crater may have filled with many thin surges of lava. Each flow (related to a single surge) stagnated in the crater for a period of time, allowing the denser magnetite to settle and the lighter plagioclase to rise. This process was repeated many times, producing the banded nature of the lava-lake basalt. An alternative way to produce the banding is by lava flow. Flow velocity is different in different parts of a lava flow, resulting in shear as faster parts of the flow move against slower areas. Flow shear can result in banding and mineral zonation. Flow banding, common in obsidian domes and flows, is produced in this manner.



Figure 3. Volcanic bomb in phase-2 scoria cored by a granite block.



Figure 4. Photograph of the subtle banding in the lava-lake basalt. The quarter coin on the ledge in the upper part of the photo is for scale.

Near the end of the second phase the lava lake overflowed, producing lava flows that traveled to the east toward Sheepeater Cliff, and toward the south to the present site of the Indian Creek campground. The flow near the Indian Creek campground is approximately 3.5 meters thick, while the flow exposed at Sheepeater Cliff is 8 meters thick. The total volume of the flows produced during this phase of activity is approximately 0.03 km³. Near the lava lake many of these lava flows have a swirly appearance. The visible swirls appear to be the same light and dark gray bands visible in lava-lake basalt. The swirly texture was formed by the folding of the bands as the lava flows spilled over the rim of the summit crater and down the slopes of the broad cone. Lava flows with this swirly texture are found as far south as Indian Creek, and as far north as 0.5 km southwest of Swan Lake.

During the third phase, the eruption produced a cone of welded scoria that sits on the lava lake deposits. The reddish-brown agglutinated scoria produced during this phase lacks the partially melted granitic blocks characteristic of the first eruptive phase. Much of these deposits has been eroded, so their original extent cannot be determined.

The conduit, or feeder dike for the Panther Creek volcano is exposed on the northeast side of the cone (Figure 5). Identifying the feeder dike is important because it represents the pathway to the surface of magma produced by partial melting of the mantle. Furthermore, it is strong support of the hypothesis that the Panther Creek feature is a volcano. Feeder dikes are often complex, because multiple batches of magma commonly use the same conduit to reach the surface. This is the case for the Panther Creek dike. Its outer part (about 25 cm wide) is



Figure 5. Contact of the dike (left) with phase-2 scoria (right). The contact is just to the right of the hammer. The hammer sits on the outer part of the dike; the more massive basalt (behind the tree and to the left of the hammer) is the central part of the dike.

massive basalt that contains a few crystals of plagioclase feldspar, and partially-melted granitic blocks 4–25 cm in diameter that are similar to those in the phase-1 scoria. We suggest that the outer part of the dike represents the conduit for the phase-1 scoria. The inner part of the dike is two meters wide and is also composed of massive basalt with small plagioclase crystals; however, it does not contain melted granitic blocks. This part of the conduit is probably responsible for the eruption of the lava-lake basalt, Sheepeater Cliff and Indian Creek lava flows, and the phase-3 scoria. Near the top of the inner dike, the dike appears to “turn over” and travel to the north as a thin, short flow that overlies the phase-3 scoria. This thin flow may be the last eruption from the Panther Creek volcano.

Swan Lake Flat Basalt

Christiansen and others (2001) identified three volcanoes related to Swan Lake Flat basalt. Our work showed that each of these volcanoes erupted at least one basalt flow (Figure 6). To the east of basalt flows erupted from the Panther Creek volcano is the Tower Road volcano, a broad, 120-m-high, shield-type volcano. This volcano is very difficult to study because it is covered by thick vegetation; however, it can be recognized as a volcano by its shield shape and by the occurrence of agglutinated scoria at its summit. Basalt flows radiated from this cone and



Tower Road shield volcano.

traveled to the Mammoth-to-Tower Fall road to the north and as far as eight km to the south. Two additional volcanoes are located just east of Obsidian Cliff. These features, called the Horseshoe Hill volcanoes, were the source of two flows. The western volcano erupted a flow that traveled nearly 30 km to the north, to just south of Sheepeater Cliff. The eastern cone erupted flows that abutted against basalt from the Tower Road cone. Another area of Swan Lake Flat basalt to the east of the Tower Road volcano appears to have erupted from another volcano, but its location has not yet been determined.

Radiometric dating is a precise way of determining the age of basalt flows. The technique is based on the principle of radioactive decay. Isotopes of potassium (potassium with a mass number of 40, or ^{40}K) present in feldspar crystals in

lava flows decay to an isotope of argon (argon with a mass number of 40, or ^{40}Ar). The decay takes place at a predictable pace, so that the amount of ^{40}Ar in feldspar is directly related to the age of the rock. Using a high-precision $^{40}\text{Ar}/^{39}\text{Ar}$ dating technique, we determined that Swan Lake Flat basalt erupted over a 150,000-year period. The youngest eruptions were from the Panther Creek volcano 209,000 years ago, and the oldest occurred at the Tower Road volcano 350,000 years ago.

Importance of the Panther Creek Volcano and Swan Lake Flat Basalt

An obvious question is why the discovery of the Panther Creek volcano and the study of Swan Lake Flat basalt are

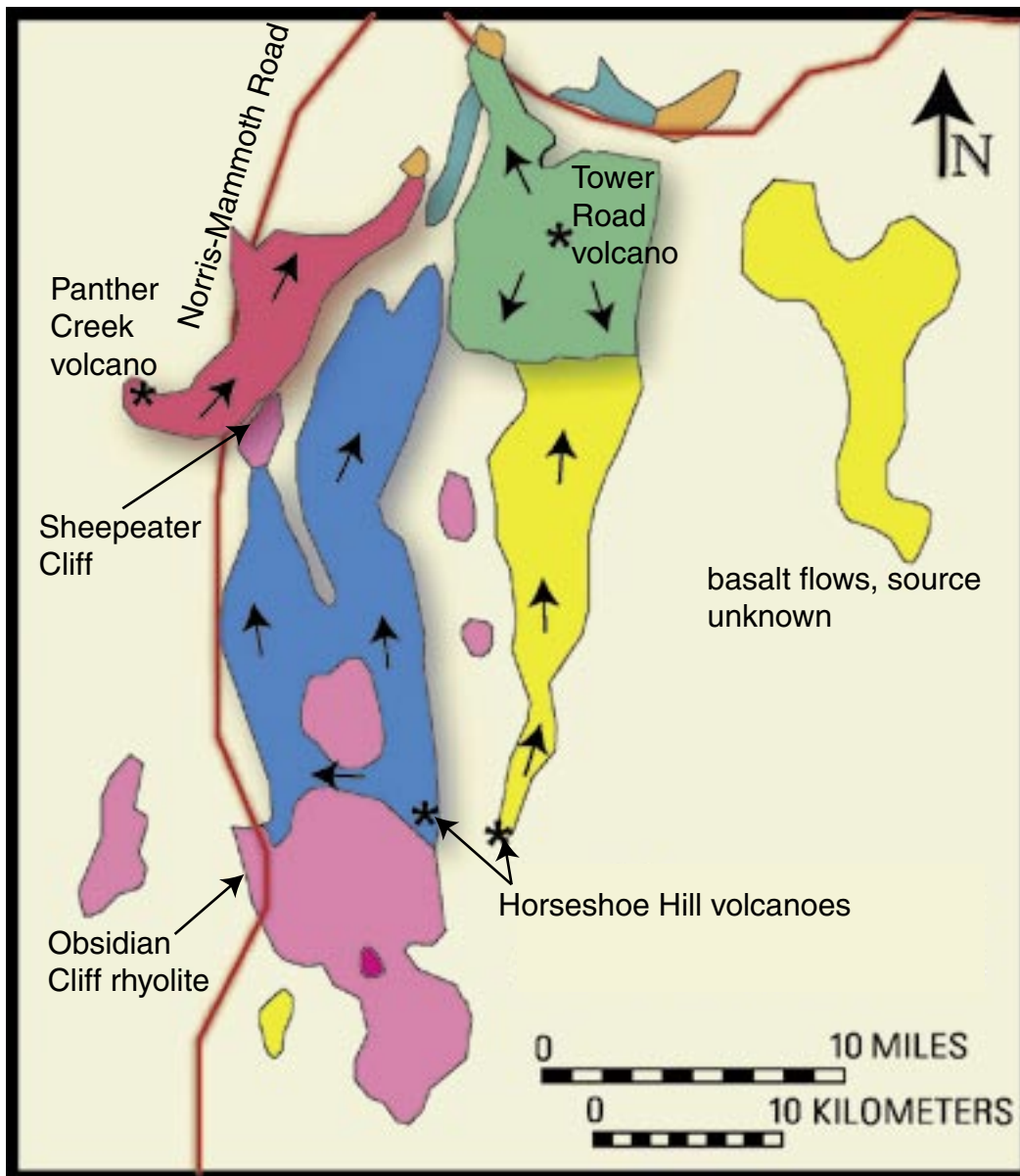


Figure 6. Generalized map showing the four volcanoes forming the Swan Lake Flat basalt (Panther Creek, Tower Road, and the two Horseshoe Hill volcanoes). Lava flows and approximate direction of flow (shown by arrows) are also indicated on the map.

important. In addition to satisfying scientific curiosity about the volcanic history of Yellowstone National Park and identifying a style of eruption that may be a future volcanic hazard, the study of the Panther Creek volcano and Swan Lake Flat basalt has important implications for understanding future volcanic activity. In the Norris-to-Mammoth corridor, eruptions of basalt occurred at roughly the same time as eruptions of rhyolite domes. The specific timing of eruptions, however, provides important clues to unraveling the area's volcanic history. The first eruptions of Swan Lake Flat basalt (350,000 years ago) immediately preceded the eruption of the first rhyolite dome (Willow Creek dome, 326,000 years ago). Contemporaneous production of basalt and rhyolite is demonstrated by the banded lavas found below Swan Lake Flat basalt at Sheep-eater Cliff. Mixing of basalt and rhyolite magma occurred between 316,000 and 263,000 years ago. In the corridor, basalt eruptions ended 209,000 years ago with the formation of the Panther Creek volcano, but rhyolite activity continued until 80,000 years ago. (This detailed chronology was determined by University of Nevada–Las Vegas graduate student Nicole Nastanski and her advisor, Dr. Terry Spell, using the $^{40}\text{Ar}/^{39}\text{Ar}$ dating technique.)

What are the implications of these events? We suggest that they support the model proposed by Hildreth (1981), and that they may represent the initial stage of a new caldera (supervolcano) event. Basalt magma acted as a heat source to produce rhyolite volcanism. At first, areas of rhyolite were small, and basalt found its way to the surface. After about 209,000 years ago, though, the area of rhyolite in the crust became large enough to block the rise of basaltic magma. If basalt is required to sustain rhyolitic eruptions, then basalt magma is still present in the crust but is trapped beneath a lid of rhyolite. If these observations and assumptions are correct, then they imply that a rhyolitic magma chamber may exist beneath the Norris-

to-Mammoth corridor, and that the corridor may be the site of future volcanic activity. Future studies of the Panther Creek volcano, Swan Lake Flat basalt, and rhyolite in the Norris-to-Mammoth corridor are critical to an understanding of future volcanism in Yellowstone National Park.

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