Geology of Craters of the Moon Booklet
Craters of the Moon National Monument & Preserve
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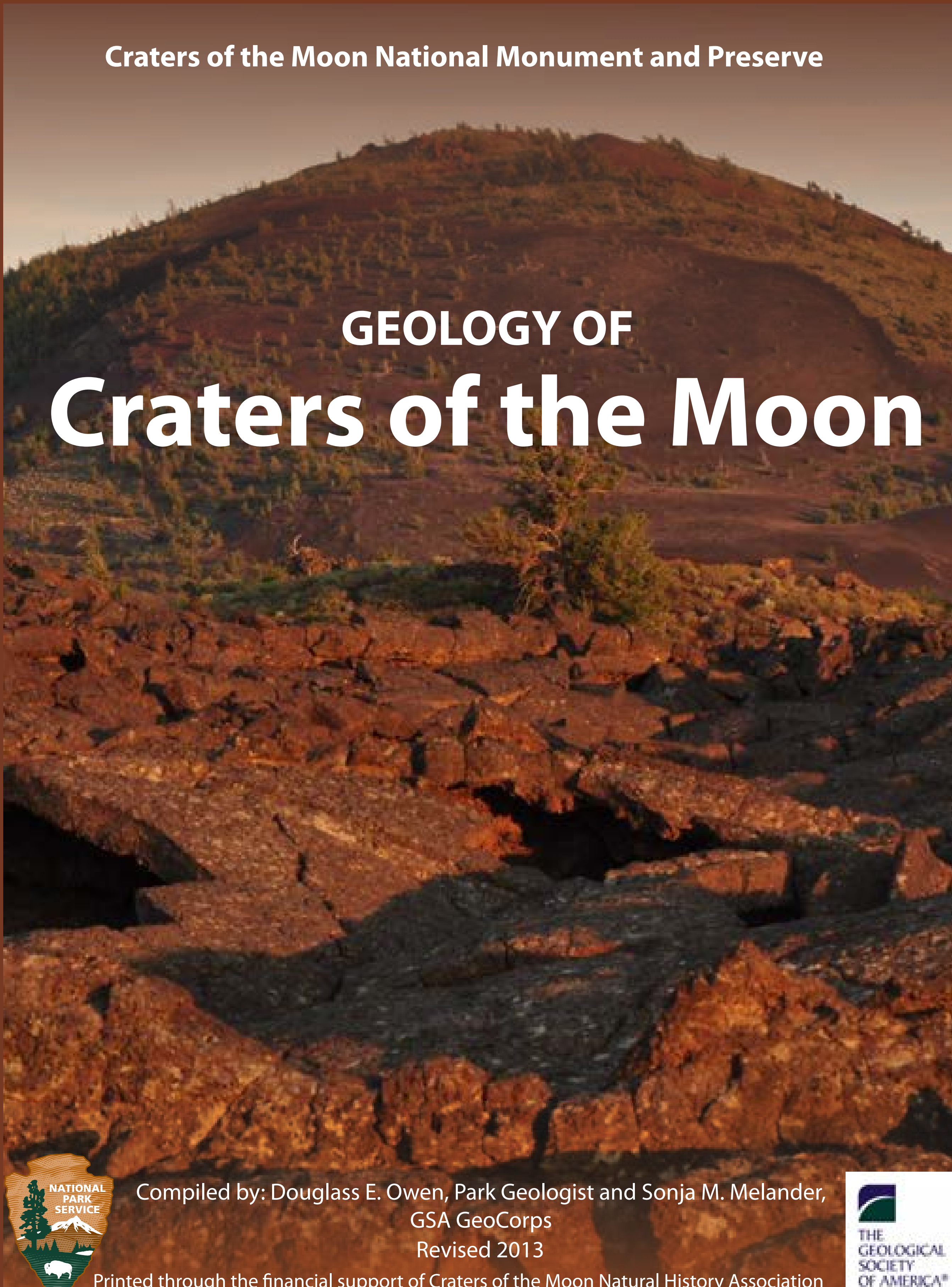
Craters of the Moon National Monument and Preserve



GEOLOGY OF
Craters of the Moon

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Executive Summary

Craters of the Moon National Monument was established in 1924 to protect the geologic features of a small portion of southern Idaho's Great Rift volcanic rift zone. It was greatly expanded in November of 2000 and now covers approximately 750,000 acres (~300,000 hectares) or about 1,100 square miles (~2,800 square km). Craters of the Moon National Monument and Preserve now contains almost all of the Great Rift, the best-developed example of a volcanic rift zone on the Eastern Snake River Plain (ESRP). See Figures 1 & 2 for setting and location. The Monument lies within the Snake River Basin-High Desert (Omernik, 1986) and is dominated by 3 geologically young (Late Pleistocene-Holocene) lava fields that lie along the Great Rift. The Great Rift varies in width between approximately 1 and 5 miles (1.6 and 8 km). It begins north of the Monument, about 6 miles (9.6 km) from the topographic edge of the Snake River Plain, in the vent area of the Lava Creek flows located in the southern Pioneer Mountains (Kuntz, et al, 1992). The Great Rift extends southeasterly from the Lava Creek vents for more than 50 miles (80 km) to at least as far as beneath Pillar Butte on the Wapi lava field (Kuntz, et al, 1982). The Great Rift volcanic rift zone is a belt of open cracks, eruptive fissures, shield volcanoes, and cinder cones.

The Craters of the Moon (COM) lava field is the northernmost and largest of the 3 young lava fields. Kings Bowl lava field is the smallest and lies between COM lava field and the Wapi lava field located on the southern end of the Great Rift. The other areas of the Monument, located either between these 3 young lava fields or surrounding them, are made up of Pleistocene age pahoehoe and 'a'ā flows, near-vent tephra deposits, cinder cones, lava cones, and shield volcanoes (Kuntz, et al, 1988). These older areas are mantled with loess deposits (windblown silt) and in some places by eolian sand. Longitudinal sand dunes are prominent features surrounding the southern end of the Wapi lava field (Greeley and King, 1977). During the Holocene (last 10,000 years), the highest volcanic activity of any of the eastern Snake

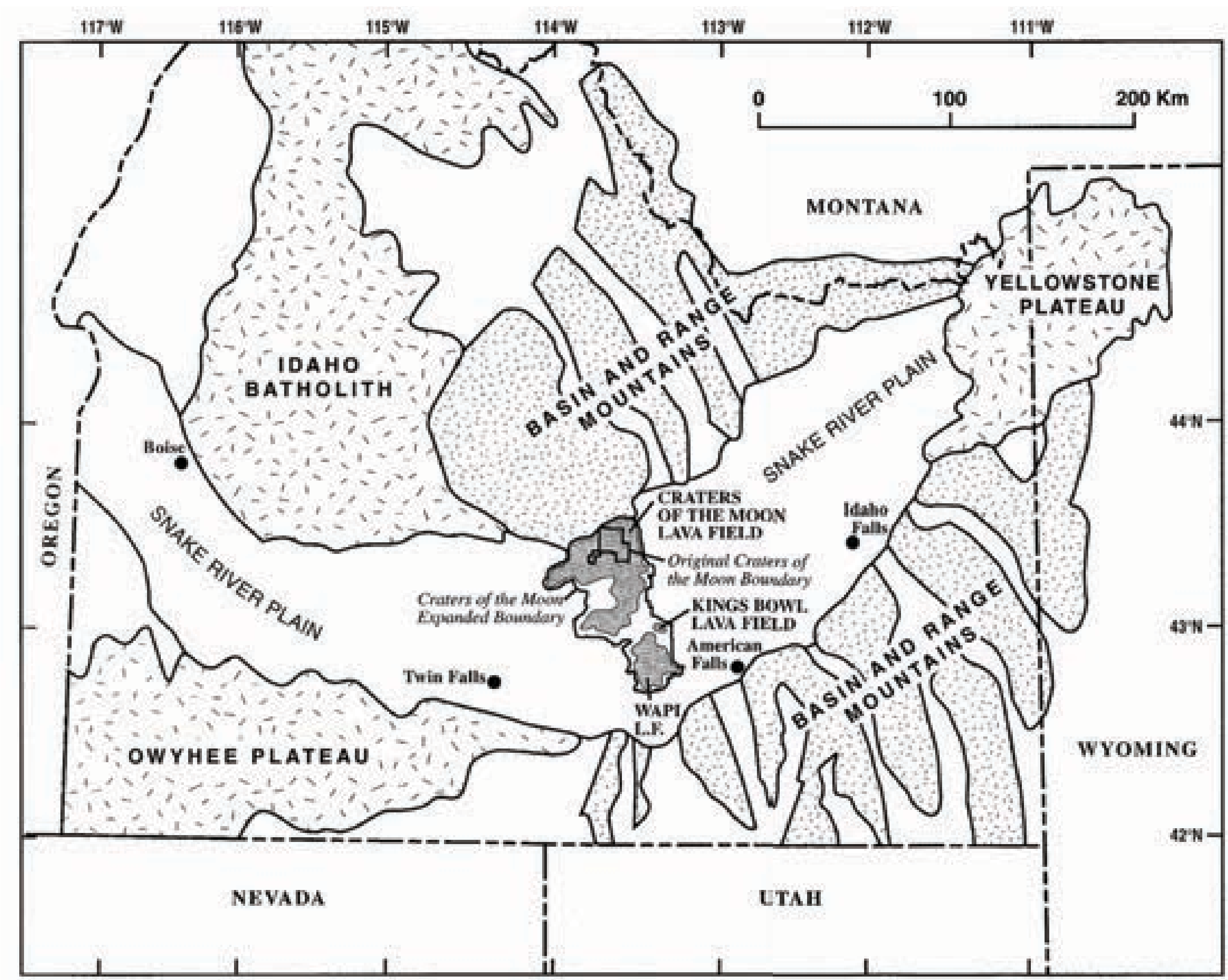

Figure 1: Regional setting and location of Craters of the Moon National Monument and Preserve.

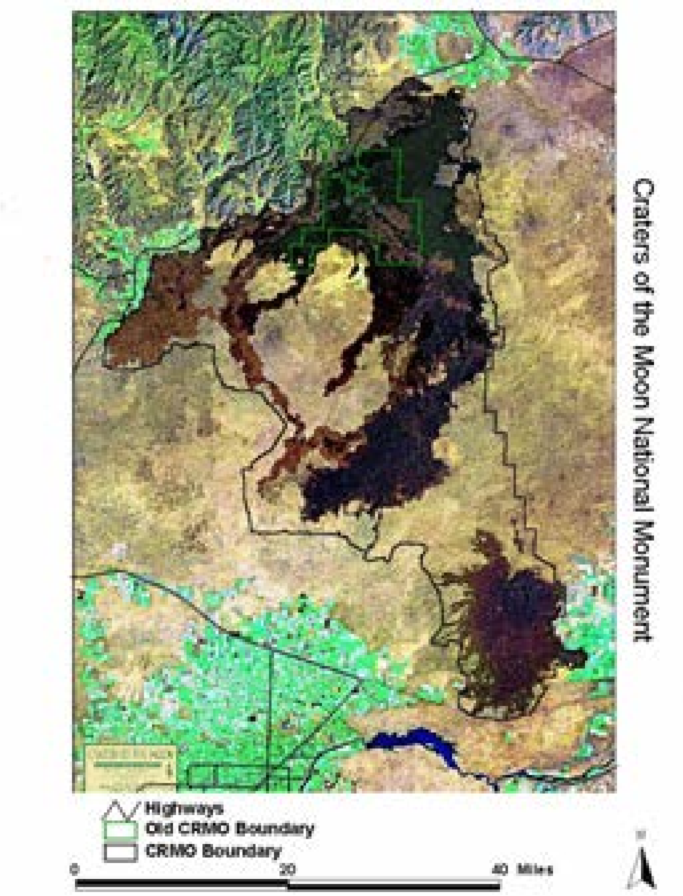

Figure 2: Craters of the Moon (CRMO). The park almost spans the width of the eastern Snake River Plain.

River Plain (ESRP) basaltic rift systems was exhibited by these 3 lava fields associated with the Great Rift (Hughes, et al, 1999).

The COM lava field is the largest dominantly Holocene basaltic lava field in the lower 48 states (Kuntz, et al, 1992); it covers 618 mi^2 (1,600 km^2). COM lava field is a composite field made up of at least 60 lava flows and 25 tephra (cinder and spatter) cones. It has 8 eruptive fissure systems that are aligned along the northern part of the Great Rift (Kuntz, et al, 1992). The COM lava field has a tremendous diversity of volcanic features, with nearly every type of feature that is associated with basaltic systems (Hughes, et al, 1999). Unlike most of the ESRP, where the basalts are predominantly diktytaxitic olivine tholeiites (or more simply-- olivine basalts) associated with small monogenetic shield volcanoes (Hughes, et al, 1999), the basalt deposits in the COM lava field exhibit a wide range of chemical compositions. Though the COM lava flows are believed to have similar parent magma to the volcanoes in the rest of the Plain, their varied compositions are due to crustal contamination from assimilating older rocks or from crystal fractionation (Kuntz, et al, 1986). The COM lava field formed during at least 8 major eruptive periods over the past 15,000 years in contrast to most of the other lava fields on the

Figure 3: View of Kings Bowl and the Great Rift.

ESRP that represent single eruptive events.

Kings Bowl lava field formed about 2,200 years ago during a single burst of eruptive activity that may have lasted as little as six hours (Kuntz, et al, 1992). Kings Bowl has a central eruptive fissure set that is about 4 miles long, which is flanked by 2 subparallel sets of non-eruptive fissures. The bowl that the field takes its name from is a phreatic explosion pit 280 feet (85 m) long, 100 feet (30 m) wide, and 100 feet (30 m) deep, caused by lava coming in contact with groundwater, producing a steam explosion (Fig. 3). Adjacent to the bowl is an outstanding example of a lava lake with well-developed levees. The crust of the lake was broken by many of the blocks ejected by the phreatic explosion. The interior of this lake was still molten and oozed up through the holes punched in its crust, resulting in a large number of squeeze-up mounds of gas-charged lava (Hughes, et al, 1999). Many of the squeeze-ups look like mushrooms or candy kisses (Fig. 15b). There is also a tephra blanket on the east side of the pit that resulted from the explosion. Fissure caves, such as Crystal Ice Cave and Creons Cave lie along the Great Rift at Kings Bowl. At South Grotto, the rift may be passable to a depth of 650 feet (198 m) below the surface (Earl, 2001). Feeding dikes drain-back features, spatter cones, and spatter ramparts can all be seen along the Great Rift at Kings Bowl.

Wapi and Kings Bowl lava fields are identical in age (approximately 2,200 years old), i.e., within the limits of analytical error (Hughes, et al, 1999). The Wapi lava field is a classic shield volcano with a flattened dome shape. Kuntz, et al, (1992) believe that the Wapi lava field began as a fissure eruption, but with prolonged activity developed a sustained eruption from a central vent complex, which produced the low shield volcano seen today. The vent complex is made up of 5 major and 6 smaller vents, with the vents being steep-sided circular depressions typically about 300 feet (90 m) in diameter and 30 feet (9 m) deep (Kuntz, et al, 1992). Rising about 60 feet (18 m) above the south side of the largest vent is a mass of agglutinate and layered flows known as Pillar Butte. Medial and distal parts of the lava field are mostly composed of pahoehoe flows fed from lava tubes. Pressure plateaus, flow ridges, and collapse depressions characterize the margins of the field where local relief can be over 30 feet or 9 meters (Kuntz, et al, 1992). Greeley (1971) reported that the only known dribblet spires in the continental U.S. occur on the flows associated with Pillar Butte. Now however, dribblet spires are known to occur at least also in Diamond Craters in Oregon. The spires found in the Wapi lava field average 12 feet (3.6 m) high and 5 feet (1.5 m) in diameter. They consist of imbricated rounded slabs of lava that range from 5 inches by 5 inches (12.7 cm by 12.7 cm) by 1 inch (2.5 cm) thick to 12 inches by 9 inches (30.5 cm by 22.9 cm) by 4 inches (10.2 cm) thick (Greeley, 1971). These bizarre spires are a type of hornito.

History of Geologic Exploration

Native Americans have visited the area of Craters of the Moon National Monument for thousands of years. They were potential witnesses to at least the last 3 eruptive periods of the COM lava field and for the formation of both the Wapi and Kings Bowl lava fields. Scientific studies began in 1901, when Israel Russell, United States Geological Survey (USGS), came to investigate south-central Idaho. Russell wrote the first scientific account of the region called "Cinder Buttes" (Russell, 1902). His intense interest in the volcanic bombs that he discovered brought him back again the following year (Russell, 1903). Starting in 1910, S.A. Paisley, who later became the first Custodian of the Monument made numerous trips into the area and Era Martin, a local resident, discovered and marked many of the caves and water holes with stone monuments (Stearns, 1928).

In 1921, Robert Limbert, a taxidermist from Boise, Idaho, visited the area and published an account of his trip in National Geographic (Limbert, 1924). In the same year, O. Meinzer, Chief of USGS Division of Ground Water, and Harold Stearns, USGS, visited the area. In 1923 Stearns, accompanied by F.E. Wright of the Carnegie Institution, made a trip to the area and published a description in Geographical Review (Stearns, 1924). The National Park Service (NPS) requested that Stearns submit a report describing the area, delineating boundaries, and stating the reasons that would justify its preservation as a National Monument and on May 2, 1924 President Calvin Coolidge proclaimed the original Craters of the Moon National Monument. In 1925, the first topographic map of the Monument was made by M.J. Gleissner, USGS (Stearns, 1928). In the fall of 1926, Stearns again returned to the Monument and spent a month mapping the geology and describing the features. He submitted a report to the USGS, but only portions of it were published (Stearns, 1928; Stearns, et al, 1938). The 1938 publication contained the first generalized geologic map of the monument.

Since these early geologic investigations, numerous additional studies have been conducted to work out the regional geology and structural setting, the source of the volcanism, the petrology and mineralogy of the lavas and underlying rocks, and the chronology of the lava flows. The 1950's and 60's produced many reports speculating on the structure of the western Snake River Plain (Malde, 1959; Malde and Powers, 1962, Malde, et al, 1963; Hill, 1963). In the 1970's detailed petrologic and geochronologic studies were initiated and research began on the geochemistry of the basalts and underlying rhyolites of the plain. Simultaneously, dating began using both radiocarbon and K-Ar (potassium-argon) techniques to determine the absolute age of the lava flows. Mineralogical studies at this time focused on the Blue Dragon flow in the Monument and on the unusual mineral deposits found in some of the lava tubes and pits (e.g.: Armstrong, et al, 1975; Bullard, 1970; Faye and Miller, 1973; Malde and Cox, 1971, Peck, 1974). Christiansen and McKee (1978) published the first report of a mantle plume theory for the formation of the Snake River Plain. From the 1980's to the present geologists concentrated on refining the petrologic characterization and absolute dating of the rocks and on magmatic and eruptive models to explain the regional volcanism. Kuntz, et al, (1982) dated lava flows within the monument and (Kuntz, et al, 1986) provided significant information regarding the source, volume and periodicity of the basaltic eruptions. Smith and Braile (1993) described the space-time evolution of the Yellowstone-Snake River Plain volcanic system. Geophysical techniques, such as seismic tomography (imaging based on P-Wave velocity structure), were used to determine the subsurface geology of the plain (Humphreys, et al, 2000).

During the first decade of the 21st century, massive amounts of data for the Craters of the Moon region became available from the EarthScope program funded by the National Science Foundation. EarthScope has/is deploying thousands of seismic, GPS, and other geophysical instruments to study the structure and evolution of the North American continent and the processes that cause earthquakes and volcanic eruptions. The huge dataset acquired from the EarthScope program allowed numerous authors to publish previously impossible images of the earth's interior and develop new or revise previous hypotheses and theories regarding the Yellowstone Hotspot (e.g.: Pierce and Morgan, 2009; Smith et al., 2009; Allen, 2009; and Obrebski et al., 2010) See Figure 6 for examples.

Geologic Setting

The Monument lies on the eastern portion of the Snake River Plain (SRP), which is a topographic low in southern Idaho that is 30 to 60 miles (50 to 100 km) wide and extends 360 miles (600 km) from Oregon to the Yellowstone Plateau. The plain is bounded by highlands to the north and south (Fig. 1). The Eastern Snake River Plain (ESRP) consists of broad flat basalt flows and thin discontinuous sedimentary deposits that together have a total thickness of ~0.6 to 1.2 miles or ~1 to 2 km (Doherty, et al, 1979). Magnetic polarity determinations and recent radiometric studies (Champion, et al, 1988; Kuntz, et al, 1992) indicate that most of the surface flows were erupted during the Brunhes Normal-Polarity Chron, and thus are younger than 780 ka (ka = thousand years ago). Data from wells that penetrate the ESRP to depths as great as 2 miles (3,500 m) show that the lava flow and sediment sequence is 0.6 to 1.2 miles (1 to 2 km) thick throughout most of the plain (Embree, et al, 1982). Drilling and field studies (Doherty, et al, 1979; Embree, et al, 1982; Morgan, et al, 1984) show that the basalt-sediment sequence is underlain by rhyolitic lava flows, ignimbrites (rock formed by the widespread deposition and consolidation of pyroclastic flows), and other pyroclastic deposits formed by volcanic explosions or aerial expulsion from a volcanic vent.

The structure of the SRP varies greatly from west to east. The northwestern plain is believed to be a graben, or fault-bounded depression (Malde, 1959). The ESRP, which includes the Monument, is less clearly defined. The earliest studies by Kirkham (1931) hypothesized that the plain was a downwarp, which had been filled with basalt both during and following the downwarping process. He believed that extrusion of lava was the major cause of subsidence and he supported this hypothesis with evidence of volcanic layers that gently dip toward the center of the plain.

Extensive field work conducted by Rodgers, et al, (2002) measured the crustal flexure caused by the loading from the mid-crustal sill (6 miles/~10 km thick of gabbroic/basaltic material) and surface basalts (as much as ~6000 feet/~1800 m thick) and attendant subsidence along the northern edge of the Eastern Snake River Plain. The plunge reaches a maximum of 25° to the SE at the toe of the Lost River Range and varies between 10° and 30° along the other ranges surveyed (Pioneer, Lemhi, and Beaverhead Ranges). The downwarped zone (Fig. 4) extends 6.2 - 12.4 miles (10 - 20 km) north of the Snake River Plain and also likely reflects the lower crustal flow that must be taking place to accommodate the subsidence.

Some have suggested that the volcanism and structure of the plain are the result of an eastward propagating rift (Myers and Hamilton, 1964; Hamilton, 1987), and transform fault boundaries across basin and range faults (Christiansen and McKee, 1978) or the plain may simply be related to a preexisting crustal weakness, i.e., the structure of the Precambrian basement in southern Idaho (Eaton, et al, 1975). A more catastrophic explanation for the formation of the plain is related to a hypothesized meteorite impact in southwestern Idaho. The impact is conjectured to have caused deep fractures in the earth's crust that initiated the eruption of flood basalts, which were followed by a lower-volume outpouring of lava from the fractures (Alt and Hyndman, 1988).

Some of the most popular recent explanations for the formation of the ESRP have

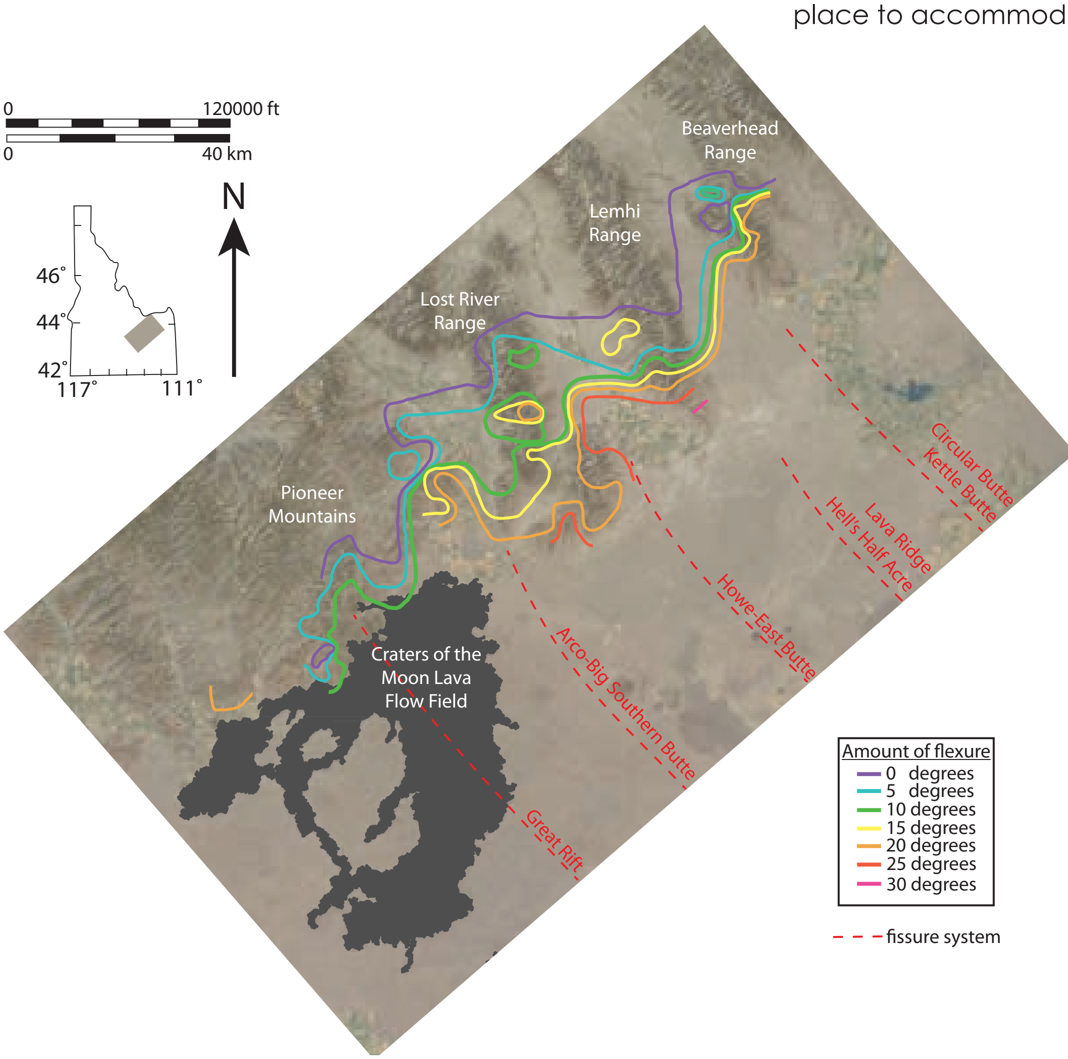

Figure 4: Amount of crustal flexure at the northwestern edge of the Snake River Plain in the CRMO vicinity. Adapted from Rodgers, et al (2002).

involved theories incorporating a deep mantle plume. Thick rhyolitic rocks encountered during drilling in the ESRP suggested that some portions of the plain represent filled rhyolitic-calderas, similar to the Henrys Fork (Island Park) Caldera in Idaho (Doherty, et al, 1979; Embree, et al, 1982; Morgan, et al, 1984). This information, along with some geophysical data, led many geologists to conclude that the ESRP is the site of a northeasterly propagating system of rhyolitic volcanic centers. It is thought that the southwesterly movement of the North American Continent, caused by plate tectonics, has passed southern Idaho over a stationary mantle plume or hotspot. In turn, the mantle plume has caused rhyolitic and associated basaltic volcanism to develop across southern Idaho.

This mantle plume is believed to be the same heat source for the volcanic and hydrothermal activity in Yellowstone National Park (e.g.: Armstrong, et al, 1975; Brott, et al, 1981; Maley, 1987; Pierce and Morgan, 1992). Some deep mantle-plume advocates believe that the plume ascended from the core-mantle boundary, was progressively overridden starting about 60 million years ago, and may be responsible for the Carlin gold deposits found in Nevada (Oppliger, et al, 1997). Along the same line, others hypothesize that the mineralization in the Carmack Group, found in the Yukon, is related to the Yellowstone hotspot of some 70 million years ago (Johnston, et al, 1996). See Pierce, et al, (2002) for a review covering many of the ideas both pro and con related to the Yellowstone hotspot.

Regardless of when the hotspot originated, the ESRP records a progressively younger trend of rhyolitic eruptions to the northeast. Henry Heasler with the Yellowstone Volcano Observatory reported that there have been 142 massive blasts, catastrophic eruptions of huge volumes of rhyolitic lava, in the last 17 million years along the ESRP (Sparrow, 2003). Based on the age and chemistry of the rhyolites, researchers have pushed that number to over 150. These eruptions typically produced calderas 10-40 miles (~16 - 64 km) wide. Many of the calderas overlapped and may be broken down into 7-13 volcanic centers. Although some of the mountain ranges that existed on the ESRP before the hotspot may have been blown away by the eruptions, it is more likely they were swallowed up as the floor of the caldera sank during the violent explosions, thus producing the trough we see today (Smith and Siegel, 2000). Kuntz, et al, (1992) believe that the source of the material for the ESRP eruptions is lithospheric mantle with the melting being driven by plume upwelling and decompression-melting. Teleseismic (utilizing distant seismic events) studies done at the end of the 20th century led Smith and Siegel (2000) to believe that the root of the hotspot was only at a depth of about 125 miles (200 km), while Humphreys, et al, (2000) envisioned convective rolls within the athenosphere or local upper-mantle convection instead of a deep mantle plume. Teleseismic work by Yuan and Dueker (2005) imaged the dipping plume of the Yellowstone hotspot to a depth of 310 miles (500 km) and at an angle of 20°.

Data from the EarthScope program enabled Smith, et al, (2009) to produce images of the Yelowstone hotspot to a depth of 410 miles (660 km) and dipping to the NW at about 60°. Allen (2009) showed the Yellowstone Hotspot extending to at least 621 miles (1,000 km) with a similar dip. Obrebski, et al, (2010) imaged the hotspot to a depth of 745 miles (1,200 km). Smith, et al, (2009) say that the best fit for their data is to take the plume all the way to the core-mantle boundary. They also calculated that the plume is relatively cool, about 120 °K in excess of the surrounding mantle, and represents a body with a maximum melt of 2.5%. In contrast, a typical plume temperature is about 200 °K in excess of the surrounding mantle. Though the EarthScope data reveals that the Yellowstone Hotspot is a deep mantle plume (see Figure 5 showing the layers of the earth), there is still debate about whether the Yellowstone Hotspot came up beneath the old Farallon-Juan de Fuca plate or in front of it. Both interpretations are diagramed in Figure 6.

Recent seismic data also suggests that the Yellowstone hotspot left behind a slab of basalt 6 miles (10 km) thick in the mid-crust and that it contains partial melt. Smith and Siegel (2000) figuratively describe this slab as representing the slag left in the bottom of the numerous magma chambers spawned

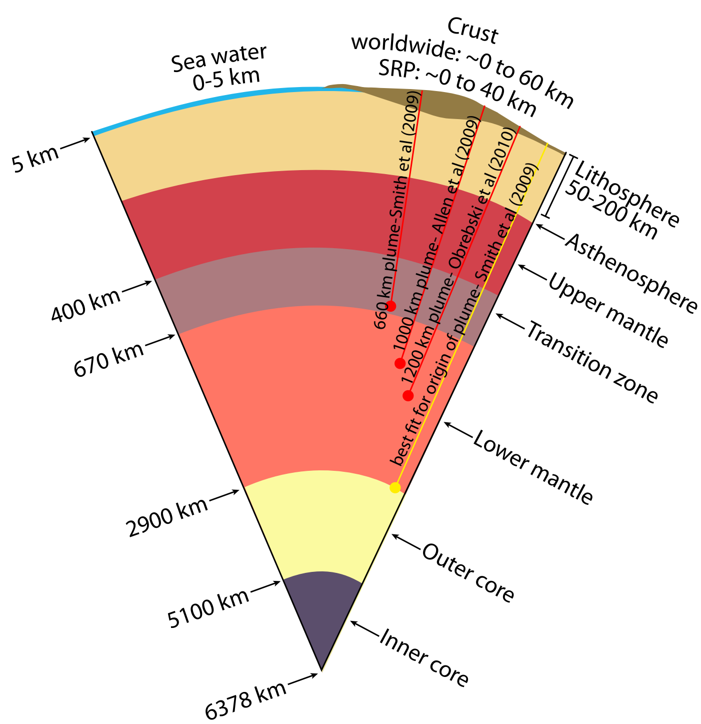

Figure 5: Schematic diagram showing the layers of the earth and the depths to which the mantle plume has been imaged by various authors. Not to scale. Adapted from AGI Datasheets 4th edition.

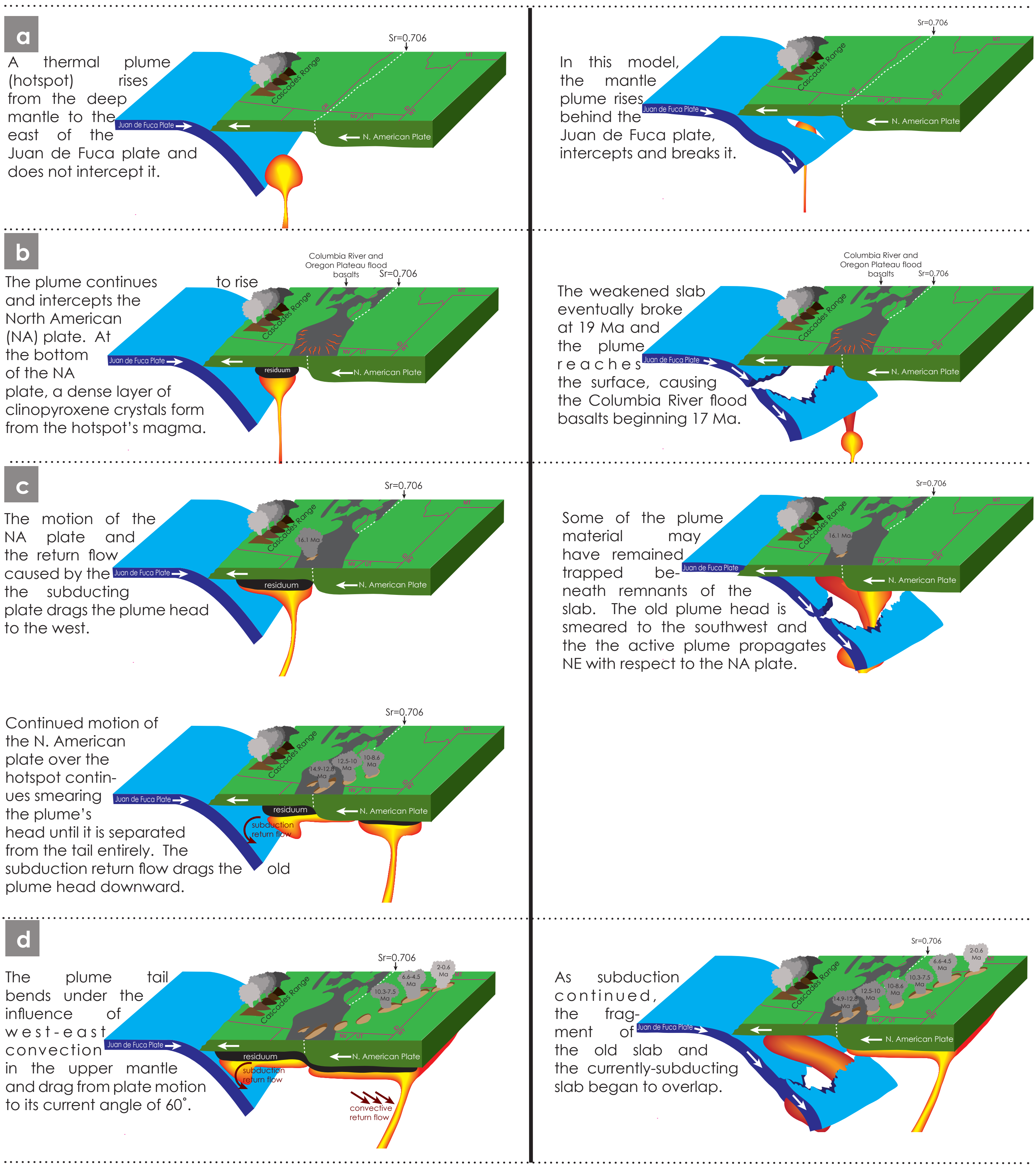

Figure 6: Sketch showing differing interpretations (**left:** modified from: Smith, et al, 2009; **right**: modified from: Obrebski, et al, 2010) of the interaction between the mantle plume and the Juan de Fuca plate. **a)** The mantle plume rises from below **b)** The plume reaches the surface, triggering the Columbia River flood basalts beginning 17 Ma. **c)** The formation of extensive magma chambers and crustal melting leads to rhyolitic caldera-forming volcanism. Caldera volcanism continues as the N. Americna plate continues to move over the hotspot. **d)** The N. American plate continues moving over the plume to its current position below Yellowstone National Park.

by the hotspot (Fig. 7). The region surrounding the ESRP continues to experience basin-and-range type faulting, which is stretching or pulling apart the crust. This crustal extension continues to uplift the mountain ranges such as the Lost River Range, where a magnitude 6.9 earthquake occurred in 1983. On the ESRP in the wake of the Yellowstone hotspot, where all of these hot rocks have been left behind, instead of producing mountain ranges, the tensional forces help to create decompression melting, which results in dike emplacement and periodic eruption of molten rock onto the surface (Fig. 8). As long as these forces continue to act, more eruptions will eventually occur. It is estimated that the ESRP is made of 8,000 shield volcanoes and the typical volume erupted is 1.2 mi^3 or 5 km^3 (Kuntz, et al, 1992). Coalesced shield volcanoes and lava cones constitute >95% of the total volume of basalt in the ESRP and the lava flows are dominantly of the tube-fed type (Kuntz, et al, 1992).

Carpenter et al. (2011) reported that in 2010 alone there were five earthquakes recorded at Craters of the Moon at mid- and lower-crustal depths that

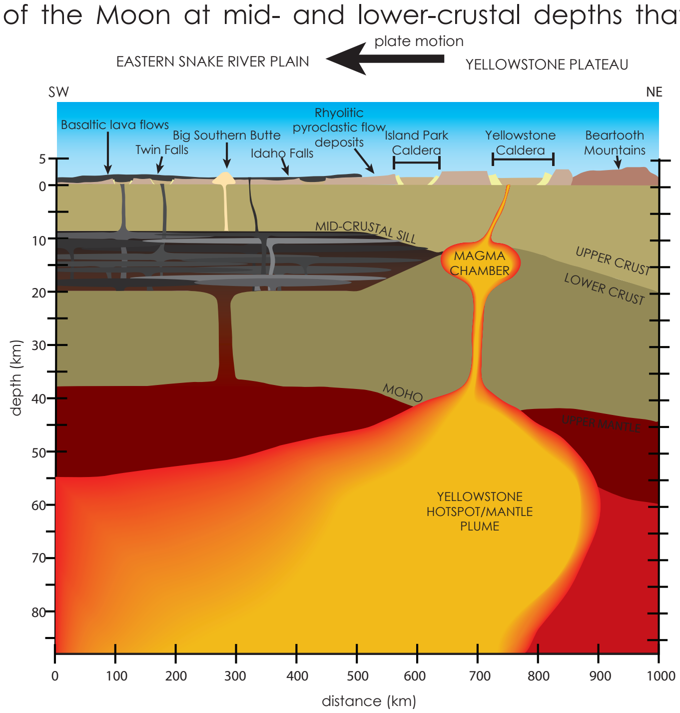

Figure 7: Sketch showing the crustal structure beneath Yellowstone and the Eastern Snake River Plain, including the basaltic/gabbroic mid-crustal sill.

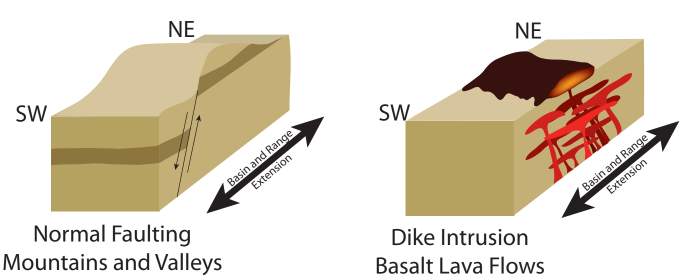

Figure 8: Sketch showing the crustal response to tensional forces in the **a)** Basin and Range and **b)** Snake River Plain.

they interpret to be related to fluid movements (i.e., magma). The Idaho National Lab Seismic Monitoring Program recorded 22 deep micro earthquakes (M ≤ 2.3) in the vicinity of Craters of the Moon between 1972 and 2010. These mid-crustal quakes are at the presumed depth of the Eastern Snake River Plain magma chambers within the mid-crustal sill and the deeper ones represent where potential magma recharge is working its way up into the crust from below the Moho. If in fact new recharge of magma chambers is taking place beneath Craters of the Moon, it could suggest that renewed volcanic activity at Craters of the Moon lies somewhere in the monument's future.

Several prominent rhyolitic domes lie along the ESRP in the Arco Desert and are visible from ten's of miles away. The tallest, Big Southern Butte, is a landmark and navigation aid visible from much of the Monument. It towers 2,500 feet (760m) over the ESRP and extends another 2,950 feet (900 m) into the subsurface. Big Southern Butte, one of the largest rhyolite domes in the world, has been dated at ~300 ka. Other buttes of the ESRP include East Butte (~600 ka), Middle Butte (~600 ka) and Cedar Butte (~400 ka). Current research indicates that these rhyolite domes formed through extreme fractionation of basaltic magma (McCurry, et al, 1999).

As magma in chambers beneath Craters of the Moon continues to evolve through such processes as fractionation or differentiation, it could also mean that someday a rhyolite dome, like East Butte or Big Southern Butte, could form at Craters of the Moon (Mike McCurry, Geology Department, Idaho State University, personal communication, 2013).

Basaltic Volcanism

The basaltic volcanism on the ESRP is localized in lava fields along volcanic rift zones. These zones are narrow belts, typically 3-12 miles (5-20 km) wide, composed of faults, grabens, eruptive and non-eruptive fissures, spatter cones, cinder cones, and low shield volcanoes (Kuntz, 1977a, 1977b; Kuntz, et al, 1992). Most volcanic rift zones are perpendicular to the long axis of the plain, and may be extensions of faults that bound basin-and-range mountains north and south of the plain (Kuntz, 1977b). Eight separate young basaltic lava fields (Craters of the Moon, Kings Bowl, Wapi, Shoshone, North Robber's, South Robber's, Hell's Half Acre, and Cerro Grande) can be identified in Landsat images of the ESRP (Lefebvre, 1977; Champion and Greeley, 1977; King, 1977). The largest of these is the Craters of the Moon (COM) lava field, which is also the largest basaltic lava field of dominantly Holocene age (less than 10,000 years) in the conterminous United States.

The COM lava field consists of more than 60 lava flows that cover an area of 618 mi^2 (1600 km^2) and

Figure 9: Great Rift (vertical crack) at South End of Kings Bowl. Note person for scale.

a volume of 7.2 mi^3 (30 km^3). The volcanic vents that supplied the lava flows of the COM lava field are aligned along the northern part of the Great Rift. The Great Rift is approximately 53 miles (85 km) long and extends from the southern Pioneer Mountains southeastward through the Monument to Pillar Butte, located about 18 miles (30 km) northwest of American Falls. The Great Rift is the best example of a volcanic rift zone on the ESRP and can be divided into four sections. The northern-most section lies beneath the COM lava field. Just south of the COM lava field, the rift changes to an inactive open fissure system. The southern portions of the rift gave rise to the Kings Bowl lava field and to the Wapi lava field. Figure 9 is a view down the axis of the Great Rift in Kings Bowl.

The variety of lava flows and volcanic vents in the COM lava field represent a nearly complete range of the types of volcanic features formed by basaltic eruptions. Lava flows and volcanic landforms, such as cinder cones and spatter cones, are highly concentrated in the northern end of the COM lava field. Based on observations of active basaltic eruptions, geologists believe that these volcanic landforms are the result of combinations of distinct eruptive phases (Kuntz, et al, 1982).

Many eruptions in the COM lava field are believed to have begun with a phase characterized by a "curtain of fire". Curtains of fire are lines of gas-charged lava erupting in elongate, low fountains. These curtains can extend for up to several miles, are generally 100-200 feet (30-60 m) tall, and can be sustained for hours and up to several days. As a curtain of fire continues to erupt, segments of the fissure begin to clog. This results in the same amount of lava being forced to erupt from a limited number of vents producing fire fountains many hundreds of feet in height.

Ejection of lava by both curtains of fire and fire fountains can produce spatter ramparts, cinder cones, mounds of cinder, and generate several kinds of volcanic bombs. The fire fountains that produced many of the Monument's cinder cones were probably >1,000 feet (300 m) high. Big Cinder Butte, the tallest cinder cone in the Monument is over 700 feet (210 m) high and may have had a fire fountain >1,500 feet (450 m) high.

Four kinds of bombs are found in the Monument, all of which started off as globs of molten rock thrown or ejected into the air. If the glob got twisted during its flight it is called a spindle bomb (Fig. 10a) and typically ranges from a few inches to several feet in length. If the bomb was very tiny and twisted it is called a ribbon bomb (Fig. 10b). When a glob of molten rock forms a crust as it flies through the air and the gases inside continue to expand and crack that crust, it is called a breadcrust bomb, because of its similarity to bread rising in an oven (Fig. 10c). If the bomb did not completely solidify during flight and flattened on landing, it is called a cow-pie bomb or is sometimes also referred to as a pancake bomb (Fig. 10d). Some cow-pie bombs in the Monument are over 10 feet long.

The first landforms to develop from the lava fountains are cinder cones, which are accumulations of cinders (light fragments riddled with gas holes), volcanic bombs, spatter and lava flows that collect around the vent forming a cone with a central crater. There are more than 25 major cinder cones within COM lava field. Prevailing winds from the west and southwest have caused a preponderance of downwind accumulation of cinders from many of the vents. This has resulted in an elongation of many cinder cones to the east or northeast, making them asymmetrical. The Great Rift volcanic rift zone is about 1.5 miles (2.5 km) wide in the COM lava field where many of the cinder cones are found. The cones are generally located along the outer margins of this zone. Cones on the western margin include (north to south) Grassy Cone, Silent Cone, Big Cinder Butte, Echo Crater, the Sentinel and Fissure Butte. The eastern margin includes Sunset Cone, Paisley Cone, Half Cone, Broken Top, and the Watchman (Fig. 11) cinder

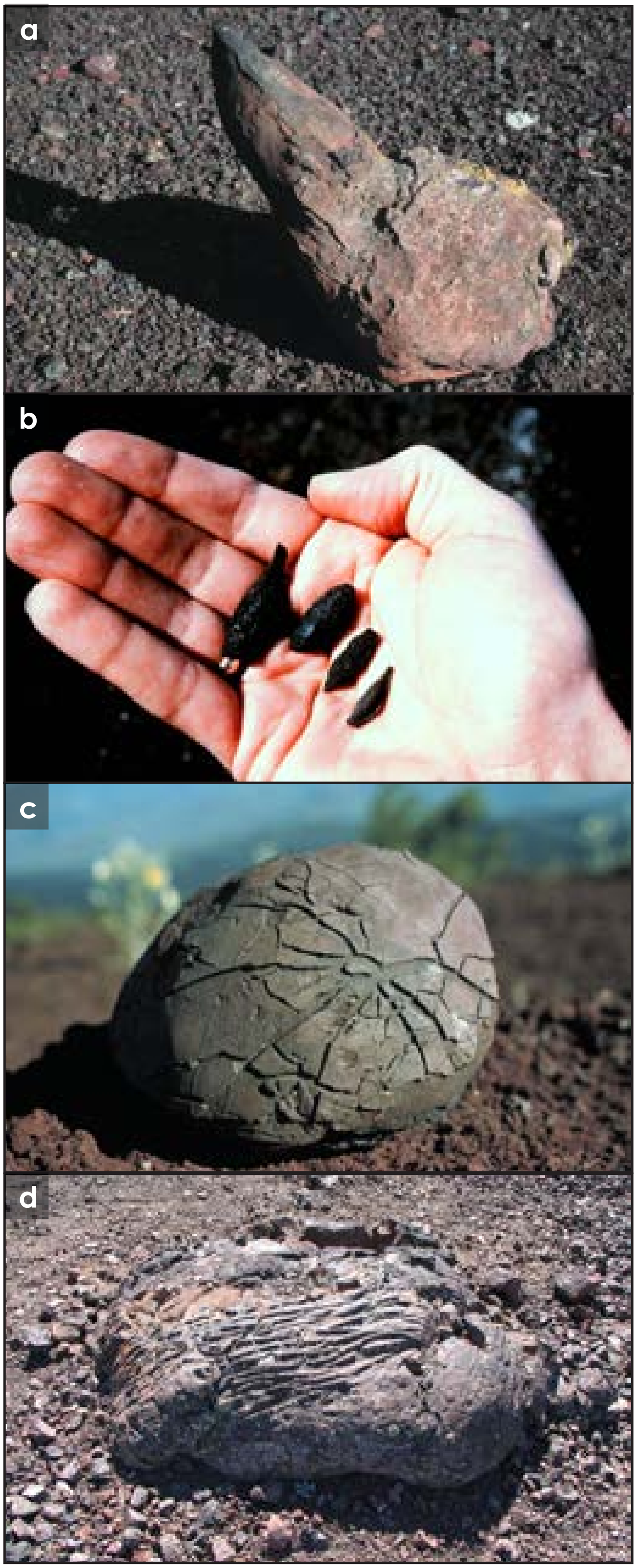

Figure 10: Volcanic bombs found at Craters of the Moon. **a)** Spindle bomb **b)** Ribbon bomb **c)** Breadcrust Bomb and **d)** Cow pie bomb

Figure 11: Watchman Cinder Cone- Note younger eruption on the cone flank related to Trench Mortar Flat event.

cones.

After several hours, days, or weeks, a decrease in magma pressure and the amount of dissolved gases in the magma can produce a corresponding change in the output of lava. At this time, the amount of lava spraying from the vent(s) decreases and begins pouring out as lava flows. This phase may last many years and start and stop many times. The lava flows can vary greatly in temperature and composition from one vent to another and with time; therefore, they also vary in viscosity. This creates fields of pahoehoe, slabby pahoehoe, 'a'ā, and block lava flows, which can transition back and forth between each other, depending on the physical properties of the lava (e.g., effective viscosity) and the underlying surface (e.g., slope, roughness).

The source of these lava flows can be from the same vent that formed a cinder cone, spatter rampart or spatter cone. When enough spatter is ejected from spatter ramparts and cones, the spatter can coalesce and form a lava flow. When a cinder cone is the source of a flow, the lava burrowing through the side of the cone may breach the cone. This commonly results in a notch in the cone above the feeder fissure. The lava flow that breaches the cone may occur concurrently with the cinder cone development or it may occur long after the formation of the cone because of reactivation of the fissure system underlying it. In the COM lava field, reactivation of this sort probably occurred in vents of North Crater, Broken Top, and the Watchman cinder cones (Fig. 11) where the lava flows seem to be significantly younger than the cones. It is also common for lava flows to originate from portions of active rifts that have not previously undergone fountain-type eruptions. In this case, lava can flow directly out of the unobstructed vent and onto the landscape.

When the eruption of lava continues for a long time from an unobstructed vent, a large shield volcano can be produced. Shield volcanoes are gently-sloping and have a flattened dome shape. Wapi lava field in the southern part of the Monument is an outstanding example of a shield volcano. Kuntz, et al, (1992) estimated from the calculated volume of basalt on ESRP and typical eruption volumes that the ESRP is made up of about 8,000 shield volcanoes. The largest shields are typically located near the center of the plain, suggesting that they overlie the central region of magma generation. Lava can travel great distances through lava tubes with very little loss of heat. Lava tubes and tube systems, therefore, facilitate the transport of lava over great distances. Some flows extend up to 30 miles or 48 km (Hughes, et al, 1999).

A lava flow is described by its physical appearance, which is largely determined by its composition, temperature, fluid and crystal content, and the influence the surface and slope it is flowing down exert on it. Block lava (Fig. 12a) has a surface of angular blocks and forms from very dense lava. The typical composition of block lava in the Monument is trachyandesite (an extrusive rock, intermediate in composition between trachyte and andesite).
'A'ā (Fig. 12b) has a rough, jagged, or clinkery surface. 'A'ā forms from highly gas-charged lava which is sufficiently turbulent to continually pull apart the lava on the surface of the flow, forming the jagged "clinkers." Pahoehoe has a smooth, ropy, or billowy surface (Fig. 12c). Pahoehoe can be further broken down into several types. Shelly pahoehoe (Fig. 12d) forms from highly gas-charged lava, often near vents or tube skylights, and contains small open tubes,

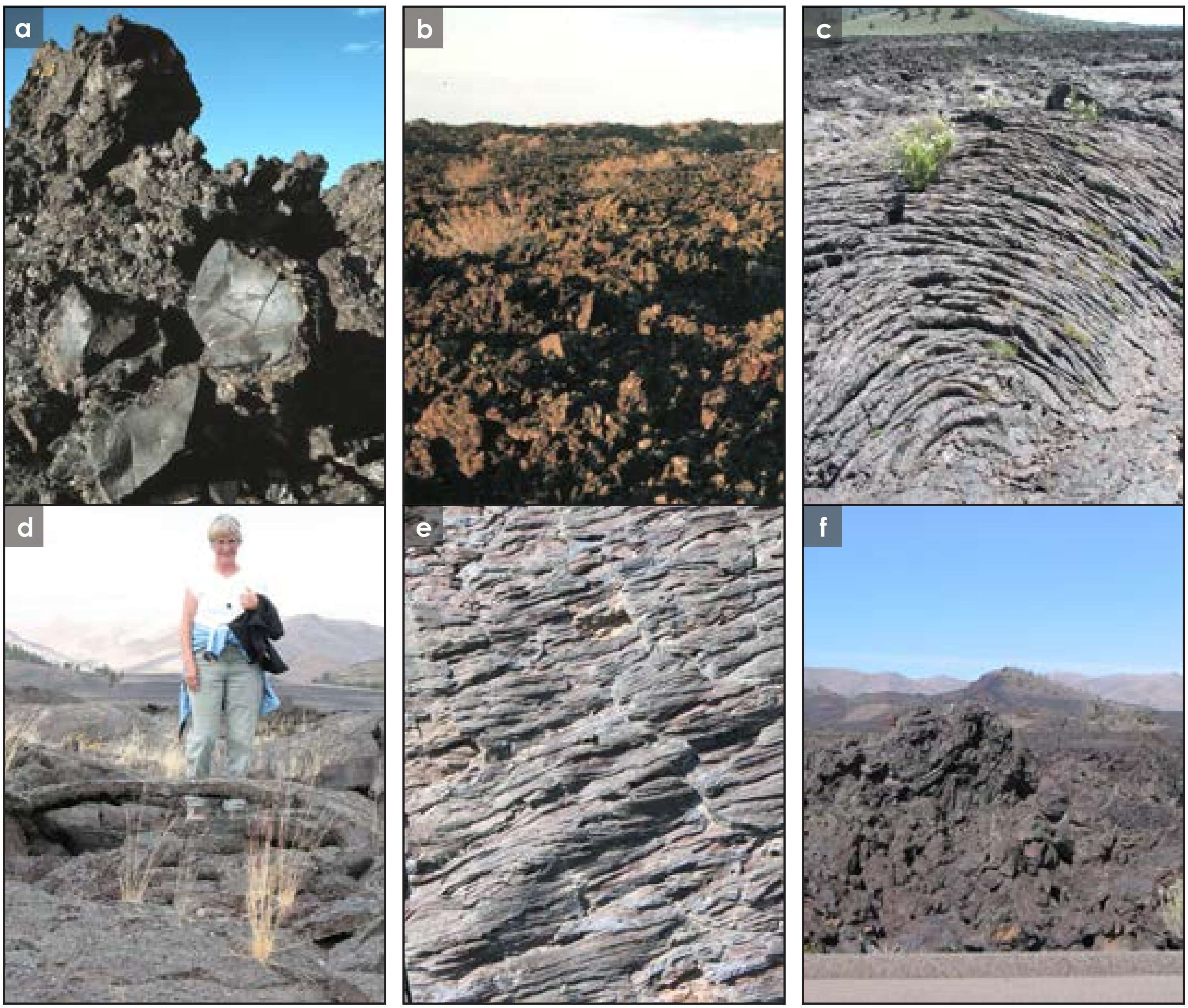

Figure 12: Types of lava flows at Craters of the Moon **a)** Block lava **b)** 'A'ā **c)** Pahoehoe **d)** Shelly pahoehoe **e)** Spiny pahoehoe **f)** Slabby pahoehoe

Figure 13: Small lava tube in Broken Top flow

blisters, and thin crusts. Spiny pahoehoe (Fig. 12e) forms from very thick and pasty lava and contains elongated gas bubbles on the surface that form spines. Spiny pahoehoe is the dominant form of lava found in the Monument. Slabby pahoehoe (Fig. 12f) is made up of jumbled-up plates or slabs of broken pahoehoe crust. Both slabby and spiny pahoehoe are transition phases to 'a'ā.

Lava tubes (Fig. 13), which are hollow spaces beneath the surface of solidified lava flows, are formed by the withdrawal of molten lava after the formation of the surface crusts. Indian Tunnel in the northern part of the Monument has a 40-foot (12 m) high ceiling and is 800 feet (240 m) long. Bear Trap Cave, which lies between COM and Kings Bowl lava fields is >10 miles (16 km) long, but is not continuously passable.

Figure 15: Lava river in Blue Dragon Flow with well-developed levees

Inside lava tubes, one can see skylights (Fig. 14a), lava stalactites (Fig. 14b.), lava curbs (Fig. 14c), stacked tubes, bifurcating and coalescing channels, tube linings, and other features. Internal and remelt features include submetallic appearance caused by a lack of gas bubbles in remelted material (Fig. 14d), soda straw like formations on the ends of lava stalactites (Fig. 14d), flowstone appearing linings (Fig. 14e), and small slumps.

Based on aerial photography and analysis of Landsat images, at least 60 lava flows have been mapped in the COM lava field. Some flows can begin as one flow type and change to another over time. Some flows are much like a river and deposit levees along their sides (Fig. 15). Therefore, textural differences cannot be used as the sole method of separating

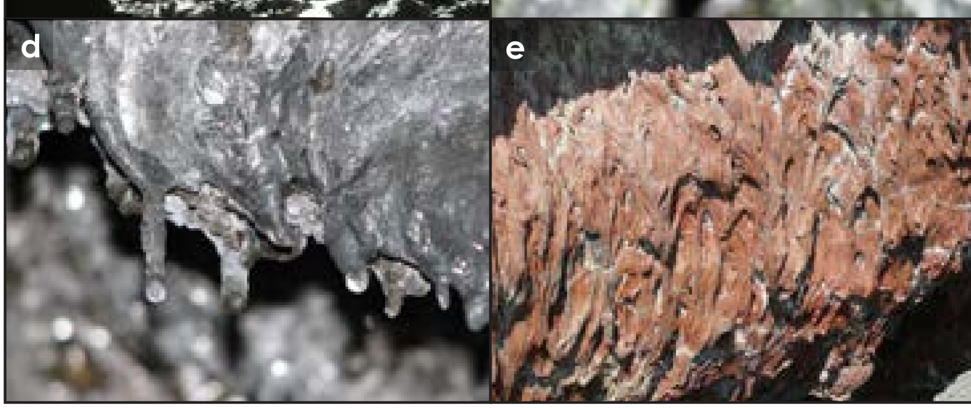

Figure 14: Some features of lava tubes at Craters of the Moon **a)** Skylight at Indian Tunnel **b)** Lava stalactite **c)** Lava curb **d)** Remelt features, including "soda straw" formation and submetallic appearance **e)** Flowstone-appearing lining

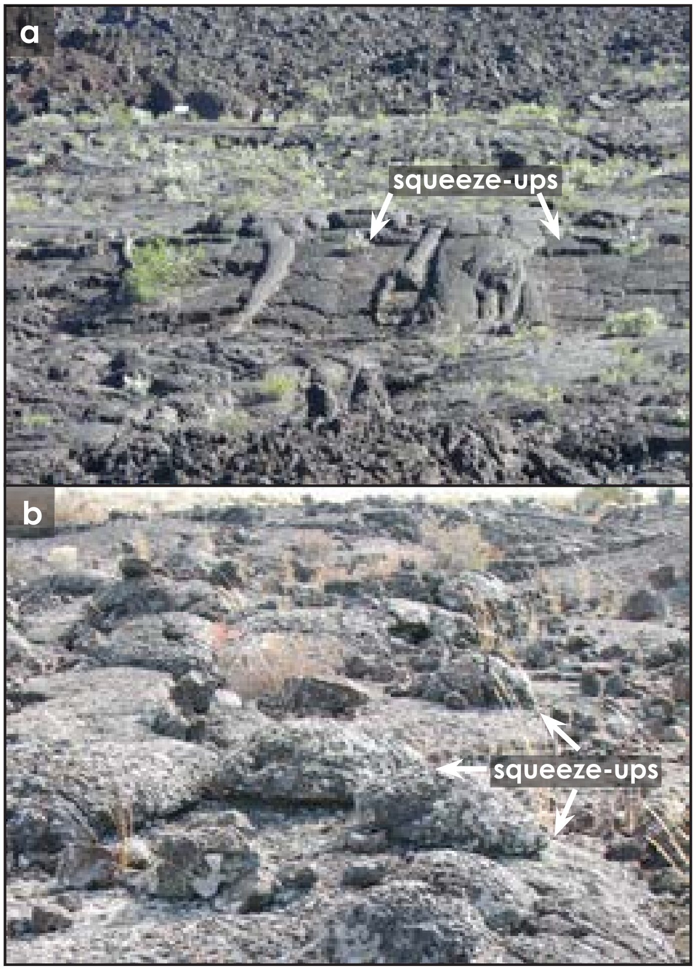

Figure 16: a) Squeeze-up that came from the tension fracture in the top of a flow/pressure ridge **b)** Squeeze-ups that look like mushrooms or candy kisses that oozed up through a crack in the crust of a lava pond

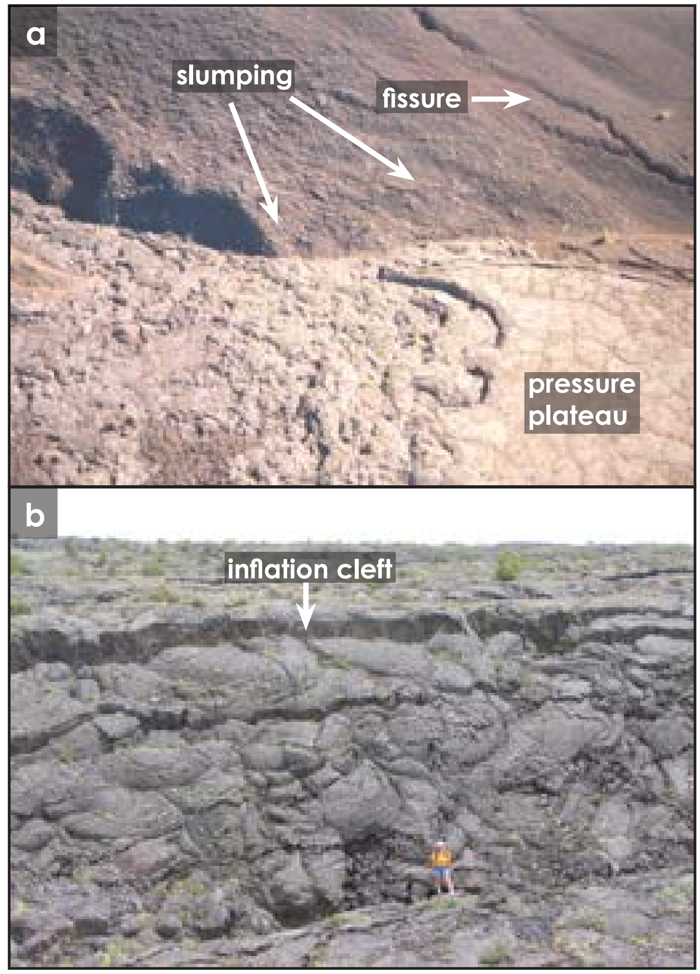

Figure 17: a) Pressure Plateau on the south side of Broken Top. Also note slumping and open fissures on side of cone. **b)** Side view of a pressure plateau

flows. Subtle differences in lava surfaces can often be detected on the images. These surface variances result from differing vegetation, weathering, and sediment coverage on individual flows (Lefebvre, 1977). However, individual flows can also have uneven vegetation, differential weathering, and varying sediment coverage.

Most of the lava flows in the Monument are pahoehoe and were fed through tubes and tube systems, though there are some sheet flows. Structures representing both inflation and deflation of the lava surface can be seen along with both hot and cold collapses of lava tube roofs. Some lava flows produce tumuli (small mounds) or pressure ridges (elongate ridges) on their crusts. In some places squeeze-ups formed when pressure was sufficient to force molten lava up through tension fractures in the top of pressure ridges or cracks in the solidified crust of lava ponds (Fig. 16a&b). There are also pressure plateaus (Fig. 17a&b) that were produced by the sill-like injection of new lava beneath a still-flexible crust of an earlier sheet flow. Pressure plateaus often contain steep-sided fissures called inflation clefts (Fig. 17b) produced when the crust stretched to the point of breaking during the injection of lava from beneath.

Although it is not a convenient field method, geochemistry is the most accurate way to distinguish lava flows. The chemistry of the COM lava field has been studied in more detail than any other lava field in the ESRP. Geochemical examinations of the ESRP rocks have shown that the majority of the basalts to be olivine tholeiites. However, COM basalts are enriched in iron, phosphorus, titanium, and the alkali elements. Leeman, et al, (1976) believe the magma that fed the COM eruptions evolved from the SRP tholeiites (silica-oversaturated basalt). Conversely, the non-evolved olivine tholeiites typical of most of the ESRP are believed to have had little time for cooling or assimilation in the middle crust before ascent to the surface (Putirka et al, 2009).

Evolution of COM basalts could be the result of fractionation of the source magma (separation through crystallization) or crustal assimilation (melting and incorporation of crustal rocks as the magma migrated toward the surface of the earth) (Leeman, et al, 1976; Leeman, 1982; Kuntz, et al, 1992). Xenoliths give evidence of this assimilation (Fig. 18). For evolved lava, crustal contamination produces lava with silica (SiO_2) ranges of ~49% to 64%, while crystal fractionation produces lava with silica ranges of ~44% to 54% (Kuntz, et al, 1986).

Other lava features include spatter cones (Fig. 19a) that formed when fluid globs (spatter) were ejected short distances (generally<200 ft or <60 m) from a vent and accumulated immediately around the vent, forming short, steep-sided cones. Along eruptive fissures where a whole segment erupted, spatter can accumulate to produce low ridges called spatter ramparts.

The Monument has generally circular features known as sinks or pit craters, formed by the collapse of lava tubes after the withdrawl of lava (Fig. 19b). Hornitos (Fig. 19c), also known as rootless vents, are similar in appearance to spatter cones, but formed from spatter ejected from holes in the crust of a lava tube instead of directly from a feeding fissure.

During some eruptions, pieces of crater walls were carried off like icebergs by the lava flows. These wall chunks are known as rafted blocks (Fig. 19d). Devil's Orchard in northern part of the Monument is an entire field of rafted blocks that were carried off from South Highway Cone and North Crater. The Monument contains more than 500 Kipukas. Kipukas (Fig. 19e) are older and usually higher areas that younger lava flowed around, but not over. They often appear as grassy hills surrounded by relatively barren lava.

Caves

Besides shelly pahoehoe areas that contain many small open tubes and blisters and the numerous lava tubes associated with tube fed pahoehoe flows there are other kinds of caves found in the Monument. They include fissure caves associated with the Great Rift. Many, such as Bear's Den waterhole (Fig 20a), are

Figure 18: Xenoliths in basalt **a)** Pumice **b)** Challis volcanics **c)** Granulite

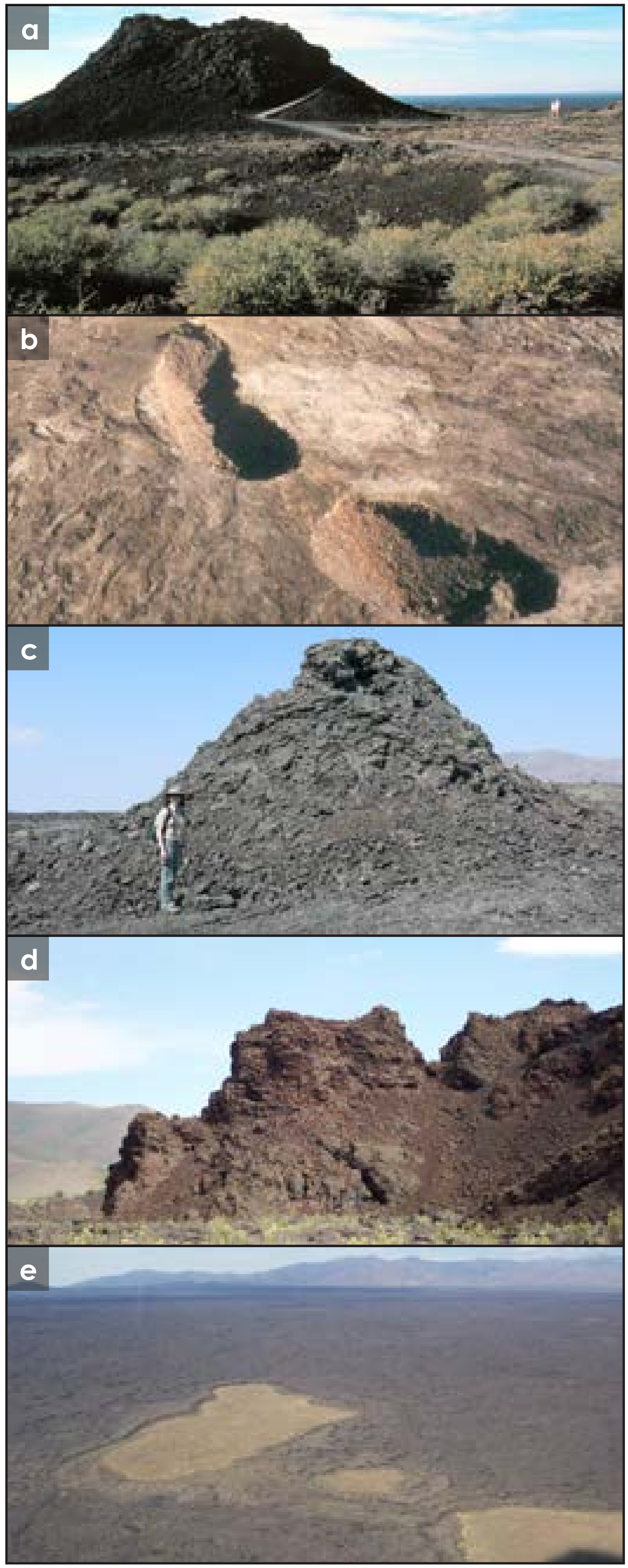

Figure 19: a) Spatter cone **b)** Pit craters **c)** Hornito **d)** Rafted blocks at Devil's Orchard **e)** Kipukas- older areas that are often higher and much more vegetated than the surrounding darker young lava

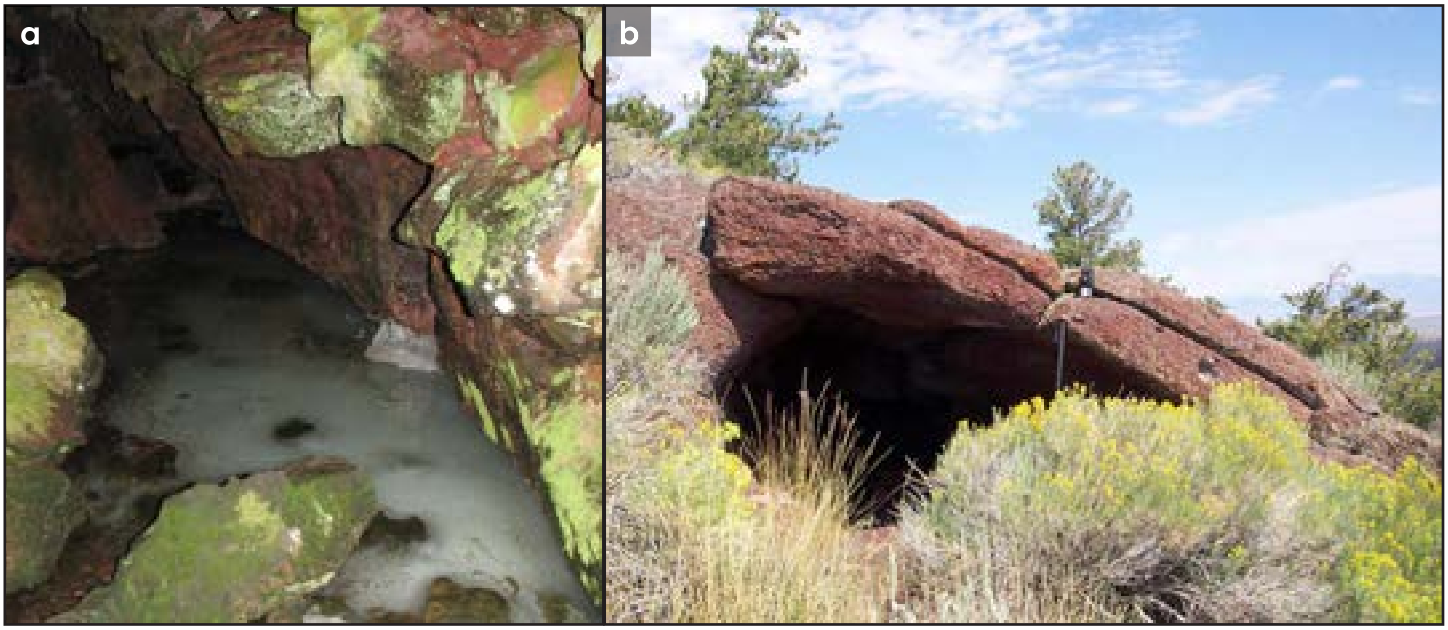

Figure 20: a) Bear's Den Watering Hole **b)** Differential watering cave

ice floored. Flowing lava also can produce shallow caves and overhangs at flow fronts and as a result of the inflation process. Differential weathering of agglutinated cinders on some cinder cones has also generated a few shallow caves (Fig. 20b); less firmly welded or sintered layers being more easily eroded. Some of these small caves are over 10 feet deep. There are also talus caves produced by collapse, slumping, and landslides. Inflated lava flows can have inflation fractures/clefts chalked with break-down or with squeeze-ups, which also produce caves (Fig. 17b).

Stratigraphy and Dating

A stratigraphic section for the Monument consists of very few rock types. Surficial lithology is limited to the basaltic lava flows in all locations except the north end of the monument. It is assumed that the rocks that underlie other parts of the ESRP, such as rhyolitic pyroclastic flow deposits, also underlie much of the Monument, though no drilling has been conducted. Unconsolidated sediments primarily include windblown silt (loess) and sand deposits, cinder deposits, alluvium along streams, colluvium at the base of steep slopes, and lacustrine deposits associated with ponds.

Dating methods used in the Monument include mapping field relations, magnetic polarity studies, dendrochronology, radiocarbon analyses, and K-Ar dating. In the past few decades, Kuntz, et al, (1988, 1989, 1989a, 1989b) and Champion, et al, (1989) have achieved detailed mapping of flows and their relationships with one another. The sequence of eruptions deduced from the superposition of volcanic landforms forms the base for other stratigraphic investigations.

The first efforts to determine the age of the lava flows in the Monument utilized dendrochronology (tree ring dating). One of the first attempts involved a limber pine tree known as the "Triple Twist Tree", which was growing in a crack on the North Crater Flow. It can still be seen today, but died back in 1961 and at the time of study already had rotted heartwood. The tree, about 16 inches (40 cm) in diameter, had 1,350 countable rings and was estimated to be 1,500 years old, allowing for the missing heartwood. The lava would be a minimum of 1,650 years old if it is assumed that it took at least 150 years for the soil to accumulate for it to grow in (Stearns, 1963). Dendrochronology is not applicable to the older flows because the trees despite their remarkable longevity are not long-lived enough, but at least tree ring dating helps establish a minimum age for the younger flows.

For a more precise age, absolute dating techniques that employ radioactive decay rates of various elements can be used. The decay of potassium to argon in the basalts of the Monument was analyzed by Armstrong, et al, (1975). K-Ar did not prove to yield good results for the basalts in the Monument. However, recent work by Kuntz, et al, (2007) using Argon-argon ($^{40}Ar/^{39}Ar$) dating coupled with paleo-magnetic studies and stratigraphic relationships has now provided ages for all the older flows in the Monument.

Basalts have accumulated to depths of over 6000 feet (1828 m) in the area of Craters of the Moon. Project Hotspot drilled a hole just west of the park boundary near Kimama, took continuous core to a depth of 6272 feet (1912 m), and was still in basalt when they stopped drilling. The surface basalt had an age of 700 ka and the age of the basalt at the bottom of the core was 6.5 Ma (Ma= million years). Potter, et al, (2012) found over 100 chemically distinct basalt flow groups comprising 550 individual lava flows within 54 periods of volcanic activity, separated by hiatuses that ranged from decades to thousands of years.

Carbon-14 dating has been the most successful technique used to date Late Pleistocene and Holocene age flows in the Monument. Because lava flows obliterate nearly all carbon life during the eruptions, sources of carbon for dating are scarce. To find datable carbon for the first radiocarbon investigation, scientists dug beneath the lava flows at the perimeter of the lava field to uncover buried carbonized roots of the plants burned by the flowing lava (Bullard, 1970). What is believed to be sagebrush rootlets were found beneath a pahoehoe flow at the southern edge of the Blue Dragon flow. Analyses of two separate samples resulted in carbon-14 dates of 2,110 ± 90 years BP (BP= years before present) and 2,050 ± 80 years BP. Based on stratigraphy, it was estimated that the Blue Dragon flow is one of the youngest flows in the COM lava field. Later investigations used both carbon retrieved from digging under the lava and small carbonized pieces of trees collected (Fig. 21) from tree molds in lava flows. Dating carbon from many localities throughout the Monument lava fields has yielded age dates ranging from approximately 15,000 to 1,700 years BP (Bullard, 1970; Kuntz, et al, 1982). Based on all dating techniques and stratigraphic investigations, it has been determined that COM lava field was formed during at least 8 eruptive periods/episodes between approximately 15,000 years to 2,000 years BP (Kuntz, et al, 1982, 1986, 1988, 1992). Within limits of analytical error, Kings Bowl and Wapi lava fields are contemporaneous and formed about 2,200 years ago.

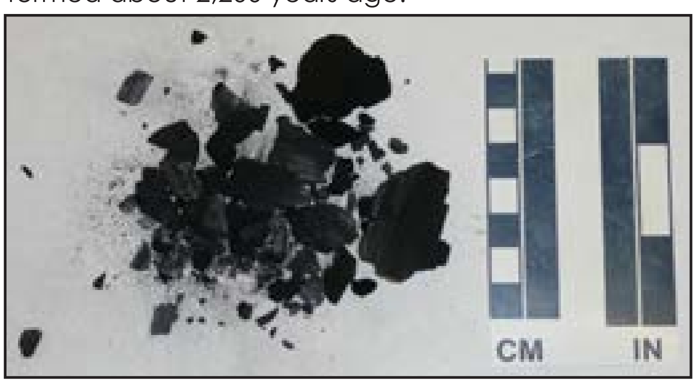

Figure 21: Charcoal from COM tree mold

Other Rock Units

There are no bore holes with cores to provide direct information about the rock units underlying the basalt flows in the Monument. It is assumed that rhyolite exists at depth beneath the surface of the Monument, as it does elsewhere in the ESRP. Xenoliths of pumice (Fig. 18a), Challis volcanics (Fig. 18b), and granulite (Fig. 18c) have been found in some of the basalts of the COM lava field. The granulites are Archean-age lower crustal rocks that have been dated at as much as 3.2 - 3.5 billion years old (Wolf, et al, 2005). The pumice may have come from decompression melting of the granulite, from melting Challis volcanics or Tertiary intrusives (both of which are ~ 50 Ma), or from the Yellowstone Hotspot rhyolites (6 - 10 Ma).

The north end of the Monument is unlike the rest of the Monument and contains six sedimentary, volcanic, and intrusive rock units. Two intrusive-rock map units are exposed in outcrop in the north end of the Monument. Hornblende quartz monzonite is highly weathered and altered, weakly foliated, medium grained and equigranular. Plagioclase is the most abundant mineral in the monzonite and is accompanied by orthoclase, quartz and chloritized hornblende. Biotite granite is also exposed along the base of the Pioneer Mountains within the Monument. The granite contains quartz, biotite (altered to chlorite) and orthoclase (altered to the sericite). It also is highly weathered and is medium-coarse grained and equigranular in texture.

Eocene age Challis volcanics are present in the north end of the Monument and consist of welded tuff, lava flows interbedded with tuff breccia, and tuff breccia. The Challis tuff is an pyroclastic flow deposit that overlies the tuff-breccia unconformably. The tuff ranges in color from light brownish gray to moderate orange pink with silica veins and lenses. The tuff breccia consists of lithic fragments (some of which are pumice), crystals and devitrified glass. These fragments were apparently derived from previously deposited or interbedded rhyodacite lava flows. Both units probably originated from pyroclastic flows containing variable amounts of angular material issuing out of eruptive centers north of the monument boundary during Eocene time.

There are also Mississippian age sandstone, siltstone, claystone, and minor conglomerate of the Copper Basin Formation in the north end of the Monument. The conglomerate is gray with clasts to cobble size. The sandstone is very fine to fine grained, olive gray to medium gray, and sole marks are common in places. The siltstone is locally laminated and medium to dark gray. The claystone is dark gray to black, locally laminated, and contains pebbles of chert and quartzite in places.

Surficial deposits are the youngest materials mapped inside the Monument. The thickness of the sediments in the north end of the Monument ranges up to about 100 feet (30m) along some of the stream drainages based on the well logs from the Monument water wells. Eolian silts and sands mantle some of the older lavas and continue to be eroded, transported, and deposited, particularly after such events as fire or strong winds when the top layer of cinders are moved, exposing the finer-grained loess to the wind. Recent fires in the Kings Bowl area freeing sediments of their

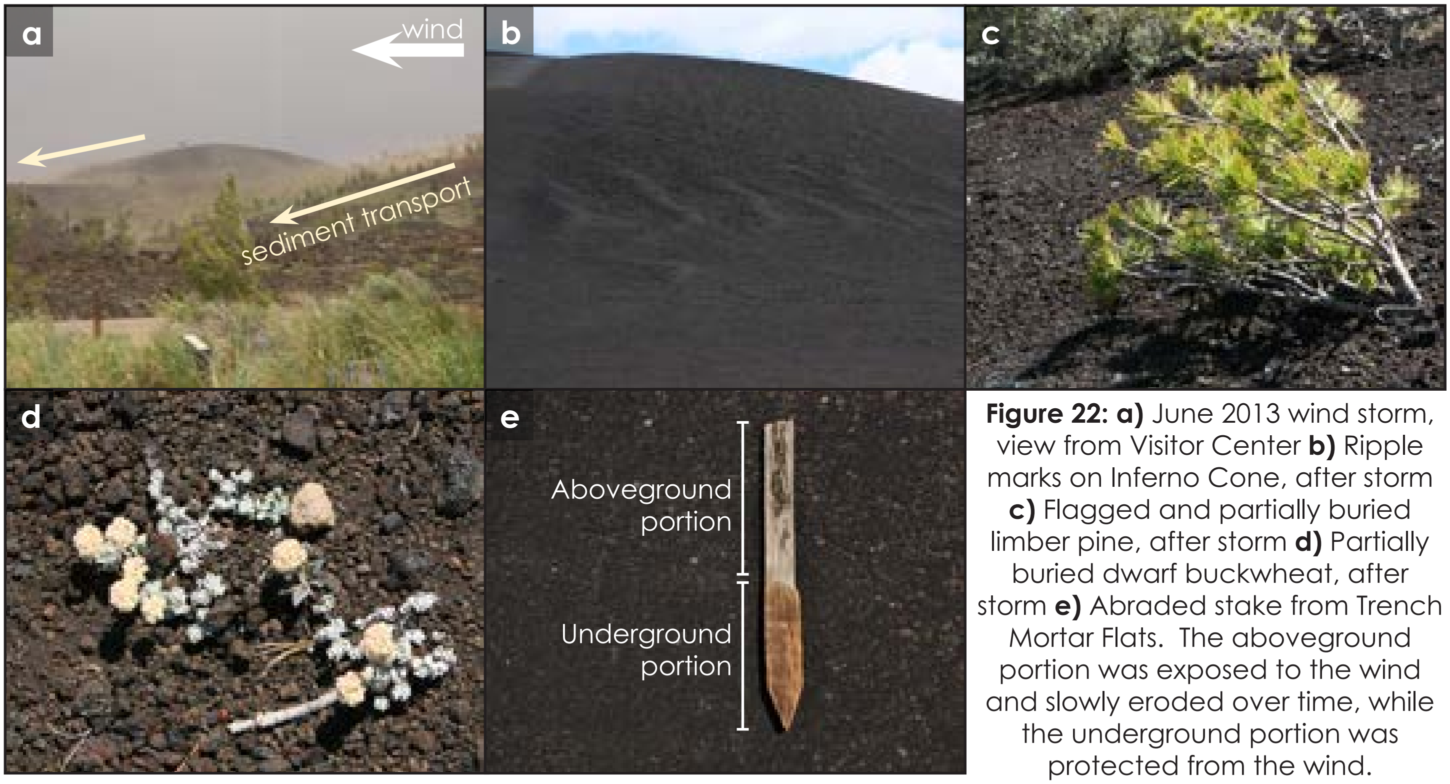

Figure 22: a) June 2013 wind storm, view from Visitor Center **b)** Ripple marks on Inferno Cone, after storm **c)** Flagged and partially buried limber pine, after storm **d)** Partially buried dwarf buckwheat, after storm **e)** Abraded stake from Trench Mortar Flats. The aboveground portion was exposed to the wind and slowly eroded over time, while the underground portion was protected from the wind.

anchors clearly demonstrated eolian processes in action, i.e., deflation, active ripple migration and formation and migration of small sand dunes. Cinders also can often be observed saltating on cinder cones on windy days, thus the cones are a landform in flux and ever changing. See Figure 22 a-e as an example of eolian processes and their impact on life.

Mineralization

The mineralization within Crystal Pit spatter cone is unique. This open chamber contains large quantities of the secondary sulfate minerals, gypsum, mirabilite, and jarosite, all of which seem to be scarce or absent in caves in other volcanic regions. Crystal Pit is a teardrop-shaped cavity approximately 120 feet (36 m) deep that most likely fed the spatter cone at the surface. Microcrystalline mirabilite ($Na_2SO_4 \cdot 10H_2O$) and crystalline gypsum ($CaSO_4 \cdot 2H_2O$) are abundant at the bottom of the pit, covering the walls, and jarosite (($KFe_3(SO_4)_2(OH)_6$)) occurs as a loose powdery yellow material on the cave floor (Peck, 1974). The presence of such large quantities of these minerals in a volcanic cave is at best unusual and their origin is still unknown. Peck (1974) proposed that the mirabilite and gypsum are likely capillary groundwater deposits. Another suggestion is that the minerals are precipitates from an underground lake in Crystal Pit. However, the rocks forming the bottom of the pit are porous and would not likely allow a lake to form. Thus, the origin of these minerals is still in debate.

A unique blue lava surface is found on a few flows in COM lava field. One flow has been named the Blue Dragon lava flow because of the color (Fig. 23). This pahoehoe lava flow extends south and east from the base of Big Craters and was first noted by Russell (1902). The broken lava surface seems to have a series of color layers to the naked eye. The outermost layer is a thin (<5 μm) film that appears pale to deep blue. Beneath this layer is a 0.1 inch (3 mm) thick blue colored glass layer that grades with depth into a brown glass. Thin sections of the flow surface appear brown in transmitted light but the outer blue glass appears blue in reflected light. Faye and Miller (1973) suggested that the blue color is as a result of an electron transfer between iron ions or iron and titanium ions due to oxidation that alters the light absorption in the rock surface. The reason for this blue color is not yet clearly understood and awaits further research.

Paleontology

The igneous nature of the majority of the rocks in the Monument precludes a typical fossil record. The

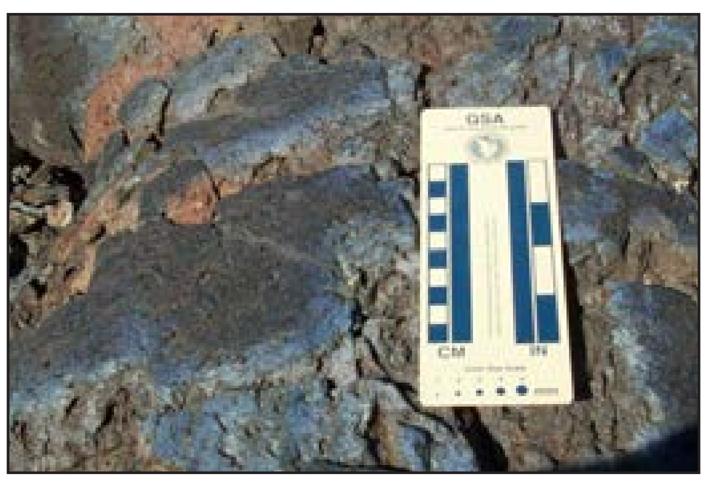

Figure 23: Blue Dragon lava flow

exception is the sedimentary rocks of the Mississippian age Copper Basin Formation found on the northern edge of the Monument. The Copper Basin Formation is made up of interbedded claystone, siltstone, sandstone, and minor conglomerate. The trace fossil Helminthoida (believed to be burrows of a marine worm) is found on some bedding surfaces of the Copper Basin Formation. Because of the relative youth of the volcanism that dominates the Monument, fossils found within the lava fields must have accumulated since the volcanic activity, and therefore, are Pleistocene to recent in age. They are primarily unaltered remains and trace fossils like tree molds.

Figure 24: a) Tree mold of charred wood **b)** Vertical tree mold **c)** Horizontal tree mold

Volcanic activity tends to destroy organic remains. However, tree molds are found in the lava flows of the ESRP. Tree molds are impressions in the solidified lava that form as trees are enveloped by the lava flows, begin to burn, release water and other vapors that quickly cool the surrounding lava, and leave behind a mold of the charred tree (Fig. 24a) and occasionally some carbon residue (Fig. 21). Generally, tree molds preserve impressions of the cracked, partly burnt wood but do not preserve bark or other textures that would aid in the identification of tree species. Tree molds can be both vertical (where the tree remained standing as it burned resulting in a columnar shaped hole in the lava) and horizontal (where the tree fell as it burned resulting in a linear mold in the lava). See Figures 24b & c. The deepest vertical tree mold mapped in the Monument to date is 2.9 meters (82 inches) and largest trunk width is 0.9 meters (35 inches). Some tree molds provide evidence of more than a dozen tree limbs. In the northern end of the Monument, more than 140 tree molds have been mapped. The two flows with the largest number of mapped tree molds are the Blue Dragon and Trench Mortar Flat flows.

When lacking abundant sedimentary deposits to preserve the flora and fauna, the organic remains must be protected in some other way in order to survive over time. Lava tubes are commonly used by animals as hibernation/estivation, roosting, and den sites. They often provide a source of water and an escape from high temperatures (Fig. 25, next page). Animal bones accumulate in the tubes as inhabitants die naturally or are hunted and killed in the caves. Bones are also introduced into the caves as a result of human or animal disposal. Once in the cave, wind blown sediments may bury the bones, helping in the preservation process. Exploration of such deposits in the lava tubes of the Snake River Plain has revealed bones of extinct animals, such as mammoth and camel, as well as modern large animals such as bear, wolf, bison, elk and pronghorn (Miller, 1989). Small animals identified mainly from regurgitated owl pellets include birds, reptiles, amphibians, snails and fish. Although these animals may not have occupied the caves in life, they do offer some information about surrounding paleoecology. It should be noted that paleontological exploration of lava tubes on the ESRP has not been systematic and few have been within the Monument boundaries. Those caves, which have been excavated, were commonly archeological sites.

Figure 25: Ice and water in lava tube cave

Figure 26: Packrat midden

In addition to lava tubes, lava blisters have also accumulated a faunal record. The openings to lava blisters are generally small and drop to a floor, which can be 8-10 feet below the surface or more. This creates and excellent trap for larger animals that fall in and cannot escape. Generally, these animals are carnivores that most likely were lured into the trap by smaller prey such as a rabbit or a squirrel. Carnivores found in these blister traps on the ESRP include the now extinct noble marten, as well as other animals no longer found in the area such as bison, wolverine, and Canada lynx (Miller, 1989). Although these traps contain a random collection of carnivores, they do not represent an accurate percentage of herbivores in relation to the carnivores, because herbivores are less likely to be lured into the trap.

Figure 27: Yellowjacket water hole

A third type of unaltered fossil accumulation occurs in packrat nests. These nests, or middens (Fig. 26), often contain twigs, leaves, pollen, cactus spines, porcupine quills and bones cemented by highly concentrated urine or "amber rat", which hardens and preserves the contents (Miller, 1989). These middens record a variety of information because of the ability to date the pollen and bone assemblages and correlate the pollen and bone assemblages to the paleoecology of the area.

Geologic Processes

In late summer of 2000, a Geoindicators Scoping Meeting was held at COM to determine what geologic processes are active within the Monument. Table 1 lists the geoindicators (a proxy for geologic processes) that are applicable to the Monument and indicates the relative ecological importance,

Table 1: Geoindicators (proxies for geologic processes)

GEOINDICATOR	ECOLOGICAL IMPORTANCE	HUMAN INFLUENCE	MANAGEMENT SIGNIFICANCE
ALPINE and POLAR			
Geological controls on perched water systems	H	L	M
Frozen ground activity (frost wedging)	L	L	H
ARID and SEMI-ARID			
Desert microbiotic crusts and pavements	H	M*	M
Eolian processes	H	M	M
GROUNDWATER			
Groundwater chemistry in the unsaturated zone	L	L	M
Groundwater level	H	M	M
Groundwater quality	L	L	H
SURFACE WATER			
Surface water quality	M	M	H
Stream channel morphology	M	H	M
Streamflow	H	H	H
Wetlands extent, structure, and hydrology	H	M	H
HAZARDS			
Volcanic unrest	H	L	H
Seismicity	L	L	L
OTHER (MULTIPLE ENVIRONMENT)			
Soil and sediment erosion	L	H	M
Soil compaction	L	M	M
Cave temperature and humidity regime	H	L	H
Hillslope processes	M	M	L

H- HIGHLY influenced by, or with important utility
M- MODERATELY influenced by, or has some utility
L- LOW or no substantial influence on, or utility
*adjusted to reflect BLM input about grazing after the Monument expansion

Figure 28: Microbial mats

human influence, and management significance of each geoindicator as rated by the scoping meeting work group. These geoindicators were adapted from Berger (1995). For the entire report see National Park Service (2001). Figure 22 illustrates why Eolian processes were rated of high ecological importance. Figure 27 is a perched water table over ice and easily accessible by wildlife (water temperature was 0.5 °C at the time of photo) and illustrates why groundwater level and geologic controls on perched water tables are of high ecological importance. Though unknown at the time of the report, there are also a few thermal (warm) springs that support microbial mats (Fig. 28) within the borders of the park.

Potential for Future Eruptions

We are at the end of the normal repose interval, the time of quiescence between eruptive periods. The COM lava field formed during eight eruptive periods with a recurrence interval averaging 2,000 years and it has been over 2,000 years since the last eruption. The constancy of the most recent output rates suggests that if this pattern continues, slightly over one cubic mile of lava will be erupted during the next eruption period. In the past, eruptions in the COM lava field have generally shifted to the segment of the Great Rift with the longest repose interval. Therefore, it is likely that the next eruptive period will begin along the central portion of the Great Rift in the COM lava field, but may well propagate to the northern part of the monument in proximity to the loop road (Kuntz, et al, 1986). Initial flows, based on past history, will probably be relatively non-explosive and produce large-volume pahoehoe flows. Eruptions from potential vents on the northern part of the Great Rift may be comparatively explosive and may produce significant amounts of tephra, destroy cinder cones by both explosion and collapse, and build new ones (Kuntz, et al, 1986). As yet, no comprehensive volcanic hazard assessment or plan has been done for the Monument.

The Idaho National Lab (INL) has had their volcanic hazards assessed (Hackett, et al, 2002). Based on their assessment, COM might expect the following from a basaltic eruption in the park: (1) Lava flows covering 0.1 to 400 km^2 (0.04 - 155 mi^2) that may travel >40 km (25 mi); (2) Ground deformation - fissuring and faulting extending up to ~ 6 km (4 mi), and broad uplift and collapse that can cover 100 km^2 (38 mi^2); (3) Volcanic earthquakes associated with magma movement with magnitudes likely less than 4; (4) Gas release usually restricted to near-vent areas that can affect several square kilometers (~1.5 mi^2) downwind; and (5) Tephra fall (cinders, bombs, and spatter) that could affect several square kilometers (1.5 mi^2).

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Glossary

agglutinate: A welded pyroclastic deposit characterized by vitric material cementing the fragments, the presence of scoria, and the absence of a tuff matrix.

alluvium: A general term for unconsolidated detrital material deposited during comparatively recent geologic time by a stream or other body of running water as a sorted or semisorted sediment in the bed of the stream or on its flood plain and delta, or as a cone or fan at the base of a mountain slope

Archean: The geologic time period spanning 2.5 to 4 billion years ago.

asthenosphere: The layer or shell of the Earth below the lithosphere, which is weak and in which isostatic adjustments take place, in which magmas may be generated, and in which seismic waves are strongly attenuated. It is equivalent to the upper mantle.

basalt: A dark- to medium- colored , commonly extrusive (locally intrusive, as dikes) mafic igneous rock.

bifurcation: The separation or branching of a channel into 2 parts

breadcrust bomb: A volcanic bomb whose surface has cracked open due to vesiculation and expansion of the bomb interior after chilling of its surface.

breccia: A coarse-grained clastic rock composed of large (greater than sand-size, or 2 mm in diameter), angular, and broken rock fragments that are cemented together in a finer-grained matrix (which may or may not be similar to the larger fragments)and can be of any composition, origin, or mode of accumulation

caldera: A large, basin-shaped depression, more or less circular or cirquelike in form, the diameter of which is many times greater than that of the included vent or vents, no matter what the steepness of the walls or the form of the floor

cinder: A vitric (glassy), vesicular (containing holes from gas bubbles present at the time of solidifcation), typically basaltic fragment of lava ejected from a vent, which is typically solid by the time it falls to the ground.

cinder cone: A conical hill formed by the accumulation of cinders and other scoriaceous ejecta, normally of basaltic or andesitic composition.

claystone: An indurated clay having the texture and composition but lacking the fine lamination or fissility of shale

colluvium: A general term applied to any loose, heterogeneous, and incoherent mass of soil material or rock fragments deposited chiefly by mass wasting, usually at the base of a steep slope or cliff; e.g. talus, cliff debris, and avalanche material

conglomerate: A coarse-grained , clastic sedimentary rock composed of rounded to subangular fragments larger than 2 mm in diameter set in a finer-grained matrix of sand, silt, or any of the common naturally cementing materials

cow-pie bomb: Type of volcanic bomb resembling cow dung, whose flattened shape is due to its impact while still viscous.

craton: A part of the Earth's crust which has attained stability, and which has been little deformed for a prolonged period.

crystal fractionation: Magmatic differentiation resulting from the settling, by gravity, of the heavy crystals as they form

decompression melting: The melting that occurs when pressure is released or reduced by moving closer to the surface, such as due to convective rise or upwelling of mantle peridotite beneath midocean ridges and volcanic arcs.

deflation The shrinking of a lava flow due to draining out of lava from beneath a lava crust OR the shrinking of the ground surface due to sediment removal from eolian processes

dike: A tabular igneous intrusion that cuts across the planar sructures of the surrounding rock

downwarp: The downward subsidence of a regional area of the Earth's crust, usually as the result of isostatic pressure

Eocene: The geologic time period spanning 56 to 33.9 million years ago.

eolian: Pertaining to the wind; esp. said of rocks, soils, and deposits (such as loess, dune sand, and some volcanic tuffs) whose constituents were transported (blown) and laid down by atmospheric currents, or of landforms produced or eroded by the wind, or of sedimentary structures (such as ripple marks) made by the wind, or of geologic processes (such as erosion and deposition) acoompanied by the wind.

feeding dike: A dike which behaves as a conduit through which magma passes to reach the Earth's surface.

fissure: A surface of fracture or a crack in rock along which there is a distinct separation

flowstone: A general term for any cave formation of calcium carbonate or any other mineral formed by flowing water on the walls or floors of a cave

fractionation, also: fractional crystallization. Separation of a cooling magma into parts by successive crystallization of different minerals at progressively lower temperatures

graben: An elongate, relatively depressed crustal unit or block that is bounded by faults on its long sides

granite: A plutonic rock in which quartz constitutes 10 to 50 percent of the felsic components and in which the alkali feldspar/total feldspar ratio is generally restricted to the range of 65 to 90 percent.

granulite: A rock formed at the high pressures and temperatures of the granulite facies, which may exhibit a crude gneissic structure.

Holocene: The geologic time period spanning the last 10,000 years.

hornito: A feature like a spatter cone around a rootless vent on a lava flow, i.e. tube-fed

ignimbrite: Pyroclastic deposits primarily formed by volcanic ash and pumice, resulting from great explosive eruptions that generate pyroclastic flows.

imbrication: The slanting, overlapping arrangement of tabular or platy fragments or flat pebbles in a stream bed or on a beach, in a manner of tiles or shingles on a roof

inflation: The swelling of a lava flow due to the accumulation of additional lava beneath it

kipuka: An older, usually-higher area surrounded by a younger flow.

lacustrine: Pertaining to, produced by, or formed in a lake or lakes

lava curb: Shelf-like projection of hardened lava in a lava tube from the crusting over of an intermittent lava flow.

lava tube: A hollow space beneath the surface of a solidified lava crust formed by the withdrawl of lava or the decrease in the height of the active lava flow beneath the lava crust.

levee: A retaining wall of hardened lava along the side of a lava channel or lake, built up incrementally by successive overflow, overthrusting of lava crusts or blocks, or spatter.

lithology: The description of rocks, esp. in hand specimen and in outcrop

lithosphere: The solid portion of the Earth

Mississippian: The geologic time period spanning 359 to 323 million years ago.

Moho (Mohorovičić discontinuity): The boundary between Earth's crust and mantle, as determined by sharp seismic velocity difference (and thus sharp difference in the physical properties) between the two.

monzonite: A group of plutonic rocks intermediate in composition between syenite and diorite, containing approximately equal amounts of orthoclase and plagioclase, little or no quartz, and commonly augite as the main mafic mineral.

paleo-magnetic: Referring to the record of Earth's magnetic field in rocks.

phreatic: Said of a volcanic eruption or explosion of steam, mud, or other material that is not incandescent; it is caused by the heating and consequent expansion of groundwater due to an underlying igneous heat source

pit crater: see "sink"

Pleistocene: The geologic time period spanning 2.6 million to 10,000 years ago.

PreCambrian: All of geologic time before 541 million years ago.

pressure plateau: An uplifted area of thick, ponded lava flow caused by the sill-like injection of molten lava beneath a previously formed crust.

pressure ridge: An elongate uplift of the congealing crust of a lava flow, probably due to the pressure of still-flowing lava beneath.

pyroclastic flow: Ground-hugging flows made of volcanic ash, rocks, gas and other debris that are often several hundred degrees Centigrade and that can move at speeds over 100 miles per hour.

rhyolite: A group of extrusive igneous rocks, generally porphyritic and exhibiting flow texture, with phenocrysts of quartz and alkali feldspar (esp. orthoclase) in a glassy to cryptocrystalline groundmass

ribbon bomb: A type of volcanic bomb that is twisted and "ribbon-like" in shape and usually several cm's in length. Forms when lava is ejected from a vent, still partially molten, and twists as it cools and solidifies in flight.

saltation: A mode of sediment transport in which the particles are moved progressively forward in a series of short intermittent jumps, hops, or bounces from a bottom surface that can behave like marbles or billiard balls.

sandstone: A medium-grained, clastic sedimentary rock composed of abundant and rounded to angular fragments of sand size.

sheet flow: A lava flow which moves as a continuous, relatively uniform and broad flow over the subsurface.

shield volcano: A low-angle volcano built primarily of basaltic lava flows with a shape like the gentle arch of a knight's shield laying on the ground.

siltstone: An indurated or somewhat indurated silt having the texture and composition but lacking the fine lamination or fissility of shale

sink: A circular or ellipsoidal depression formed by collapse of a lava tube after evacuation of lava

skylight: An opening in the top of a lava tube cave, caused by the collapse of part of the lava tube's ceiling

sole marks: A structure at the bottom of a geologic unit which is the preserved remains of the ground surface at the time of infill by the above geologic unit

spatter: A partially-fluid accumulation of small pyroclastic fragments ejected from a vent or fissure.

spatter cone: A steep-sided cone of spatter built up around a vent or fissure.

spatter rampart: An elongate buildup of spatter forming a low hill on one or both sides of an eruptive fissure.

spindle bomb: A type of volcanic bomb with a spindle-like (rounded and tapered) shape. Forms when lava is ejected from a vent, still partially molten, and twists during flight.

squeeze-ups: The extrusion of a small volume of viscous lava from a crack or opening on the solidified surface of a lava flow, in response to the pressure of fluid lava within the flow interior.

stacked tube: A lava tube with more than one story formed by lava flows from the same source.

stalactites: A conical formation of lava hinging from the ceiling or walls of a lava tunnel or other cavity and developed by the the dripping of fluid lava

submetallic: A type of rock or mineral luster where similar to metallic, but duller and less reflective.

teleseismic: Pertaining to earthquakes originating at large distances from the measurement site.

tephra: A general term for all pyroclastics from a volcano

tomography: (seismic) A method of imaging the geologic structure of the interior of the earth by measuring the velocities of seismic waves that pass through the earth.

trace fossil: A sedimentary structure consisting of a fossilized track, trail, burrow, boring, or tunnel resulting from the life activities (other than growth) on an animal. In lava, molds of trees enveloped by lava can be preserved.

tube lining: A layer of hardened lava left against the interior surface of a lava tube by an intermittent flow.

tuff: A general term for all consolidated pyroclastic rocks.

tumulus: A doming or small mound on the crust of a lava flow, caused by pressure due to the difference in rate of flow between the cooler crust and the more fluid lava below.

volcanic bomb: Mass of lava ejected from the volcano which can be molten, solid, or partially molten when ejected. It usually refers to particles at least 64 mm in diameter, with the exception of ribbon bombs.

volcanic rift zone: A zone of volcanic features associated with underlying dike complexes

xenolith: An inclusion in an igneous rock of country rock to which it is not genetically related