BORN OF FIRE: IN SEARCH OF VOLCANOES IN U.S. NATIONAL PARKS, FOUR STRIKING EXAMPLES

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ABSTRACT

Geologic features, particularly volcanic features, have been protected by the National Park Service since its inception. Some volcanic areas were nationally protected even before the National Park Service was established. The first national park, Yellowstone National Park, is one of the most widely known geothermal and volcanic areas in the world. It contains the largest volcanic complex in North America and has experienced three eruptions which rate among the largest eruptions known to have occurred on Earth. Half of the twelve areas established as national parks before the 1916 Organic Act which created the National Park Service are centered on volcanic features. The National Park Service now manages lands that contain nearly every conceivable volcanic resource, with at least seventy-six managed lands that contain volcanoes or volcanic rocks. Given that so many lands managed by the National Park Service contain volcanoes and volcanic rocks, we cannot give an overview of the history of each one; rather we highlight four notable examples of parks that were established on account of their volcanic landscapes. These parks all helped to encourage the creation and success of the National Park Service by inspiring the imagination of the public. In addition to preserving and providing access to the nation's volcanic heritage, volcanic national parks are magnificent places to study and understand volcanoes and volcanic landscapes in general. Scientists from around the world study volcanic hazards, volcanic history, and the inner working of the Earth within U.S. national parks. Volcanic landscapes and associated biomes that have been relatively unchanged by human and economic activities provide unique natural laboratories for understanding how volcanoes work, how we might predict eruptions and hazards, and how these volcanoes affect surrounding watersheds, flora, fauna, atmosphere, and populated areas.

Keywords: National Park Service, volcanology, volcanoes, national park, national monument
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1. INTRODUCTION

Volcanoes and volcanic landscapes have been integral to national parks since the beginning of the national park idea. The world's first federally protected national park—Yellowstone National Park—was designated in 1872. At that time, the new national park was placed under the auspices of the Department of the Interior, but there was no specific U.S. bureau or agency that oversaw national parks. Shortly after Yellowstone was designated a national park, other parks and monuments were created. By the time the Organic Act creating the National Park Service was signed by President Woodrow Wilson forty-four years later in 1916, fourteen national parks and twenty-one national monuments had been established. Of those early national parks and monuments, twelve were dominated by volcanic features and the majority of those listed preservation of volcanic features in their enabling legislation (Table 1).

Table 1. Volcanic national parks and monuments established prior to the creation of the National Park Service

Park/Monument name when established	State	Date Established	Historical Notes
Yellowstone National Park	WY	01 March 1872	Yellowstone is the world's first national park. When first established, Yellowstone was located in the Territories of Wyoming and Montana before they became states. At the present time, the majority of the park is in the Wyoming, but small parts of it reach into Montana and Idaho. Yellowstone National Park is considered to be of world-wide significance and was inscribed as a UNESCO World Heritage site in 1978.
Mount Rainier National Park	WA	02 March 1899	Mount Rainier was established as the fifth national park and was the first of many national parks to be created from a national forest. It was part of the Pacific Forest Reserve from 1893-1897, and part of the Mount Rainier Forest Reserve from 1897 until its designation as a national park in 1899.
Crater Lake National Park	OR	22 May 1902	Crater Lake was part of the Cascade Range Forest Reserve from 1893 to 1902 prior to being designated a national park.
Devils Tower National Monument	WY	24 September 1906	Prior to being designated the nation's first National Monument, Devils Tower was part of a temporary forest reserve from 1891 to 1906.
Cinder Cone National Monument	CA	06 May 1907	Cinder Cone National Monument was combined with Lassen Peak National Monument and designated Lassen Volcanic National Park in 1916.
Lassen Peak National Monument	CA	06 May 1907	Lassen Peak National Monument was combined with Cinder Cone National Monument and designated Lassen Volcanic National Park in 1916.
Grand Canyon National Monument	AZ	11 January 1908	Grand Canyon National Monument was later designated Grand Canyon National Park in 1919. Grand Canyon was initially administered by the US Forest Service, but was transferred to the National Park Service in 1933. Grand Canyon is considered to be of world-wide significance and was inscribed as a UNESCO World Heritage site in 1979.
Pinnacles National Monument	CA	16 January 1908	Pinnacles National Monument originally administered by the US Forest Service and then the General Land Office before being transferred to the National Park Service in 1933. It was designated Pinnacles National Park in 2013.
Devils Postpile National Monument	CA	06 July 1911	When established as a national monument in 1911, Devils Postpile was administered by the US Forest Service and transferred to the National Park Service in 1933. Prior to its designation as a national monument, Devils Postpile was briefly part of Yosemite National Park.
Bandelier National Monument	NM	11 February 1916	Bandelier National Monument was initially administered by the US Forest Service and was enlarged and transferred to the National Park Service in 1932.
Hawaii National Park	HI	01 August 1916	Hawaii National Park was later split into the present-day Hawai'i Volcanoes National Park and Haleakala National Park in 1961. Hawaii Volcanoes National Park is considered to be of world-wide significance and was inscribed as a UNESCO World Heritage site in 1987.
Capulin Mountain National Monument	NM	09 August 1916	Capulin Mountain National Monument was redesignated Capulin Volcano National Monument in 1987.
Lassen Volcanic National Park	CA	09 August 1916	Lassen Volcanic National Park combined two existing national monuments: Lassen Peak and Cinder Cone. It was originally administered by the US Forest Service and was transferred to the National Park Service in 1933.

National parks are natural laboratories for scientific study. In many parks today, mining and other surface disturbance has not occurred or has happened to a lesser extent than in surrounding areas, allowing geologic features and landforms to be observed in their natural form. Many national parks and monuments contain unique examples of volcanic features that have been studied by scientists worldwide. In some cases, parks contain the best-preserved examples of particular volcanic features that have been crucial to our modern scientific understanding of magmatic systems and volcanic processes (Figure 1).

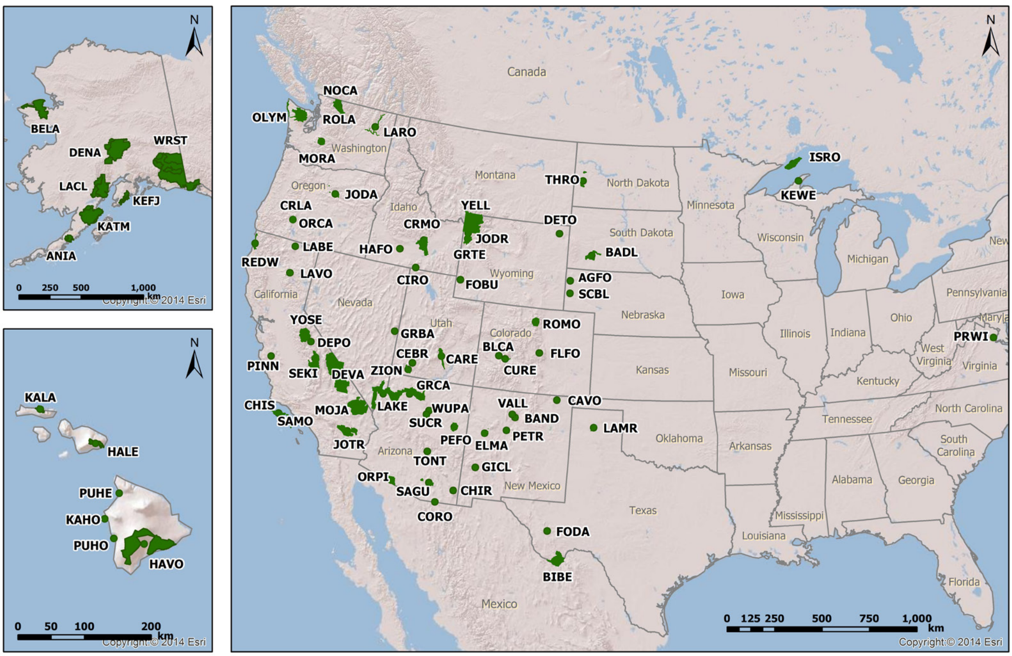

Figure 1. Map of national parks and monuments that contain volcanoes or volcanic deposits. Parks are labeled with NPS 4-letter abbreviations, for a description of these units and their full names see Table 2. Not pictured: National Park of American Samoa (NPSA) and Virgin Islands National Park (VIIS)

Many of these volcanic lands that are now national parks and monuments were also important to the indigenous cultures that first lived there. Long before formal scientific studies of these volcanoes took place, we find rich oral histories through which indigenous people explained the world, including the creation of new land and new beginnings as well as the violent and terrifying experiences that can result from residing near active volcanoes. From the Cascade volcanoes in the Pacific Northwest, to the Hawaiian Islands, to the American Southwest, to Alaska, and Yellowstone, oral traditions providing explanation of natural events and observations of volcanic activity can be found. These oral traditions provide a glimpse into early human perceptions of volcanoes and early attempts to answer questions about volcanism. Many of these same questions still fascinate and confound humankind today.

Due to the overwhelming number of National Park Service units containing volcanoes and volcanic resources, a comprehensive overview of the history of all, or even any one, of the volcanic parks and monuments is outside of the scope of this work. Instead we focus on highlighting a few notable examples of National Park Service volcanic parks: Yellowstone, Mount Rainier, Hawai'i Volcanoes, and Katmai, while acknowledging that there are numerous additional exceptional volcanic parks and monuments administered by the National Park Service

(Table 2). Each of these highlighted examples was influential in National Park Service history and is significant to the study of volcanology.

Table 2. National parks and monuments administered by the National Park Service that contain volcanoes or volcanic deposits. See Figure 1 for a location map of the same National Park Service units. References for this table include the following: Graham 2005, 2006a, 2006b, 2008a, 2008b, 2009a, 2009b, 2009c, 2009d, 2009e, 2010, 2011a, 2011b, 2012a, 2012b, 2014a, 2014b; Harris et al. *2014; Hall and KellerLynn 2010; Hults and Fierstein 2016; Hults and Neal 2015; KellerLynn 2004, 2006, 2007, 2010a, 2010b, 2012, 2013, 2014a, 2014b, 2014c, 2015a, 2015b, 2015c, 2016; Thornberry-Ehrlich 2005a, 2005b, 2006, 2008a, 2008b, 2009a, 2009b, 2010a, 2010b, 2010c, 2011a, 2011b, 2011c, 2011d.*

Park Name	NPS Abbrv.	State	Date Established	Volcanic Significance
Agate Fossil Beds National Monument	AGFO	NE	14 June 1997	These fossil beds contain numerous mammal fossils from the early Miocene. The fossil-bearing sediments are interbedded with volcanic ash layers from the western US. The agate after which the park is named can be found alongside ash deposits just above the Miocene bone beds.
Aniakchak National Monument and Preserve	ANIA	AK	1 December 1978	Aniakchak Caldera is the largest caldera in the Aleutian Island Chain. The volcano experienced a cataclysmic eruption approximately 3,400 years ago, causing the collapse of the peak from an estimated 2,000 meters to its present height of 1,340 meters. The most recent eruption occurred May–June of 1931. Fortuitously, the caldera was observed the year prior by geologist and Jesuit Priest Bernard Hubbard. He returned in 1931 and documented portions of the eruption and changes within the caldera.
Badlands National Park	BADL	SD	4 March 1929 (national monument) 10 November 1978 (national park)	The majority of the rocks in Badlands National Park are sedimentary rocks deposited during the late Cretaceous throughout the late Oligocene. Several distinctive ash layers are deposited throughout the park as well, including the Rockyford ash, which is a distinctive marker bed.
Bandelier National Monument	BAND	NM	11 February 1916	The Bandelier Tuff was deposited by two explosive, caldera-forming eruptions from the Valles Caldera that filled ancient canyons with hundreds of meters of tuff. The Bandelier Tuff contains many caves formed during the escape of volcanic gasses and subsequent erosion. Thousands of years ago, the ancestral Pueblo people took advantage of many of these natural caves, enlarging them and carving out their homes in cliffs of the relatively soft rock.
Bering Land Bridge National Preserve	BELA	AK	1 December 1978 (national monument) 2 December 1980 (national preserve)	Bering Land Bridge National Preserve protects a small remnant of the grassland that connected Asia and North America during the last Ice Age. In early Miocene, ashfall totally buried the entire preserve area. It now contains extensive basaltic lava fields, granite spires, calderas, maar lakes, and hot springs.
Big Bend National Park	BIBE	TX	12 June 1944	Big Bend National Park contains spectacular geological variety. The majority of rocks within the park are sedimentary rocks that were deposited during the Paleozoic, Mesozoic and Cenozoic eras. However, many of the mountains within the park are composed of volcanic rocks.

Black Canyon of the Gunnison National Park	BLCA	CO	2 March 1933 (national monument) 21 October 1999 (national park)	Several volcanic tuffs are present within and near Black Canyon of the Gunnison, erupted from volcanic calderas to the south. The oldest volcanic rocks, the West Elk Breccia, came from an Eocene eruption in West Elk Mountains to the north. A series of tuffs followed from the San Juan Mountains during the Oligocene. The Black Canyon also contains remnants of Mesa Falls Ash and Lava Creek B Ash, both from large, caldera-forming eruptions of Yellowstone.
Capitol Reef National Park	CARE	UT	2 August 1937 (national monument) 18 December 1971 (national park)	The majority of Capitol Reef National Monument's spectacular geology is sedimentary strata. Distal volcanic eruptions contributed volcaniclastics to the Chinle Formation, so while technically sedimentary, this formation contains significant volcanic input. Pliocene dikes and sills can be found in Upper Cathedral Valley
Capulin Volcano National Monument	CAVO	NM	9 August 1916	Capulin Volcano National Monument preserves a 60,000 years-old monogenetic cinder cone volcano and associated lava flows and other volcanic features. Capulin cinder cone is one of about 120 cinder cones in the Raton-Clayton Volcanic Field.
Cedar Breaks National Monument	CEBR	UT	22 August 1933	Cedar Breaks contains volcanics from the Marysvale volcanic field (active 36–14 Ma). There are two ash-flow tuffs; the Oligocene Baldhills Tuff Member of the Isom Formation and a tuff of the late Oligocene Leach Canyon Formation, and small amounts of basaltic material from the Western Grand Canyon basaltic field.
Chiricahua National Monument	CHIR	AZ	18 April 1924	Chiricahua National Monument was established to protect and preserve the exceptional geologic features including pinnacles, columns, spires, and balanced rocks carved by wind and water from the Rhyolite Canyon Tuff, which was erupted from the Turkey Creek Caldera in the Oligocene.
Channel Islands National Park	CHIS	CA	26 April 1938 (national monument) 5 March 1980 (national park)	Channel Islands National Park protects five of California's eight Channel Islands and the surrounding ocean. Subduction-generated volcanic rocks make up a significant portion of the Channel Island.
City of Rocks National Reserve	CIRO	ID	18 November 1988	City of Rocks National Reserve is mostly known for its two granitic intrusions; the Oligocene Almo pluton and the Proterozoic Green Creek Complex. These plutons were unroofed before 10 Ma, when voluminous rhyolite flows were erupted nearby and deposited on top of the Almo pluton in Emigrant Canyon in the southern portion of the reserve.
Coronado National Memorial	CORO	AZ	5 November 1952	Coronado National Memorial contains the Montezuma caldera, which spans nearly the entire memorial, in addition to two smaller calderas. These calderas were formed by large, highly explosive eruptions in the mid-late Jurassic. Montezuma Peak is an intrusive body of granite formed during the same volcanic interval.
Crater Lake National Park	CRLA	OR	22 May 1902	Crater Lake is the deepest lake in the United States, the second deepest in North America, and the ninth deepest lake in the world. Pyroclastic deposits from the catastrophic eruption of Mount Mazama 7,700 years ago are world-famous in volcanology for their excellent preservation of a complete sequence of eruption from a zoned magma chamber.

Craters of the Moon National Monument	CRMO	ID	2 May 1924	The Craters of the Moon lava field is the largest Holocene lava field in the contiguous United States. In addition to the lava flows, the youngest of which is only about 2,000 years old, the monument contains many cinder cones, spatter cones, and shield volcanoes. The lava flows contain multiple lava tube caves and tree molds.
Curecanti National Recreation Area	CURE	CO	6 February 1965	Within the national recreation area, the Dillon Pinnacles are eroded volcanic breccia from lahars induced by pyroclastic eruptions in the West Elk Mountains. Many of the mesas at Curecanti are topped by welded tuff from explosive eruptions of the San Juan Mountains.
Denali National Park and Preserve	DENA	AK	26 February 1917	Many of the geologic formations in the park contain volcaniclastics and lavas. Miocene pillow basalts are exposed along the Denali Park highway. The colorful rocks at Polychrome overlook are formed from interbedded lava flows and rhyolitic tuffs from the Eocene Teklanika Formation. Mt. Galen is formed from tuffs, breccias, and lava flows ranging from basalt to rhyolite.
Devils Postpile National Monument	DEPO	CA	6 July 1911	Devils Postpile National Monument is named after a large outcrop of basalt that displays spectacular columnar jointing. The basalt that makes up the Postpile was erupted from a vent outside of the monument boundary approximately 82,000 years ago. The monument also contains Rainbow Falls, a spectacular waterfall that drops 31 meters over a massive rhyodacite flow.
Devils Tower National Monument	DETO	WY	24 September 1906	Devils Tower National Monument has the distinction of being the first national monument established under the authority of the Antiquities Act in 1906. Devils Tower is an iconic volcanic landform composed of the igneous rock phonolite. The tower displays world-renown columnar jointing.
Death Valley National Park	DEVA	CA	11 February 1933 (national monument) 31 October 1994 (national park)	The rocks of Death Valley National Park preserve the most complete geologic record in the National Park Service, with representation from the late Paleoproterozoic to the present. The park contains numerous examples of lava flows and airfall tephra layers. One of the more striking examples of volcanic features within the park is Split Cinder Cone, which was erupted on top of a strike-slip fault and has been faulted apart. The Miocene Artist Drive Formation contains striking multi-colored rocks including gravel, playa deposits, and volcanic deposits. The colors in this formation were caused by hydrothermal alteration and chemical weathering of the volcanic rocks.
El Malpais National Monument	ELMA	NM	31 December 1987	El Malpais National Monument contains cinder cones, ice caves, and a lava tube system that extends for 19 kilometers. In addition to earlier flows, the monument contains the McCartys flow, which erupted 3,900 years ago. This flow is not only the most recent in this volcanic field, but it is also the most recent in New Mexico. It is among the most voluminous young basalt flows in the southwestern United States, containing three to six cubic kilometers of lava.
Florissant Fossil Beds National Monument	FLFO	CO	20 August 1969	The Florissant Formation is composed of Eocene lacustrine fossil-rich sediments interbedded with numerous ash beds from the Guffy Volcanic center. The influx of silica from periodic ashfalls created massive diatom blooms that have also been preserved as distinct layers within the lakebeds and were instrumental in preservation of the fossils. The lake itself is thought to have resulted from volcanic activity, due to the damming of local streams by lahars from the Guffy Volcanic Center. The monument also contains a small petrified forest of Eocene tree stumps imbedded in lahar deposits.

Fossil Butte National Monument	FOBU	WY	23 October 1972	Fossil Butte National Monument preserves a small portion of an Eocene lake called Fossil Lake. The majority of the fossiliferous lake sediments are limestone and dolomite, but numerous tephra layers are interbedded with the sediments and have been used to provide chronostratigraphic control for the fossils.
Fort Davis National Historic Site	FODA	TX	8 September 1961	Fort Davis National Historic Site contains Eocene lava flows of the nearby Davis Mountains. The Davis Mountains are composed of rhyolitic and trachytic lava flows and ashflow tuffs that erupted from two nearby volcanic centers: the Paisano Volcano, west of Alpine, and the Buckhorn Caldera, northwest of Fort Davis.
Gila Cliff Dwellings National Monument	GICL	NM	16 November 1907	Gila Cliff Dwellings National Monument is located near the eastern margin of a large Oligocene volcanic collapse structure called the Gila Cliff Dwellings caldera. The rocks in the monument are predominantly volcanic rocks or sedimentary rocks with a large proportion of volcaniclastics.
Great Basin National Park	GRBA	NV	24 January 1922 (national monument) 27 October 1986 (national park)	Eocene to Oligocene volcanic rocks can be found within Great Basin National Park. There are several ashflow tuffs exposed in Johns Wash and a small linear feature made up of rhyodacite flows and subvolcanic intrusive rocks can be found in the southwest part of the park
Grand Canyon National Park	GRCA	AZ	11 January 1908 (national monument) 26 February 1919 (national park)	The volcanic basalts of the Uinkaret volcanic field in western Grand Canyon are little known, but spectacular. They were erupted on the canyon rim and within the canyon itself. Multiple eruptions spilled lava over the sides of the canyon, leaving dramatic drapes of black basalt over the layers of white, orange, pink and red sedimentary rock, like chocolate frosting dripping down the sides of a giant layer cake. The lava affected the erosional and geomorphic processes occurring within the canyon by armoring terraces and slopes. Lava from the eruptions sometimes dammed Colorado River briefly until it overtopped or destroyed the lava, creating some of the rapids that still exist on the river.
Grand Teton National Park	GRTE	WY	26 February 1929	Grand Teton National Park contains many volcanic rocks. Volcanic conglomerates and welded tuffs from the Eocene Absaroka volcanoes are scattered throughout the park. The banded cliffs of the Wiggins Formation near Togwotee Pass contain Oligocene volcanic conglomerates interbedded with volcanic tuff. During the Miocene, volcanoes erupted at the north end of the Teton Range and east of Jackson Lake, contributing volcanic conglomerates and tuffs to the Colter and Camp Davis Formations. Following that, an ancestral Jackson Lake—Teewinot Lake—accumulated tephra from Yellowstone-SRP eruptions. These lake beds now underlie Jackson Lake Lodge and are exposed on the upper mountains on the east side of the park. During the Pliocene, the Conant Creek Tuff was erupted from the Heise volcanic field and deposited in northern Jackson Hole. Later, pyroclastic flows from Yellowstone left deposits of welded tuff on Signal Mountain and the Gros Ventre Buttes just south of the park.
Hagerman Fossil Beds National Monument	HAFO	ID	18 November 1988	The Hagerman fossil beds contain a diverse early-middle Pliocene (~4.2-3.0 Ma) faunal assemblage. The Glenns Ferry Formation exposed within the Monument preserves lacustrine and fluvial deposits interbedded with silicic and basaltic tephra and basaltic lava flows sourced from the Cascades Range and the Snake River Plain. These tephra have been used to establish chronostratigraphic context for the fossils.

Haleakala National Park	HALE	HI	1 August 1916	Haleakalā Volcano on Maui is the only Hawaiian volcano not located on the Big Island that is potentially active today. It last erupted a mere 400 years ago. In addition to the volcano itself, the park also contains fragile native Hawaiian ecosystems, rare and endangered species, and cultural sites.
Hawaii Volcanoes National Park	HAVO	HI	1 August 1916	Hawai'i Volcanoes National Park contains two active volcanoes. Mauna Loa is the most voluminous volcano in the world and last erupted in April 1984. Kīlauea is the most active volcano in the world and has been erupting continuously since 3 January 1983.
Isle Royale National Park	ISRO	MI	3 April 1940	There are two major bedrock formations on the island and both are volcanic: the Portage Lake Lava series and the volcanoclastic Copper Harbor Conglomerates, both are Precambrian in age.
John Day Fossil Beds National Monument	JODA	OR	26 October 1974	The monument contains a well-preserved Cenozoic fossil record of plants and animals. Multiple lava flows, tuff beds, and tephra layers are deposited throughout the sedimentary fossil-bearing layers and provide chronostratigraphic control.
John D. Rockefeller Jr. Memorial Parkway	JODR	WY	25 August 1972	The parkway links Grand Teton National Park and Yellowstone National Park and contains geological features characteristic to both, including many Yellowstone-derived volcanics, which line the Snake River and outcrop on the tops of ridges
Joshua Tree National Park	JOTR	CA	20 October 1976 (national monument) 31 October 1994 (national park)	The bedrock geology within Joshua Tree National Park is almost entirely igneous and metamorphic. In addition to the famous granites within the park, there are also Jurassic volcanics and Miocene lava flows.
Kaloko-Honokohau National Historic Park	KAHO	HI	10 November 1978	The national historic park was established for the preservation and interpretation of traditional native Hawaiian activities and culture. It is located on the western shore of the island of Hawaii and developed from the eruptive activity of the volcano Hualalai. Nearly all of the rocks in this park are basaltic lavas.
Kalaupapa National Historic Park	KALA	HI	22 December 1980	Kalaupapa National Historic Park is situated on the northern shore of the island of Molokai, Hawaii. The island is mostly formed from two Pleistocene shield volcanoes: West Molokai Volcano and East Molokai Volcano. In the Holocene, another small volcano, Puu Uao erupted in the north of the island. The rim of this volcano forms Kauhako Crater, which contains a lake at the bottom that is over 240 m in depth.
Katmai National Park	KATM	AK	24 September 1918 (national monument) 2 December 1980 (national park)	The violent volcanic eruption at Novarupta in June 1912 was the 20th century's most voluminous volcanic eruption, and is one of the five largest eruptions in recorded history. The eruption included a sequence of ash-flows known as the Valley of Ten Thousand Smokes ignimbrite. The area in which this ignimbrite was emplaced once contained thousands of active fumaroles, which are what gave the area and rock unit its name. Katmai National Park and Preserve contains more than twenty volcanoes in addition to Novarupta, including compound multi-vent stratovolcanoes, volcanic domes, calderas, and monogenetic volcanoes

Kenai Fjords National Park	KEFJ	AK	1 December 1978 (national monument) 2 December 1980 (national park)	Resurrection Bay contains pillow basalts originally erupted on the sea floor, they have now been uplifted and are exposed in sea cliffs along the bay.
Keweenaw National Historic Park	KEWE	MI	27 October 1992	The Keweenaw National Historic Park focuses on the copper mining heritage of the Upper Michigan Peninsula. It is underlain by two formations, both of which are volcanic: the Portage Lake Lava series, and the Copper Harbor volcanoclastic conglomerates.
Lava Beds National Monument	LABE	CA	21 November 1925	Lava Beds National Monument lies on the northern flank of Medicine Lake volcano, a shield volcano that has been active for half a million years. Medicine Lake Volcano has erupted many times, most recently 950 years ago. It has one of the highest eruptive frequencies among Cascade volcanoes and has erupted a variety of lava types, though the majority has been basaltic. The volcano has experienced at least two explosive eruptions that produced widespread tephra fallout. The national monument also contains the largest concentration of lava tube caves in North America with more than 700 lava tube caves.
Lake Clark National Park and Preserve	LACL	AK	1 December 1978 (national monument) 2 December 1980 (national park)	Lake Clark National Park and Preserve contains two active stratovolcanoes; Mount Redoubt, which last erupted in 2009, and Mount Iliamna. The last eruption of Mount Iliamna is poorly constrained, but is thought to have occurred around 350 years ago. Iliamna contains numerous fumaroles on its eastern flank. These vents often emit steam and gas. Many false eruptions have been suspected because of steam clouds emanating from these vents.
Lake Mead National Recreation Area	LAKE	NV	13 October 1936	The Triassic Chinle Formation makes up a portion of the bedrock within the national recreation area. During deposition, volcanic eruptions occurred to the west and south and contributed a great deal of volcanic sediment to the formation in this area.
Lake Meredith National Recreation Area	LAMR	TX	28 November 1990	Lake Meredith and surrounding areas contain windblown ash from multiple eruptions along the Yellowstone-Snake River Plain (SRP) volcanic track, including ash from all three caldera-forming eruptions of Yellowstone and an older Miocene ash suspected to have originated from the Twin Falls volcanic field, an earlier volcanic center along the Yellowstone-SRP track. Aeolian ash was used here to make Borger cordmarked pottery. Cordmarked pots have impressions of cords pressed into their exteriors and ash was used to temper the clay, making it less likely to shrink and crack as it dried.
Lake Roosevelt National Recreation Area	LARO	WA	April 1946	The Lake Roosevelt area contains large-volume late Miocene - Early Pliocene basaltic lava flows. These basalts were erupted over approximately 10-15 million years and accumulated to a thickness greater than 1,800 meters, producing the Columbia Plateau.

Lassen Volcanic National Park	LAVO	CA	6 May 1907 (national monument) 9 August 1916 (national park)	Lassen Peak is one of two Cascade volcanoes that erupted in the twentieth century. It erupted from 1914 to 1917, with the most powerful explosion occurring 22 May 1915. Lassen Volcanic National Park also contains a number of other volcanoes, including Cinder Cone, a basaltic cinder cone that erupted approximately 350 years ago. The park also features several hydrothermal areas containing acidic hot springs, boiling mud pots, and steaming fumaroles.
Mojave National Preserve	MOJA	CA	31 October 1994	Mojave National Preserve contains many volcanic features, including lava flows, lava tubes, cinder cones, and pyroclastic deposits. Most of the volcanics date from the early to middle Miocene, but some volcanic activity has occurred within the last several thousand years as pottery chards can be found imbedded in basaltic flows. Most of the cinder cones have been affected by mining. The Cinder Cones portion of the national preserve is listed as a National Natural Landmark
Mount Rainier National Park	MORA	WA	2 March 1899	Mount Rainier is an active volcano, and is the tallest mountain in the Cascade Range. It is considered to be one of the most dangerous volcanoes in the continental United States due to the combination of a propensity for unleashing catastrophic lahars and its proximity to densely populated areas. Mount Rainier contains the most glacial ice of any peak in the United States outside of Alaska. Its last significant eruption was 1,000 years ago. There are active fumaroles at the summit and bubbling cold springs on the flanks of the mountain today.
North Cascades National Park	NOCA	WA	2 October 1968	North Cascades contains a hodgepodge of geologic terrains including rocks from basaltic ocean floor, ocean sediments, mantle rocks, and volcanic island arcs. Additionally, a number of deposits from nearby young Cascades Range volcano Mount Baker are preserved within the park.
National Park of American Samoa	NPSA	AS	31 October 1988	The National Park of American Samoa has park units on the islands of Tutuila, Ofu, and Tau in the Territory of American Samoa, south of the equator in the central South Pacific Ocean. Shield volcanoes and cinder cones are the predominant volcanic edifices and lavas are basaltic, trachytic, and andesitic in composition. The most recent volcanism to occur in American Samoa occurred in 2003 with the eruption of the submarine volcano Vailuluu.
Olympic National Park	OLYM	WA	2 March 1909 (national monument) 29 June 1938 (national park)	The southeast side of Maynard Peak within Olympic National Park is comprised of a large 40-55 Ma formerly submarine basalt known as the Crescent Formation.
Organ Pipe Cactus National Monument	ORPI	AZ	13 April 1937	Organ Pipe Cactus National Monument includes part of the Pinacate volcanic field in the northern Ajo Range. Volcanic rocks from this volcanic field consist primarily of high-viscosity rhyolite flows and small tuffs separating the rhyolite flows. The most recent eruption in the Pinacate volcanic field took place about 250 km to the southwest of the monument in the 1600s.

Petrified Forest National Park	PEFO	AZ	8 December 1906 (national monument) 9 December 1962 (national park)	A large basin containing numerous ephemeral lakes covered northeastern Arizona during the late Miocene and early Pliocene. Volcanoes of the Hopi Buttes volcanic field to the northwest erupted ash and lava into the basin, creating a series of maars and lava flows in the Bidahochi Formation. Most of this formation has been removed from the park by erosion, but three volcanic structures still exist today - Pintado Point, Pilot Rock, and Black Knoll. The park also contains smaller volcanic features such as volcanic bombs and blocks, and large boulders of volcanic agglomerate.
Petroglyph National Monument	PETR	NM	27 June 1990	Petroglyph National Monument was created primarily to preserve archeological features. However, the archeological features within the monument are inextricably linked to the geology. Petroglyph National Monument contains an estimated 25,000 rock art images carved into basalt erupted from the Albuquerque volcanic field.
Pinnacles National Park	PINN	CA	16 January 1908 (national monument) 10 January 2013 (national park)	The Pinnacles volcano began to erupt some 23 million years ago in what is now southern California. It grew to be slightly smaller than Mount Saint Helens is today and then the plate tectonic regime changed. Subduction ceased and strike-slip motion began along the newly-developed San Andreas Fault. The San Andreas Fault happened to split the Pinnacles volcano in two and the Pinnacles part of the volcano (about two-thirds of the original mass) moved approximately 300 kilometers northwestward on the Pacific plate, while the east side remained in place on the North American plate.
Prince William Forest Park	PRWI	VA	14 November 1936	This park contains Ordovician metavolcanic rocks of the Chopawamsic Formation, and includes lava flows, breccia, and tuff interbedded with metasedimentary rocks. The Cabin Branch Mine, active 1889–1919, extracted metals from metavolcanic rocks.
Puukohola Heiau National Historic Site	PUHE	HI	17 August 1972	Puukohola Heiau National Historic Site is located on the northwest coast of the Island of Hawaii. This portion of Hawaii was formed by the eruptive activity of Kohala volcano, the first of the five volcanoes on the Island of Hawaii to emerge from the ocean, and thus is the source of the oldest rocks on the island. The Kohala volcanics are predominantly basaltic lavas. The older Pololu Volcanics have been K-Ar dated to between 400,000 to 250,000 years old. The more recent Hawi Volcanics yield K-Ar dates between 230,000 and 120,000 years old.
Pu'uhonua o Honaunau National Historic Park	PUHO	HI	26 July 1955 renamed in 1978	Puuhonua o Honaunau National Historical Park was originally established as City of Refuge National Historical Park. The site was renamed its current designation in 1978. This area was the seat of power for the Kona chiefs and includes many archaeological sites. It is located seaward of Honaunau village on the shoreline of Mauna Loa volcano, on the western shore of the island of Hawaii. The majority of the lithologies within the park are Mauna Loa basalts that date between 750 and many thousands of years old.
Redwood National Park	REDW	CA	2 October 1968	The Franciscan Formation makes up the bedrock of Redwood National Park, this formation ranges in age from Late Jurassic to Miocene, and includes mafic volcanic rocks, many of which have been altered to greenstone.

Rocky Mountain National Park	ROMO	CO	26 January 1915	Rocky Mountain National Park contains rhyolitic welded tuffs and basaltic lava flows, visible at Lava Cliffs on the Trail Ridge Road summit area. The Never Summer Mountains in the northwestern portion of the park are formed of late Oligocene intrusive and volcanic rocks known as the Braddock Peak volcanic complex.
Saguaro National Park	SAGU	AZ	1 March 1933 (national monument) 14 October 1994 (national park)	The Tucson Mountain District of Saguaro National Park has many fantastic exposures of the 25 km-wide Tucson Mountains Caldera, formed approximately 70-75 Ma from a gigantic explosive volcanic eruption and subsequent caldera collapse. Many igneous rocks, including intrusive dikes and plutons, and volcanic tuffs and lava flows can be found throughout the park. Cat Mountain is formed of tuff and the Twin Hills, Safford Peak, and Tumamoc Hill all contain lava flows.
Santa Monica Mountains National Recreation Area	SAMO	CA	10 November 1978	A portion of southern California's Santa Monica Mountains and Simi Hills are located in this recreation area. Subduction and fault-block rotation caused decompression melting and widespread volcanism in this area from about 19 – 16 Ma. A large volcano grew from the sea floor in the area of the future western Santa Monica Mountains and eventually rose above sea level.
Scotts Bluff National Monument	SCBL	NE	12 December 1919	Scotts Bluff National Monument contains rocks from the White River and Arikaree Groups. Both are generally sedimentary, but contain significant amounts of volcanic tuff and airfall ash deposits, likely sourced from volcanoes located in Colorado
Sequoia and Kings Canyon National Parks	SEKI	CA	25 September 1890	Mesozoic metavolcanic rocks that began as volcanic tuffs, breccias and lava flows are exposed in portions of the park. Small sections of the park contain Tertiary remnants of basaltic and dacitic lava flows and eroded volcanic necks from the San Joaquin-Kings volcanic field which was active 3 - 3.5 Ma. Quaternary volcanic rocks exist along the eastern side of the Sierra Nevada, but mostly outside of park boundaries.
Sunset Crater Volcano National Monument	SUCR	AZ	30 May 1930	Sunset Crater Volcano is a product of the most recent eruption of the San Francisco Volcanic Field sometime between 1040 and 1100 AD. The eruption of Sunset Crater was witnessed by the ancestors of the Pueblo Indians. There are numerous pieces of archeological evidence for this, including "corn rocks", which are deliberate impressions of corn in basalt, which could only have been made while the lava was fluid. Settlements in the immediate area were buried and the deposition of volcanic tephra across a wide area functioned as a mulch to retain soil moisture and allowed agriculture in area that was too arid before the eruption.
Theodore Roosevelt National Park	THRO	ND	25 April 1947 (memorial park) 10 November 1978 (national park)	Theodore Roosevelt National Park preserves some of the badlands surrounding the Little Missouri River. The majority of the rocks in these badlands are sedimentary, but Paleocene volcanic ashes are present as well. The bentonite 'blue beds' are formed from altered volcanic ash and petrified wood in the park gained silica from the dissolution of volcanic ash.
Tonto National Monument	TONT	AZ	21 October 1907	Tonto National Monument is located at the boundary of the Sonoran Desert and primarily preserves prehistoric archeological sites, including many cliff dwellings. The primary rocks exposed in the national monument are Precambrian Apache Group sedimentary rocks and the 0.5 - 15 Ma Gila Conglomerate. The Apache Group sediments are capped with a dense, fine-grained basalt, and fine-grained volcanic debris can be found elsewhere within the Apache Group sediments.

Valles Caldera National Preserve	VALL	NM	25 July 2000	Valles Caldera National Preserve includes a twenty-two kilometer-wide caldera and is the younger of at least two calderas known to have existed in this location. Explosive eruptions formed the caldera 1.2 million years ago, with the youngest eruption of Valles Caldera taking place ~50,000–60,000 years ago. Today, an active geothermal system containing hot springs and fumaroles exists within the caldera. This is the system that erupted the Bandelier Tuff, which makes up the rock formations found in Bandelier National Monument. The caldera was also important in prehistoric times as a hunting ground and as a source of obsidian for spear and arrow points dating back at least 11,000 years.
Virgin Islands National Park	VIIS	VI	2 August 1956	Virgin Islands National Park spans over half of St. John Island, nearly all of Hassel Island, and a bit of St. Thomas Island. St. John Island is composed of subduction-related Cretaceous basalt, andesite, keratophyre (an intermediate volcanic rock), some intrusive rocks, and small amounts of calcareous rocks and chert.
Wrangell-St Elias National Park and Preserve	WRST	AK	1 December 1978 (national monument) 2 December 1980 (national park)	Wrangell-St Elias National Park and Preserve is one of the largest national parks in the world. The park contains at least twelve volcanic centers, several of which have been active in Holocene time. Mount Wrangell is Alaska's largest active volcano and the park contains the most voluminous sub-polar icefield in North America as well as the biggest glacial system in the nation.
Wupatki National Monument	WUPA	AZ	9 December 1924	Quaternary basalts from the nearby San Francisco Volcanic Field cap several mesas in the monument and beds of cinders from the eruption of nearby Sunset Crater Volcano between 1040 and 1100 AD can be found.
Yellowstone National Park	YELL	WY	1 March 1872	Yellowstone is the largest volcanic complex in North America and it has erupted three of the biggest and most powerful eruptions known to have occurred on Earth. It also contains half of the world's known geothermal features, including the world's tallest geyser and North America's largest hot spring.
Yosemite National Park	YOSE	CA	1 October 1890	While the majority of the rocks in Yosemite are granitic intrusive rocks from the Sierra Nevada batholith, there are several extrusive volcanic units in the park, including Jurassic 'roof pendants' of metavolcanic rocks. Mount Dana and Mount Gibbs are composed of these Jurassic metavolcanics. In addition, during the late Cenozoic, volcanoes erupted to the north, leaving behind a few lava flows, lahar deposits, and tuffs north of the Grand Canyon of the Tuolumne. Remnants of more local volcanic events also exist, including a small Miocene columnar basalt known as 'Little Devils Postpile,' located near the Tuolumne River west of Tuolumne Meadows. The most recent volcanic activity in Yosemite is represented by a small ~ 3.5 Ma basalt flow just south of Merced Pass.
Zion National Park	ZION	UT	19 November 1919	While the majority of the rocks within Zion National Park are sedimentary, evidence of late Cenozoic volcanism much younger than any of the famous sedimentary layers is preserved in the park. The oldest volcanic features in Zion are about 1.4 Ma, and the youngest - the Crater Hill lava flow and cinder cone - are about 100,000 years old. These volcanic features are exposed along SR-9 near the town of Virgin and along the Kolob-Terrace Road - particularly at Lava Point where the Crater Hill basalt contains columnar jointing, similar to that seen at Devils Postpile and Devils Tower National Monuments.

2. YELLOWSTONE NATIONAL PARK

Yellowstone National Park contains the largest volcanic complex in North America and is one of the most recognized volcanic areas in the world. Located in an area of older unrelated volcanic deposits, volcanism in the Yellowstone area has included three major caldera-forming eruptions in the past 2.1 million years, which rate among the largest eruptions known on Earth. The Yellowstone system also produced numerous smaller eruptions before, between, and after the major caldera-forming events. Altogether, approximately 7,000 cubic kilometers of silicic magma was erupted from Yellowstone in the past 2.1 million years (Christiansen 2001).

2.1 Early exploration and founding of the first National Park

Yellowstone National Park was established 1 March 1872 as the world's first national park. Yellowstone contains the largest volcanic system in North America and one of the largest hydrothermal systems on Earth. The area was certainly known by Native American tribes and fur traders much earlier, but was not brought to the attention of the general populace of the United States until the late 1800s.

The Lewis and Clark Expedition (1804–1806) did not explore the Yellowstone area, but John Colter, a member of the expedition, diverted from the expedition on the return journey and noted the presence of 'Hot Spring Brimstone' (Cramton 1932). After the war of 1812, fur trader Daniel Potts published the first account of Yellowstone's hydrothermal features in a letter to the *Philadelphia Gazette & Daily Advertiser*. He included descriptions of "a number of hot and boiling springs, some of water and others of the most beautiful fine clay, resembling a mush pot and throwing particles to the immense height of from 20 to 30 feet" and "places where pure sulphur is sent forth in abundance" (Potts 1827). Subsequently, other explorers including Joseph Meek, James (Jim) Bridger, and James Gemmell visited and told others about the wondrous things they saw there. Lieutenant John W. Gunnison of the U.S. Army Corps of Topographical Engineers wrote a book primarily about Mormons, that included statements from Jim Bridger about his time in Yellowstone where he described "geysers [that] spout up to 70 feet high, with a terrific hissing noise, at regular intervals" and "Great Springs, so hot that meat is readily cooked in them, and as they descend on the successive terraces, afford at length delightful baths" (Gunnison 1856, p. 151).

In 1860, the first government expedition aimed specifically for the Yellowstone region was led by Captain W. F. Raynolds. This party included Jim Bridger as a guide and geologist Dr. F.V. Hayden, however this expedition failed to complete its purpose, though a report was published in 1867 as Senate Executive Document 77 of the Fortieth Congress, first session (Cramton 1932). Several additional parties made forays into the region in the 1860s, but their reports appear to have mostly dealt with hardships encountered, attacks suffered, and discoveries of gold (Crampton 1932).

A prospecting expedition headed up by Walter W. De Lacey went up the Snake River in 1863 looking for gold and De Lacey (1876, p. 105) observed "rough basaltic country" and "conglomerate rock overlaid by basalt" on the way up the river. Once they reached Yellowstone he described the hot springs of Lower Geyser Basin:

> The water of these springs was intensely hot of a beautiful ultramarine blue some boiling up in the middle and many of them of very large size being at least twenty feet in diameter and as deep. There were hundreds of these springs and in the distance we could see and hear others, which would eject a column of steam with a loud noise These were probably geysers, and the boys called them 'steamboat springs.' No one in the company had ever seen or heard of anything like this region, and we were all delighted with what we saw. (De Lacey, 1876 p. 117).

In 1869, David E. Folsom, Charles W. Cook and William Peterson traveled from Bozeman into the area of the present park (Crampton 1932). The party successfully explored Yellowstone and updated a map made by DeLacy several years earlier. In July 1870, the party published an article entitled "The Valley of the Upper Yellowstone" in *Western Monthly* magazine that Langford later republished as *The Folsom-Cook Exploration of the Upper Yellowstone in the Year 1869* (Crampton 1932; Folsom 1894). This article caught the attention of scientists and the initial draft of the article reportedly included a reference to the idea of a public park, but the publishers edited that portion out prior to publication of the article (Cramton 1932).

In August 1870, an expedition led by Surveyor-General Henry D. Washburn and Lieutenant G. C. Doane visited the Yellowstone region. This expedition included politician and businessman Nathaniel P. Langford, who went on to become the first superintendent of Yellowstone National Park in 1872. He later appointed David E. Folsom of the Folsom-Cook Expedition as assistant superintendent in 1873. They explored Yellowstone Lake, the Lower, Midway, and Upper geyser basins, named Old Faithful and several other geysers, climbed several peaks and descended into the Grand Canyon of the Yellowstone River. Following the expedition, several newspaper stories were published, and in 1871 Lieutenant Doane submitted the first official government account of exploration of the Yellowstone region. His report indicated recognition that the Yellowstone landscape was volcanic.

> The river breaks through this plateau in a winding and impassable canyon of trachyte lava over 2,000 feet in depth, the middle canyon of the Yellowstone, rolling over volcanic boulders in some places, and in others forming still pools of seemingly fathomless depth. At one point it dashes here and there, lashed to a white foam, upon its rocky bed; at another it subsides into a crystal mirror wherever a deep basin occurs in the channel. Numerous small cascades are seen tumbling from the lofty summits a mere ribbon of foam in the immeasurable distance below. This huge abyss, through walls of flinty lava, has not been worn away by the waters, for no trace of fluvial agency is left upon the rocks; it is a cleft in the strata brought about by volcanic action, plainly shown by that irregular structure which gives such a ragged appearance to all such igneous formations. (Doane 1871, pp. 5–6).

He also hinted that the hot springs resulted from volcanic processes:

> This valley showed evidence of diminished volcanic action, calcareous mounds being frequently seen, which had originated in the action of hot springs, the waters of which had now ceased to flow (Doane 1871, p. 7).

Doane himself clearly recognized the unique and scientific value of Yellowstone as evidenced by some of his closing statements in his report:

> We saw many strange and wonderful phenomena, many things which would require volumes for adequate description, and which in future geography will be classed among the wonders of the earth . . . As a country for sight-seers, it is without parallel; as a field for scientific research, it promises great results; in the branches of geology, mineralogy, botany, zoology, and ornithology it is probably the greatest laboratory that nature furnishes on the surface of the globe (Doane 1872, pp. 37–38).

The newspaper articles published about this trip were so popular that *The Herald* made several reprintings due to strong public demand (Cramton 1932). The expedition also brought back geologic specimens and Langford displayed them at several very popular lectures he gave in Washington DC and New York City.

During the 1870 expedition there was apparently discussion prompted by Mr. Cornelius Hedges about the possibility of setting the Yellowstone area aside as a national park. There is no suggestion of this in any of the newspaper articles or the Doane report, but Mr. Langford's diary stated the following:

> Mr. Hedges then said . . . that there ought to be no private ownership of any portion of that region, but that the whole of it ought to be set apart as a great national park (Langford 1905, p. 118).

In the introduction to his published diary, Langford gives Mr. Hedges the credit for the idea of the national park and indicates that Hedges wrote a letter published in *The Helena Herald* on 9 November 1870 that pushed for the founding of a great national park. He also stated that he pushed the idea in his lectures after the expedition (Langford 1905).

In 1871, the first official federal scientific expedition to Yellowstone took place. Ferdinand V. Hayden was appointed head of the U.S. Geological and Geographical Survey of the Territories 1 May 1871, and he was instructed by Congress to explore the sources of the Missouri and Yellowstone Rivers. The expedition resulted in an improved map of the Yellowstone area and provided ample evidence of its unique volcanic, thermal, and scenic character through the photographs of William Henry Jackson and the art of Henry W. Elliot and Thomas Moran. Hayden's survey team included a mineralogist, a topographer, two botanists, a meteorologist, a zoologist, an ornithologist, and an agricultural statistician/entomologist. Hayden himself was a noted geologist. He was known for his fearless fieldwork and he never carried a gun. At one point, he was captured and subsequently released by Indians who, surprised to find him carrying a large bag of rocks, considered him demented. They thereafter knew him as "the man who picks up stones running" (Cramton 1932, p. 22). Professor Hayden wrote an official report to Secretary of the Interior Delano in 1872 and referenced the glorious volcanic and hydrothermal features of the Yellowstone region in articles in the *American Journal of Science and Arts*, and in *Scribner's Monthly*. In his 1872 *Scribner's Monthly* article Hayden queries:

> Why will not Congress at once pass a law setting it apart as a great public park for all time to come as has been done with that far inferior wonder, the Yosemite Valley? (Hayden 1872, p. 396).

The fantastic descriptions, photographs and paintings of the volcanic and hydrothermal features in the Yellowstone area prompted Delegate William H. Clagett of Montana and Senator Pomeroy of Kansas to introduce the Yellowstone National Park Protection Act simultaneously in both Houses of Congress on 18 December 1871. It passed Congress and was signed into law by President Ulysses S. Grant on 1 March 1872, creating the first national park in the world. More than one hundred years later, in 1978, Yellowstone became the twenty-eighth UNESCO World Heritage Site, demonstrating the continuing uniqueness and value of the area.

Many more scientific studies were conducted and continue to be done in and around Yellowstone. Notably, Fenner (1937) realized similarities between welded ash-flow tuffs (thought to be rhyolites at the time) and deposits in the Valley of Ten Thousand Smokes in Katmai, discussed later in this volume. The current understanding about Yellowstone's caldera and eruptive history was not known until the 1960s and 1970s, many decades after the park was created, and we continue to learn more. For an overview of early studies conducted shortly after the park was formed, see Christiansen (2000).

2.2 Volcanic history of Yellowstone

The Yellowstone area was a locus of volcanism, though in a different tectonic setting, even before the current Yellowstone system existed. The Eocene Absaroka Volcanic Supergroup underlies much of Yellowstone, and is exposed in mountains within and around the park. Mount Washburn, one of the highest points in the park, is a remnant of Absaroka volcanism. The Absaroka Supergroup consists of andesitic and dacitic extrusive rocks and smaller amounts of mafic lavas and rhyodacite ashflow tuffs, all of which were erupted nearly 50 million years ago (Smedes and Prostka 1972). The Absaroka Volcanic Province is unique in and of itself, as it is the largest volcanic field of its age in the western United States (Hiza 1998).

Yellowstone is located at the eastern end of the Snake River Plain; a crescent-shaped depression 80 to 100 kilometers wide and 560 kilometers long. It has been inundated by volcanic material during the last several million years. The majority of the Snake River Plain is overlain by Quaternary basalt ranging from several hundred to several thousand meters thick, often covering large volumes of silicic volcanic rocks.

In general, major silicic volcanic centers across the Snake River Plain become younger from west to east (Figure 2), creating the Yellowstone-Snake River Plain (SRP) track (Christiansen 2001; Christiansen *et al*. 2002; Foulger 2002, 2015; James *et al.* 2011; Pierce and Morgan 1992, 2009; Perkins and Nash 2002 and references therein). The Yellowstone-Snake River Plain track is marked by silicic ash flow tuffs marking locations of large outpourings of silicic volcanism. These ash flow tuffs mark eight silicic volcanic centers that are older than the current Yellowstone Plateau. Each of these centers was active for a time and experienced large, explosive eruptions as well as smaller rhyolitic lava eruptions. The dates of these silicic ash-flow tuffs show a pattern of more recent volcanism toward the east along the Yellowstone track (Christiansen 2000; Pierce and Morgan 1992, 2009; Perkins and Nash 2002). Magmatism along this track began approximately seventeen million years ago, nearly 700 kilometers southwest of Yellowstone, along the Nevada-Oregon border (Perkins and Nash 2002). This volcanism was part of a new regional trend of widespread bimodal basalt–rhyolite volcanism.

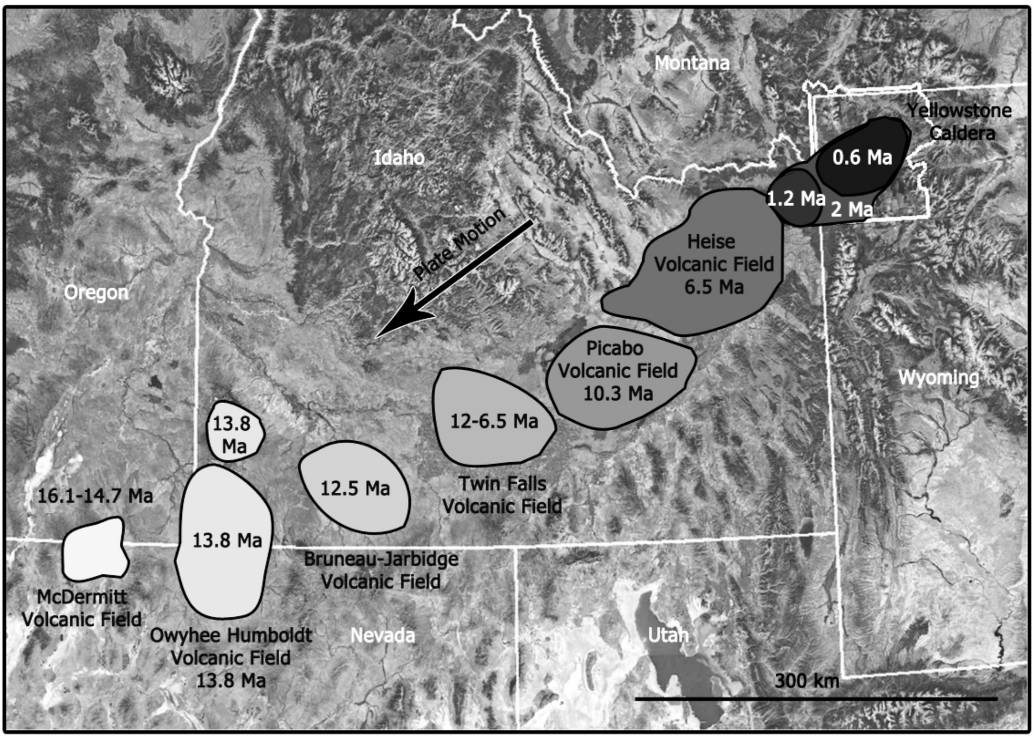

Figure 2: Age progression of the Yellowstone-Snake River Plain trend silicic centers, including the most recent calderas in and near Yellowstone National Park (figure modified from Marcus et al. *2012, and Smith and Siegel 2000).*

The current locus of volcanism, the Yellowstone Plateau volcanic field, began erupting approximately 2.5 Ma. Since then, three volcanic cycles have occurred, all involving a period of magma chamber filling and uplift with faulting/fracturing at the surface and the eruption of small basaltic and rhyolitic lava flows followed by large, caldera-forming explosive events, and post-collapse extrusion of small pyroclastic flows and rhyolitic and basaltic lava flows within or around the perimeter of the caldera (Christiansen 2001). The earliest recognized eruptive phase began with the eruption of several lavas; the Junction Butte Basalt exposed in the northeastern part of the park and the rhyolitic lava of the Snake River Butte in southern Island Park (Christiansen and Blank 1972; Obradovich 1992; Christiansen 2001).

The first ash-flow of the Yellowstone Group (the stratigraphic group comprising all three of Yellowstones major caldera-forming eruptive products) erupted at 2.1 Ma. (Christiansen and

Blank 1972). The eruption comprised an enormous eruption column and numerous pyroclastic flows. The eruption column sent ash high into the atmosphere and the accompanying ash cloud blanketed the surrounding states in ash (Figure 3). Pyroclastic flows roared from the vents, burying an area of 15,500 square kilometers in meters of hot ash. The total volume of the eruption was >2,500 cubic kilometers, making this one of the largest volcanic eruptions known.

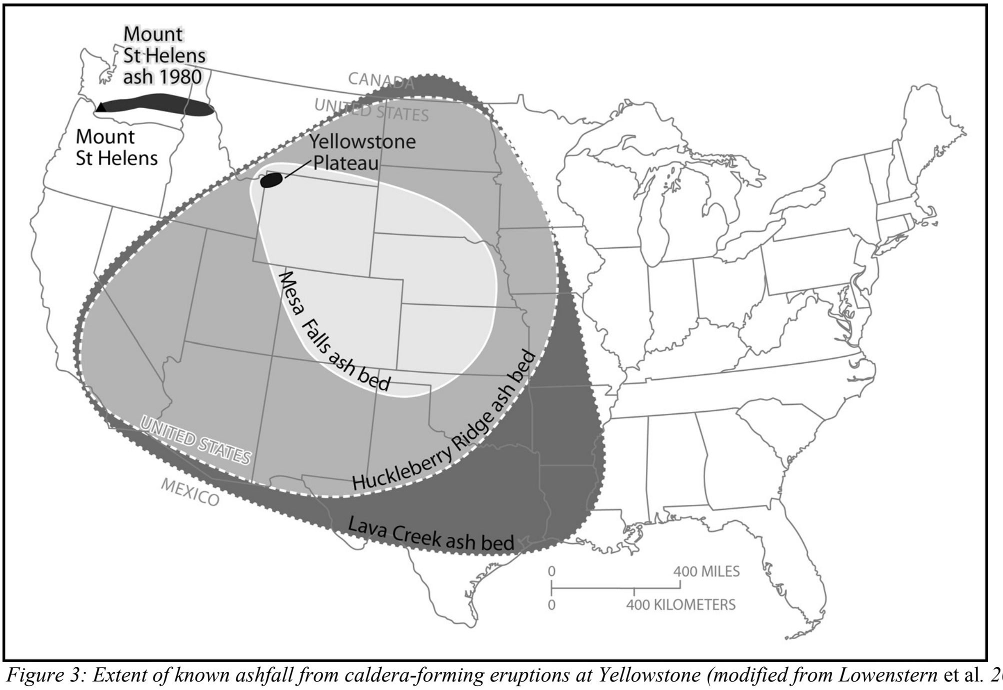

Figure 3: Extent of known ashfall from caldera-forming eruptions at Yellowstone (modified from Lowenstern et al. *2005).*

These ash flows and associated regional airfall tephra formed the Huckleberry Ridge Tuff, which consists of three members surmised to have erupted from separate parts of the magma chamber (Christiansen 2000). Due to a lack of erosion or soil formation between them and numerous similar dates of both sanidine and zircon from these deposits, all three members are generally thought to have erupted within a short duration, likely over days or weeks (Christiansen 2001; Stelten 2015; Wotzlaw 2015). Evacuation of the magma chamber led to the collapse of the ground surface and formation of a caldera measuring about 95 km long and 60 km wide, referred to as the Huckleberry Ridge Caldera (Figure 4) (Christiansen, 2001).

The second volcanic cycle, culminating in the Mesa Falls eruption, was the smallest of the three. Deposits from this cycle are not actually exposed within the park, though they can be seen just outside of the western boundary of the park. The caldera-forming eruption of this cycle transpired around 1.3 Ma and erupted >280 cubic kilometers of material, creating another caldera to the southwest, outside of the park but within the caldera created by the Huckleberry Ridge eruption. This caldera is known as the Henry's Fork Caldera; it is the smallest of the three calderas found in the Yellowstone area, but it is still sixteen kilometers in diameter (Figure 4).

The third and most recent explosive volcanic cycle began approximately 1.2 Ma with rhyolitic and basaltic lava flows, and at approximately 0.6 Ma another climactic eruption occurred with the eruption of the Lava Creek Tuff (Christiansen *et al*. 2001; Lanphere *et al*. 2002; Wotzlaw 2015). Once again, an eruption column extended high into the atmosphere and numerous pyroclastic flows buried an area >7,500 square kilometers. As in the first two climactic eruptions, windblown ash from the accompanying eruption cloud covered the surrounding states (Figure 3) and remains of this ash can still be found as far away as California, Iowa, Canada, and Mexico (Christiansen 2001 and references therein). At the end of this eruption, the magma chamber roof collapsed to form the Yellowstone Caldera, which is 85 kilometers long and 45 kilometers wide (Figure 4). Similar to the first two climactic eruptions, post-caldera lavas were erupted subsequent to caldera-formation (Christiansen, 2001)

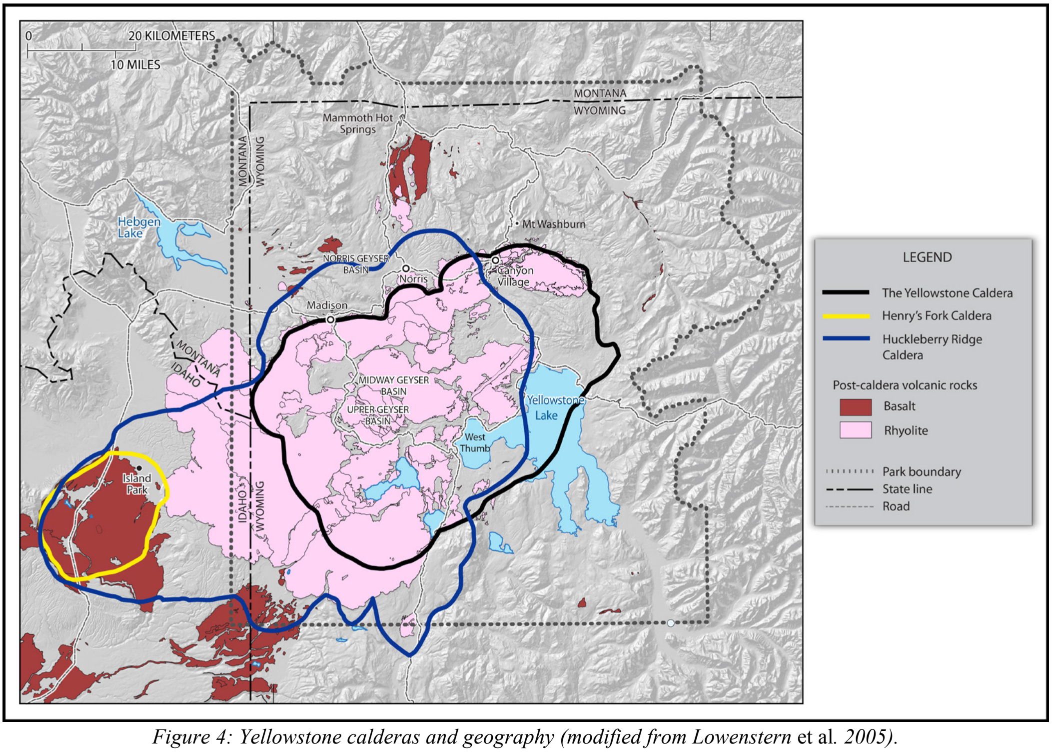

Figure 4: Yellowstone calderas and geography (modified from Lowenstern et al. *2005).*

Since the Yellowstone Caldera formed 640,000 years ago, it has partially filled with greater than 500 cubic kilometers of rhyolitic lava. Outside of the caldera, much smaller volumes of basalt have erupted from the Yellowstone volcanic system. Much of the current geography was influenced by the placement of lava flows subsequent to caldera collapse. For example, Yellowstone Lake fills a basin between the east rim of the Yellowstone Caldera and rhyolite flows to the west. The Shoshone and Lewis Lakes fill basins located between adjacent flows. The locations of both the Upper and Lower Falls of Yellowstone River are directly related to the resistant layers in post-caldera rhyolite flows. Nez Perce Creek and the Firehole River flow along seams between two lava flows and the Gibbon River flows between young lava flows and deposits of Lava Creek Tuff for much of its course (Good and Pierce 1996).

There is a lack of intracaldera basaltic volcanism that has been interpreted to indicate that there is a significant volume of silicic magma that prevents the basaltic magma from rising to the surface (Hildreth 1981; Hildreth *et al.* 1991; Christiansen 2001; Lowenstern and Hurwitz 2008). Studies have indicated that this silicic magma is likely mostly crystalline and thus Yellowstone is unlikely to erupt without changes to the current magmatic system (Stelten *et al.* 2015). These magmas, while unlikely to erupt currently, provide the heat that sustains the famous geothermal features located within Yellowstone National Park (Werner and Brantley 2003; Lowenstern and Hurwitz 2008).

Yellowstone National Park contains one of the largest hydrothermal systems on earth with thousands of hot springs, geysers, fumaroles, and mud pots, all resulting from elevated heat flow due to the magmatic system deep below. These are the features that first caught the eye of early explorers and captured the imagination of the entire country. Hot springs exist where the heated water table intersects the ground surface and there are no obstructions, so water is free to bubble out of the ground. In cases where the plumbing system of the hot spring is partially obstructed, geysers form. Fumaroles exist where gasses and water vapor can find their way out of the ground, but there is not enough water in the system to reach the surface as a liquid.

At lower elevations, most of the water has a pH that is neutral to alkaline. Silica-rich water flows out of the ground as hot springs and geysers. As this water cools, it builds terraces of amorphous silica, also called sinter. In the higher elevations of the park, mostly in the eastern part of the caldera, a different kind of hydrothermal water exists. These waters are low-chlorine and acidic. They form where gases such as CO_2 and H_2S are released by the boiling of chlorine-rich waters deep in the hydrothermal system. The acidic vapors condense just below the ground surface. Oxidation of H_2S occurs to form sulfuric acid, which alters the rhyolitic rocks to form mud and clay, which dominates these thermal areas. An example of one of these areas is Mud Volcano. These systems have very little thermal water flowing away from them and mostly exist as boiling mud pots (Lowenstern and Hurwitz 2008). These geothermal features exist as a testament to the mighty volcanic heat and power still present below Yellowstone.

2.3 The Yellowstone Volcano Observatory

If another caldera-forming event the size of the Huckleberry Ridge event were to occur at Yellowstone, it could result in ash flows deep enough bury the world's tallest building immediately adjacent to the vents and ash would be expected to accumulate to depths of up to half a meter within 300 kilometers of the vents. High eruption clouds would eject sulfur aerosols and ash particles high into the atmosphere and around the world, likely significantly altering weather patterns. The likelihood of another caldera-forming event is low, but there are still many volcanic hazards to be considered at Yellowstone. Even a small rhyolitic eruption at Yellowstone would have impacts to infrastructure and people living in and visiting the national park and surrounding communities. Seismicity is a significant hazard in the area, partly due to magmatic uplift and associated earthquake swarms, but also because Yellowstone is located at the edge of a tectonically active extensional area capable of generating large regional earthquakes (Christiansen *et al.* 2007). Hydrothermal explosions without associated volcanic eruption are one of the most common hazards in Yellowstone. These explosions result from hot water below the surface flashing to steam, breaking rock and creating craters up to several kilometers in diameter (Christiansen *et al.* 2007).

The Yellowstone Volcano Observatory, founded in 2001, monitors a variety of geophysical and geochemical parameters associated with the Yellowstone Caldera. It was initially established as a partnership between the United States Geological Survey, Yellowstone National Park, and the University of Utah as a result of a workshop regarding volcanism in national parks (Guffanti *et al.* 2001). However, it was expanded in 2013 to include five more organizations: the Idaho Geological Survey, the Montana Bureau of Mines and Geology, the University NAVSTAR Consortium (UNAVCO), the University of Wyoming, and the Wyoming State Geological Survey. Yellowstone Volcano Observatory includes the Yellowstone Seismic Network, a GPS network, borehole strain meters and seismometers, and other monitoring equipment and personnel providing hazards monitoring, hazards response plans, and scientific understanding of Yellowstone geology (Yellowstone Volcano Observatory website, 2017).

3. MOUNT RAINIER NATIONAL PARK

Mount Rainier National Park, Washington encloses the tallest mountain in the Cascade Range. Standing at 4,392 meters, Mount Rainier is also one of the highest peaks in the contiguous United States. Mount Rainier is an active volcano and is considered one of the most dangerous volcanoes in the continental United States (Swanson *et al.* 1992). This is due to the combination of its proximity to populated areas and its propensity for unleashing catastrophic lahars (or volcanic mudflows) down river valleys that are now densely populated and filled with infrastructure. In addition to being a large, potentially destructive volcano, Mount Rainier also hosts the most glacial ice of any other single peak in the United States outside of Alaska (Driedger and Kennard

1986). Ice has been instrumental in shaping the mountain. During the Pleistocene, Mount Rainier was heavily glaciated and a series of relatively fluid andesite flows streamed down the sides of the mountain. Somewhat counter-intuitively, lava flows likely did not melt large amounts of glacial ice; instead, the ice acted to slow, dam and deflect lava, thus influencing where the lava flowed and ponded. After the glaciers retreated, solidified lava flows were left behind and now form ice marginal high ridges (Lescinsky and Sisson 1998). Even before the volcanic hazards were realized, the mountain was recognized for its scenic beauty, challenging terrain, and geologic significance.

3.1 Early history and founding of Mount Rainier National Park

The natives of the Pacific Northwest held the volcanoes of the Cascade Range in awe and their eruptions, avalanches, and oft cloud-shrouded lofty summits inspired many legends about the spirits that resided in them. Mount Rainier was no exception. In general, the volcanoes of the northwest were both revered and feared, while also providing places to live, hunt, and gather in their lower elevations. Native legends include stories about great floods that inundated the lowlands, feuds between mountains in which the mountains hurled stones at one another, and times when the mountains sent forth fiery rivers of blood (Catton 1996; Pringle 2008). While these stories are fantastical, they were inspired by observations of volcanic eruption.

Mount Rainier was studied by geologists beginning in 1855 with rock descriptions and early geologic reconnaissance by George Gibbs. In 1870, Samuel Emmons became one of the first scientists to summit Mount Rainier when he visited to collect samples and describe the glaciers. Rocks from Mount Rainier were first analyzed and described in a scientific paper in 1883 (Hague and Iddings 1883).

Also in 1883, pioneer James Longmire was returning from climbing the mountain with his friends George Bayley and P. B. Van Trump when their horses wandered away from their campsite by the Nisqually River. Longmire went looking for them and stumbled across a meadow full of bubbling springs resulting from gas being released from depth. He filed a mineral claim in 1884, constructed a small cabin for his family, and proceeded to build and operate the first tourist inn on Mount Rainier in the area of the park now named after him. By 1889 the Longmire family was advertising their bathhouses and guest spa in which guests could enjoy mineral baths, mud baths, and sulfur plunges. The Longmires widely advertised the (unlikely) health benefits of these amenities and visitors flocked to the area (Catton 1996).

Scientists, particularly geologists, were instrumental in the impetus to create Mount Rainier National Park. U.S. Geological Survey geologist Bailey Willis, who previously conducted fieldwork around Mount Rainier while working for the Northern Pacific Railroad, and wrote a report on the volcanoes of the Pacific coast after climbing Mount Rainier in 1870, spearheaded a Geological Society of America committee to establish Mount Rainier National Park in 1893. This committee included Samuel F. Emmons, after whom the Emmons glacier is now named, and Dr. David T. Day. The campaign quickly gained support from other scientific organizations. Later that year, both the American Association for the Advancement of Science and the National Geographic Society created committees regarding the creation of Mount Rainier National Park. These scientific organizations partnered with mountain clubs to lobby Congress (Catton 1996).

Bailey Willis crafted a memorial to the United States Congress on behalf of the scientific committees and mountain clubs in which he touted Mount Rainier's scientific and scenic values. He described the mountain's volcanic origins, vast glaciers, and unique biosphere—characterizing Mount Rainier as "an arctic island in a temperate zone" (U.S. Congress, 1894 p. 2). Geologist Israel C. Russell spoke to the mountain's geologic significance in an article for *Scribner's Magazine* in which he promoted the mountain's importance as a natural laboratory for the volcanology and glaciology student, emphasizing that a national park would protect these natural features for scientific study (Russell 1897). Geologist George O. Smith described Mount

Rainier as "a typical example of a lofty volcanic cone built largely of projectiles, but containing also many lava streams" he also correctly observed that "at one time the mountain was more lofty than it is now," he surmised that the top was blown off in an explosive eruption (Smith 1897, p. 409).

Many pioneer climbers also played essential roles in the establishment of Mount Rainer National Park. Philemon B. Van Trump and Samuel F. Emmons in 1870 were among the first four climbers documented to reach the summit of Mount Rainier, and they actively supported the campaign for the creation of Mount Rainier National Park in the 1890s. Additional pioneer climbers who were instrumental in the formation of a national park around Mount Rainier included George B. Bayley, John Muir, Edward S. Ingraham, Earnest C. Smith, Fay Fuller (the first woman to summit Mount Rainier), and Eliza R. Scidmore, all of whom wrote articles and campaigned for the preservation of the mountain. Their motivation for preservation was more toward preserving the scenic beauty and the ability to challenge oneself with the arduous task of climbing to the summit, rather than preserving the mountain for its scientific values, though many climbers also appreciated the scientific values of preservation. John Muir, naturalist, author, and mountain climber, wrote about Mount Rainier after climbing it in 1888.

> We remained on the summit . . . looking about us at the vast map-like views, comprehending hundreds of miles of the Cascade Range, with their black, interminable forests and white volcanic cones in glorious array . . . We found two well-formed and well-preserved craters on the summit, lying close together like two plates on the table with their rims touching . . . Sulfurous fumes and steam issue from several rents giving out a sickening smell that can be detected at a considerable distance. The condition of these craters, and, indeed, to a great extent, of the entire mountain, would tend to show that Rainier is still a comparatively young mountain. (Muir 1902, p. 200).

Between 1893 and 1898, representatives from the State of Washington introduced legislation in six consecutive sessions of Congress looking to establish a 'Washington National Park' but Congress took quite some time to be persuaded that it should be the responsibility of the federal government, rather than the state, to create another national park like Yellowstone. The previous national parks had all been designated as 'forest reserve lands', though they were administered like national parks (Catton 1996). Finally, on 2 March 1899, Rainier National Park was designated and became the first national park to be clearly modeled after the prototype Yellowstone National Park, helping to launch the national park system.

3.2 Volcanic history of Mount Rainier

Mount Rainier is one of many volcanic mountains that crest the Cascade Range. This mountain range is aligned north-south and roughly parallels the Pacific coastline for approximately 1,000 kilometers. The volcanoes of the Cascade Range are but a small portion of the 'Ring of Fire', a tectonically and volcanically active zone that encircles the Pacific Ocean. Mount Rainier itself is a relatively young volcano; however, volcanic eruptions took place in this area long before the present Mount Rainier existed.

The Cascades Volcanic Arc has been active for at least 37 million years and volcanic and intrusive rocks that pre-date the current cone of Mount Rainier can be found within the park (Pringle 2008). Mount Rainier is a stratovolcano; a composite volcano formed from successive eruptions of andesite to low-silica dacite lava flows, breccias, pyroclastic flows, and tephra. Much of the lava erupted from Mount Rainier is a uniform andesite containing many light-colored crystals of plagioclase feldspar and brown and green crystals of pyroxene. The modern cone of Mount Rainier was constructed during multiple eruptive periods over the course of the past half-million years, but the volcano overlies the deeply eroded remains of an ancestral Mount Rainier that was active about 1 to 2 million years ago.

For an extensive, well-cited discussion of the geologic history of Mount Rainier and a guide to where one can see examples of many of the volcanic features discussed, see *Roadside Geology of Mount Rainier National Park and Vicinity* (2008) by Patrick Pringle. His book can be downloaded in pdf form from his Centralia College faculty page (http://www.centralia.edu/academics/earthscience/pringle/rainier_geology_guide_pat_pringle.htm).

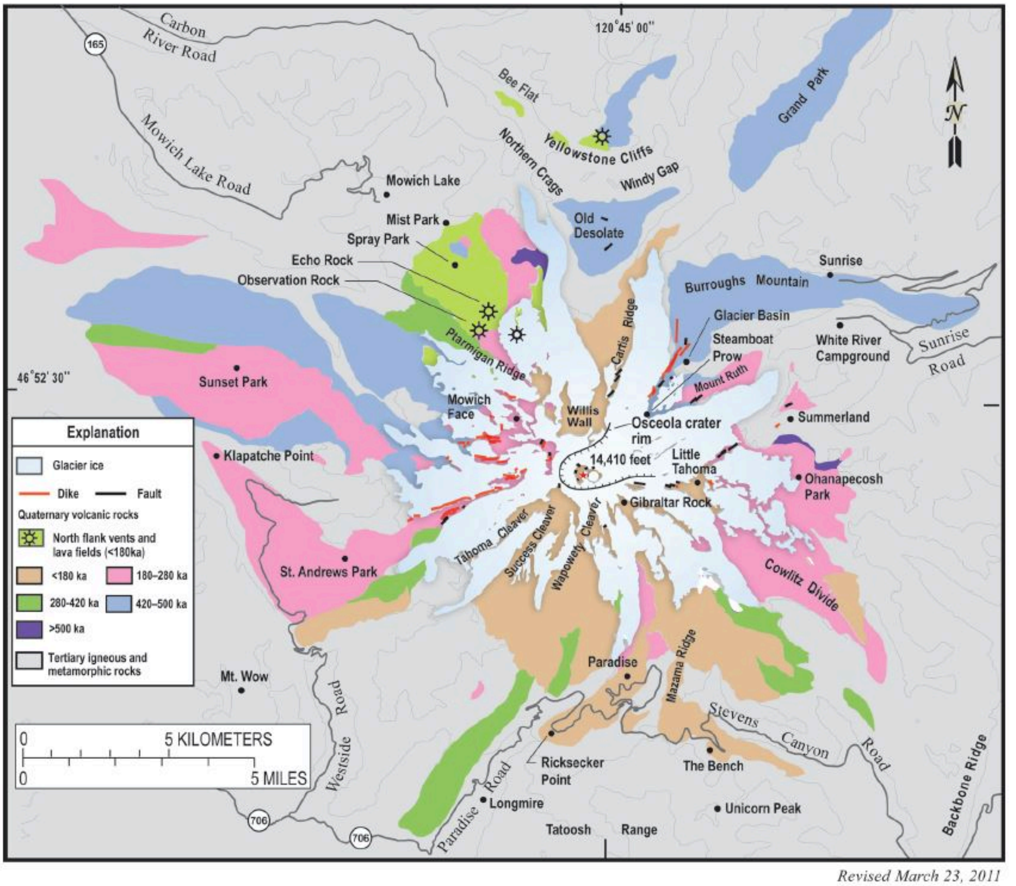

Figure 5. Simplified geologic map of Mount Rainier. USGS figure modified from Driedger et al.*, 2005.*

In general, the eruptive history of Mount Rainier was dominated by mostly andesitic lava flows, with minor block-and-ash pyroclastic flows. Large tephra falls and lava domes rarely occurred (Pringle 2008). Many early lava flows sit high above adjacent river valleys, and dark-colored glassy lava columns preserved locally on the edges of these flows indicate that glaciers were also instrumental in shaping the mountain. These 'chilled margins' indicate that the lavas solidified against the glaciers that formerly filled the flanking valleys to depths of hundreds of meters (Lescinsky and Sisson 1998).

Mount Rainier reached its tallest height some 5,600 years ago and is estimated to have attained an elevation greater than 4,600 meters (Crandell 1963). Between 5,600 and 4,500 years ago, explosive eruptions took place at the summit of Mount Rainier and triggered the catastrophic collapse of the hydrothermally-altered upper portion of Mount Rainier. An estimated 900 vertical meters of Mount Rainier mobilized to produce the Osceola mudflow, which, at approximately four cubic kilometers is one of the largest mudflows known to have occurred on Earth (Vallance and Scott 1997). The Osceola mudflow raged down the White River Valley, through the site of the present day town of Enumclaw all the way into Puget Sound, a distance of more than 100 kilometers (Crandell 1971). After reaching the Sound, which was larger than it is now, the lahar continued underwater to the present location of the port of Tacoma and the city of Kent (Figure

6). The Paradise Lahar occurred concurrently and swept down the Nisqually River Valley at least as far as the site of the former town of National.

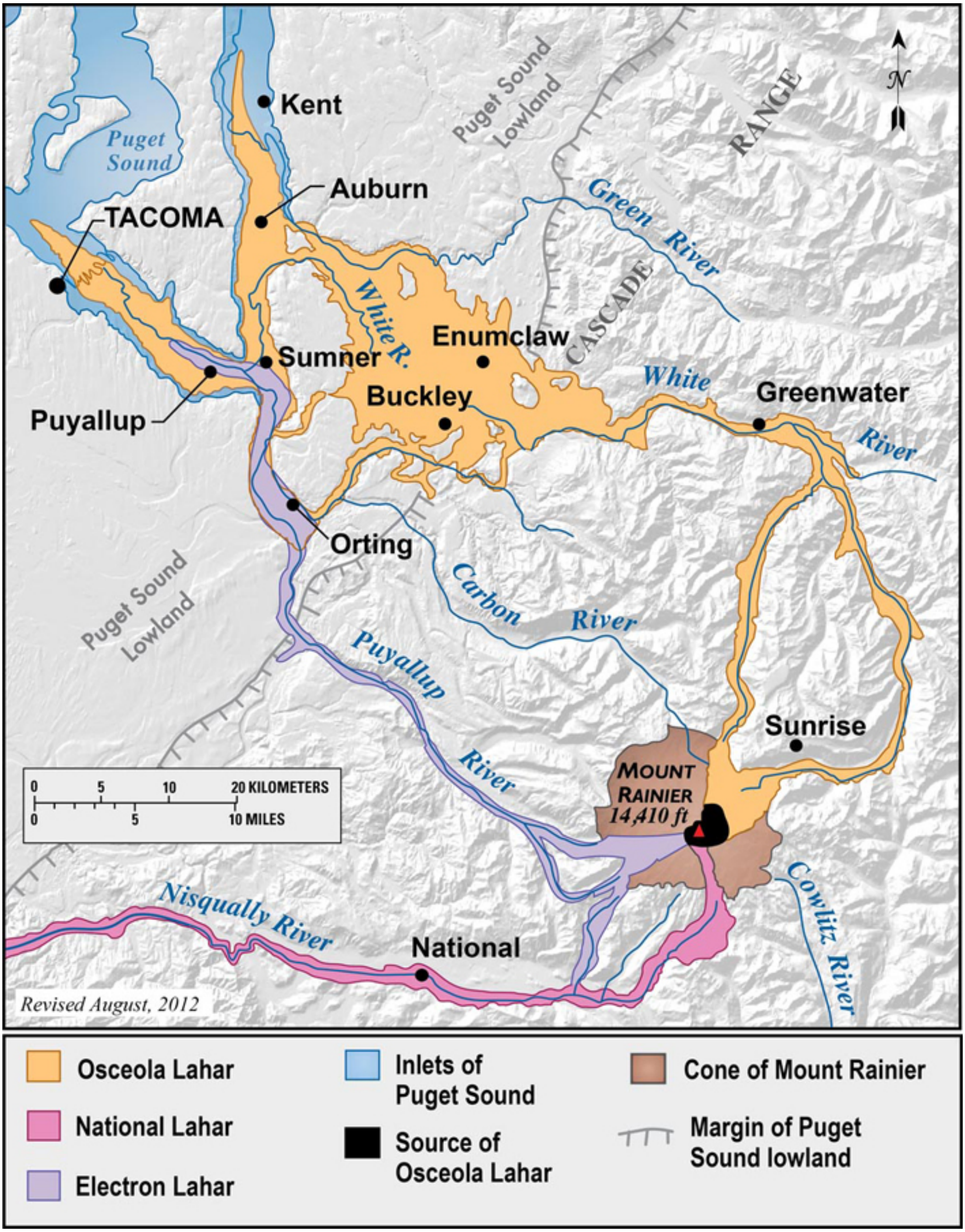

Figure 6. Map showing extents of previous lahars from Mount Rainier. USGS figure modified from Driedger et al. *2005*

The current post-ice age interval of volcanic eruption had at least six eruptive periods with intermittent eruptions between 11,000 years ago and the present, each of which lasted from several years to as long as one thousand years. Most of these eruptive periods are named after the locations where their deposits are found and detailed summaries of these eruptive periods can be found in Pringle (2008). The most recent magmatic eruption confirmed by physical evidence occurred approximately 1,000 years ago during the Fryingpan Creek eruptive period (Sisson and Vallance 2009).

The most recent large lahar, the Electron Mudflow, which occurred about 500 years ago, is particularly notable. This lahar involved approximately 0.26 cubic kilometers of clay-rich hydrothermally altered material that roared down the Puyallup River Valley at least as far as the present day town of Sumner. The Electron Mudflow is interesting in that it is not correlated with any identified volcanic eruption. It appears to have begun as a sector collapse of the hydrothermally altered upper west flank of the mountain, which may have been triggered by an earthquake, by a shallow magmatic intrusion, by an eruption too small to leave preserved deposits, or speculatively, even by a heavy rainfall event. This has serious implications for lahar hazards from Mount Rainier, particularly with regard to towns located in adjacent river valleys such as the town of Orting (Scott and Vallance 1995; Scott *et al*. 1995; Hobliitt *et al*. 1998).

While Mount Rainier has not erupted for the past 1,000 years or so, steam vents and fumaroles at the summit keep some areas of rock ice-free year-round, even in sub-zero temperatures. A lake exists at the summit below the summit glacial cap, and is kept warm enough by the heat of the volcano to exist as liquid, despite prolonged subfreezing temperatures outside of the ice caves. Warm springs and bubbling mineral springs also exist at lower elevations on the mountain, hinting at the release of heat and gas related to the magmatic system, even in the current period of quiescence. In addition, the mountain experiences small earthquakes on a regular basis.

3.3 Volcanic monitoring at Mount Rainier

U.S. Geological Survey monitoring of the volcano began in the 1960s with aerial and infrared photography and installation of seismographs. The first detailed geologic map of Mount Rainier National Park was published in 1963 (Fiske *et al*. 1963) and scientists worked with the park on hazard assessment and emergency plans. For example, Dwight R. Crandell prepared the first natural hazard planning document for the park in 1967 (Crandell and Mullineaux 1967). While mapping glacial deposits in the Puget Sound, Crandell found deposits from the aforementioned Osceola mud flow and eventually came to the conclusion that their only plausible source was Mount Rainier. This discovery led to additional work in which young tephra and lava flows were found.

Mount Rainier was designated a ‘decade volcano’ by the International Association of Volcanology and Chemistry of the Earth's Interior, which attracted notice by the scientific community (Swanson *et al*. 1992). A ‘decade volcano’ was a volcano considered particularly worthy of further multidisciplinary scientific study chiefly because of the potential of future eruptions to significantly affect nearby populated areas and “surprisingly little [was] known about its geologic setting, eruptive history, and potential for future eruptions or edifice collapse” (Swanson *et al.* 1992). This led to a host of new investigations and much of what we now know about Rainier’s geologic past is a result of work that began as a result of the ‘decade volcano’ designation.

Since 1992, numerous studies have occurred on Mount Rainier, particularly by U.S. Geological Survey scientists, university-affiliated scientists, as well as National Park Service scientists. In 1982, benchmarks and a trilateration network were installed on Mount Rainier by the U.S. Geological Survey to allow for deformation studies using Electronic Distance Measurement. This technology was made obsolete by GPS technology, and in 2007 and 2008 the benchmark network was surveyed by GPS with no appreciable deformation detected. Mount Rainier National Park now has a network of eight seismometers, seven GPS receivers, and two tiltmeters that relay real-time information to the Cascades Volcano Observatory and the University of Washington's Pacific Northwest Seismic Network. Some of the seismometers are operated by the University of Washington and some by Cascades Volcano Observatory (Seth Moran, USGS, personal communication, January 2012).

4. HAWAII VOLCANOES NATIONAL PARK

Hawai'i Volcanoes National Park, Hawai'i was first established as part of Hawai'i National Park 1 August 1916. The original park included Kīlauea and Mauna Loa volcanoes on the Island of Hawai`i, and Haleakalā volcano on the Island of Maui. The park was divided and renamed as Hawai'i Volcanoes and Haleakalā national parks, respectively, on 16 September 1961. Hawai'i Volcanoes National Park encompasses 1,348 square kilometers of volcanic craters, lava flows, forests, deserts and widespread archeological resources. The park contains two active volcanoes: Mauna Loa and Kīlauea. Mauna Loa experienced its most recent eruption in 1984, whereas Kīlauea has been actively erupting almost continuously since 1983. In 1980, the United Nations Educational, Scientific, and Cultural Organization (UNESCO) named Hawai'i Volcanoes National Park an International Biosphere Reserve because of its outstanding scenic and scientific values, a designation shared with Yellowstone National Park. The park was recognized for its important volcanic sites; its volcanic island ecosystem, which preserves one of the largest significant ecosystems on the Hawaiian Islands; and its cultural and historic sites. Hawai'i Volcanoes National Park joined Yellowstone National Park as a World Heritage Site in 1987.

4.1 Early history and founding of Hawai'i Volcanoes National Park

Long before European-Americans discovered the Hawaiian Islands, and long before the idea of national parks had been conceived, the volcanoes of Hawai'i were important to the Polynesians who first settled there. Legends of the volcano goddess Pele who lives in the fires of Kīlauea abound. There are many variations to the story of how Pele got to Kīlauea and why she went there, but many of them involve going from island to island from west to east, stopping in Ni'ihau, Kaua'i, Oahu, Moloka'i, Maui and finally Hawai'i where she finally found a place to live at the summit of Kīlauea in a crater that became known as Kalua o Pele (the pit of Pele) (Swanson 2008). This tale has her digging fire pits in the Hawaiian Islands in the geological order that they were formed, and many Hawaiian oral histories about Pele stem from observations of eruptive activity. Pele is known for her passion, capriciousness and jealousy. Tales of her wrath abound, equating her anger to volcanic eruptions and lava flows. Some contain enough detail that they are certainly referring to specific eruptive events. Additionally, several forms of volcanic ejecta have been named after Pele including Pele's hair, Pele's tears and Limu o Pele.

The first Europeans to visit the area that is now the national park arrived with Captain George Vancouver in 1794 on the ship *Discovery* (Moniz-Nakamura 2016). The naturalist Archibald Menzies, climbed to the top of Mauna Loa and wrote about it in his journal, describing the erupting Kīlauea Volcano. The next written account of Kīlauea was not until 1823, when the Reverend William Ellis visited the districts of Ka'u and Puna and wrote about the geology, fauna, flora, and cultural history of the area in his journal (Ellis 1826). Ellis, like the natives who resided in Hawai'i, recognized that the rocks were volcanic. He had this to say about the shore near the village Kaavaroa:

> The rocks which form the beach on this and the opposite side of the bay, are not, as was supposed by those who first described them, of black coral, but composed entirely of lava, porous, hard, and of a very dark colour, occasionally tinged with a ferruginous brown, bearing marks of having been in a state of fusion. Part of it has probably flowed through the cavern in which Captain Cook's body was deposited, as traces of a stream of lava from thence to the plain below are very distinct. (Ellis 1826, p. 106).

Lieutenant Charles Wilkes of the U.S. Navy headed the expedition on which the first geologic investigation of the Hawaiian Islands occurred from 1840 to 1841. James Dwight Dana, often considered the first American volcanologist, was in charge of the geologic portion of this expedition. Dana proposed that the alignment of the Hawaiian Islands was due to localized eruption along a great fissure, and this hypothesis remained a prominent one until the acceptance of plate tectonics in the late-twentieth century. Dana's scientific work arrested the attention of the scientific community, which has been interested in the volcanoes of Hawaii ever since (Tilling *et al*. 2011).

After 1845, there was a marked increase in tourism, particularly by Americans. Early visitors reached the volcano after sailing into Hilo and then riding horses over very rugged trails through the forest and lava fields. Once they arrived, they could stay in a very primitive hotel at the edge of the crater. A more modern hotel was built in 1877. People continued to visit, and the popularity of Kīlauea soon led to a movement for the preservation of the area (Moniz-Nakamura 2016). In 1906, Albert B. Lobenstein completed a topographical map of the summit of Kīlauea, after which he went to Washington D.C., and proposed that the summits of Kīlauea and Mauna Loa be made into a national park (Moniz-Nakamura 2016).

Perhaps one of the greatest proponents of a national park at Kīlauea was American businessman Lorrin A. Thurston whose grandfather, Asa Thurston, explored Kīlauea with William Ellis in 1823. Thurston practiced law in Hawaiʻi and entered politics where he supported numerous projects opening the Hawaiian Islands to the world and in developing Kīlauea Volcano. Thurston personally escorted members of Congress and other federal officials around Kīlauea and in 1911 started a public campaign to promote the proposed Kīlauea National Park. A bill was introduced in Congress to acquire Kīlauea, particularly the active lava lake in Halemaʻumaʻu , though Mauna Loa was mentioned as well (Moniz-Nakamura 2016).

Researchers from the Massachusetts Institute of Technology (MIT), including Thomas Jaggar, became interested in establishing an observatory at Kīlauea due to the relative safety and ease of access to an active volcano and thus lent their support for establishing a national park. In 1909, Thomas Jaggar spoke to the Honolulu Chamber of Commerce about establishing an observatory at the edge of Kīlauea volcano. Lorrin Thurston, active in politics at that point, spoke as well about the commercial advantages of securing such an observatory. The Honolulu Chamber of Commerce was only willing to pledge half the amount requested to start an observatory, so Jaggar returned to Boston, where he continued to seek financial supporters. Jaggar raised funds in Boston from 1909 to 1911 to purchase seismometers and instruments to measure temperature as well as construct a temporary building on the rim of Halemaʻumaʻu Crater. However, neither Jaggar nor any of the other MIT scientists was able to travel to Hawai'i at that time, so Jaggar enlisted Frank A. Perret, whom he considered to be the world's greatest volcanologist (Tilling *et al.* 2011; Poland *et al*. 2014).

The first researchers, Dr. E. S. Shepherd, of the Carnegie Institution of Washington, and Frank A. Perret, of the Volcanic Research Society of Springfield, Massachusetts, arrived in Hawai'i in 1911. At the urging of Thurston, they submitted weekly reports to the newspapers in Honolulu, which helped to keep the public interested in Kīlauea (Tilling *et al*. 2010). The first physical measurements of Halemaʻumaʻu were made by Shepherd and Perret, who wished to determine the temperature of the lava lake. They did so by stretching a 365-meter cable from the east to the west side of the fire pit and lowered their instruments ninety meters into the molten lake. After several unsuccessful attempts at measuring the lava temperature with various instruments, they accurately measured the temperature of the lava lake at 1,832 degrees Fahrenheit (Hawaii Nature Notes, 1953). In 1911, with Thurston's group of financial backers spurred on by the excitement of Perret and Shepherd's weekly volcano reports, Thurston formed the Hawaiian Volcano Research Association, which advocated for both a national park and an observatory.

On 17 January 1912, Dr. Thomas Jaggar left MIT to assume the directorship of the new Hawaiian Volcano Observatory, funded by MIT and the Hawaiian Volcano Research Association. Three years later, Jaggar went to Washington D.C., to appeal to Congress to take over the Hawai'i Volcano Observatory and to push for the establishment of Kīlauea and the summit of Haleakala on the island of Maui, as a national park. Due in part to Jaggar's efforts, the bill creating Hawaii National Park was signed into law on 1 August 1916. Due to provisions in the bill creating the park, there was little to no federal funding for the first five years of its existence, but the park was open to visitation due to the efforts of private groups and individuals who saw the value in promoting tourism there.

In order to gain federal funding, the park had to gain rights of way to it, which means that it had to acquire private lands that surrounded it. In 1920, the Governor of Hawai'i (which was still a Territory, not yet a state) purchased the privately-owned lands after Congress passed a bill allowing it to do so. After much negotiation with various private landowners, the necessary lands were officially transferred on 6 November 1920, and in 1922 funding was appropriated and staffing of Hawaii National Park began (Moniz-Nakamura 2016).

4.2 Volcanic history of Hawai'i Volcanoes National Park

Hawai'i Volcanoes National Park is located on the island of Hawai'i, which is the southeastern island in a chain of volcanoes known as the Hawaiian Ridge—Emperor Seamount Chain (Figure 7). This chain contains over one hundred large volcanoes, most of which are below the surface of the ocean. The chain extends some 6,000 kilometers from the Island of Hawai'i. The Emperor Seamount portion of the chain trends roughly north-south, while the Hawaiian Ridge portion trends northwest-southeast due to a change in the direction of plate motion (Poland *et al.* 2005).

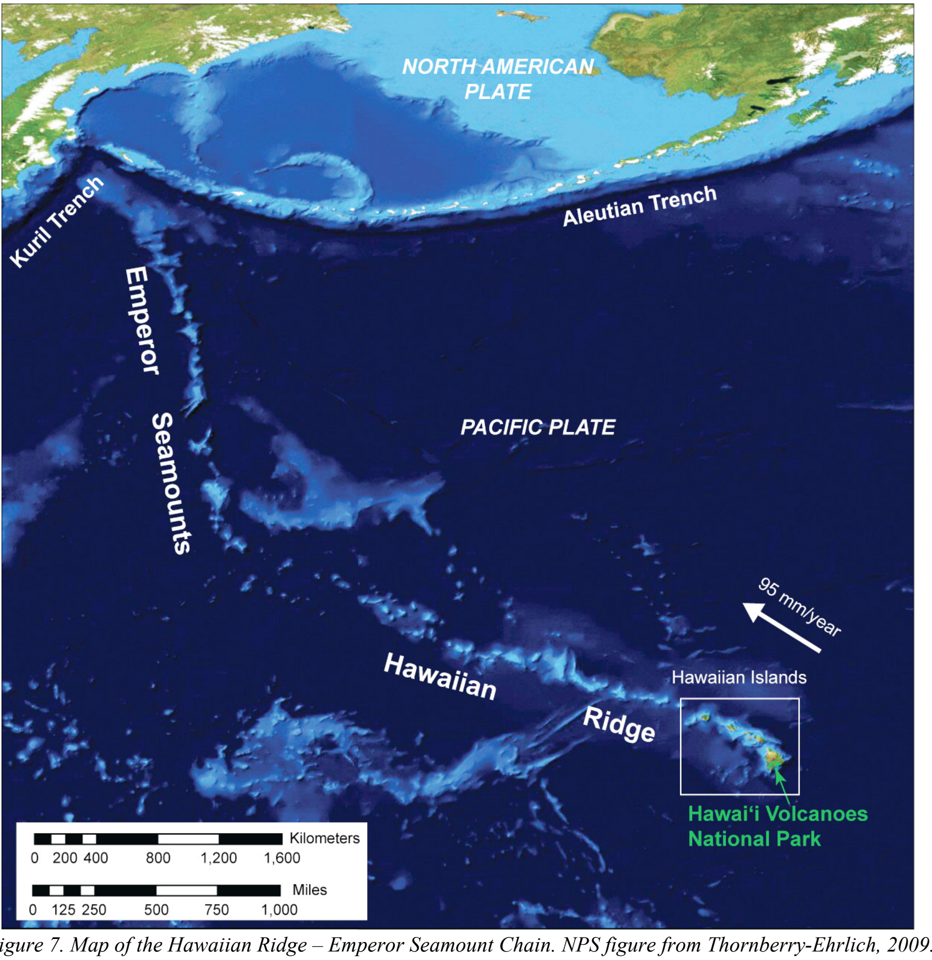

Figure 7. Map of the Hawaiian Ridge – Emperor Seamount Chain. NPS figure from Thornberry-Ehrlich, 2009.

This chain of volcanoes is the result of hot-spot volcanism. Hot spot volcanism occurs when a tectonic plate moves over a relatively fixed spot of enhanced magma production within the mantle. The Hawaiian hot spot partially melts a region just below the Pacific Plate in the current vicinity of the island of Hawai'i, causing magma to ascend and ultimately erupt, generally as basaltic lava (Poland *et al.* 2014).

The Hawaiian-Emperor Chain began to form some 70 million years ago, the exact age is uncertain because the northern portion of the chain is subducting into the Aleutian Trench in the northern Pacific Ocean and we do not know how much has already vanished beneath the crust. A sharp bend in the chain was previously interpreted as a major change in the direction of plate motion, though recent studies suggest that it may be a result of the hot spot migrating south until about 45 Ma when it became fixed in more or less its present location (Tilling *et al*. 2010). For the past forty-five million years the Pacific Plate has traveled to the northwest over the hot spot, forming the volcanoes comprising the linear chain of islands and seamounts that make up the Hawaiian Ridge.

The Hawaiian Ridge is the 2,575 kilometer-long portion of the chain between Midway Island in the northwest and the Island of Hawai'i in the southeast. Overall, volcanoes are younger to the southeast toward Hawai'i and older to the northwest (Poland *et al.,* 2014). The Hawaiian Islands range in age from approximately 5.6 Ma (Ni'ihau and Kaua'i) to present day activity on the island of Hawai'i. The island of Hawai'i contains five shield volcanoes: Kohala in the northwest, which had its most recent eruption some 120,000 years ago; Mauna Kea, which most recently erupted approximately 4,000 years ago; Hualālai, which last erupted in 1800 and 1801; Mauna Loa, which most recently erupted in 1984; and Kīlauea, which was erupting at the time of this writing (Figure 8). Lō'ihi seamount, a submarine volcano located off the southern coast of Hawai'i, is also active and may eventually become a new Hawaiian island, though its summit is currently approximately a kilometer below the surface of the ocean.

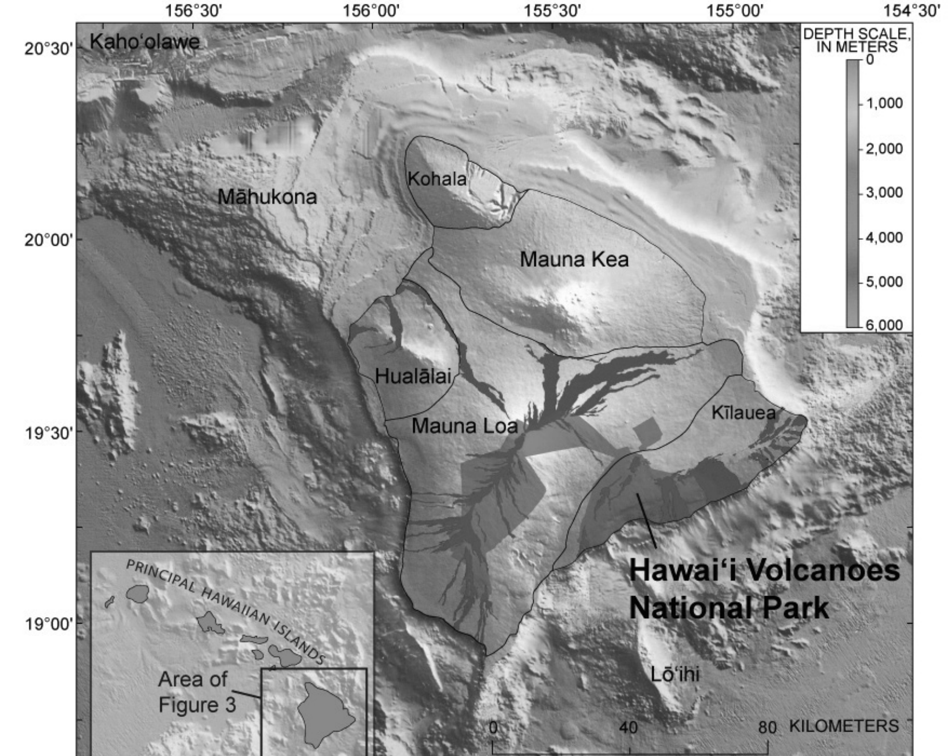

Figure 8. Topography and bathymetry of the Island of Hawaii. (NPS figure from Thornberry-Ehrlich 2009).

Hawaiian volcanoes have four stages of growth: pre-shield, shield, post-shield and rejuvenated (Figure 9). There is generally a long temporal gap of up to several million years between the post-shield and rejuvenated stages. The pre-shield lavas are buried by later lavas at all of the Hawaiian volcanoes except the Lō'ihi seamount, which is still in its pre-shield stage.

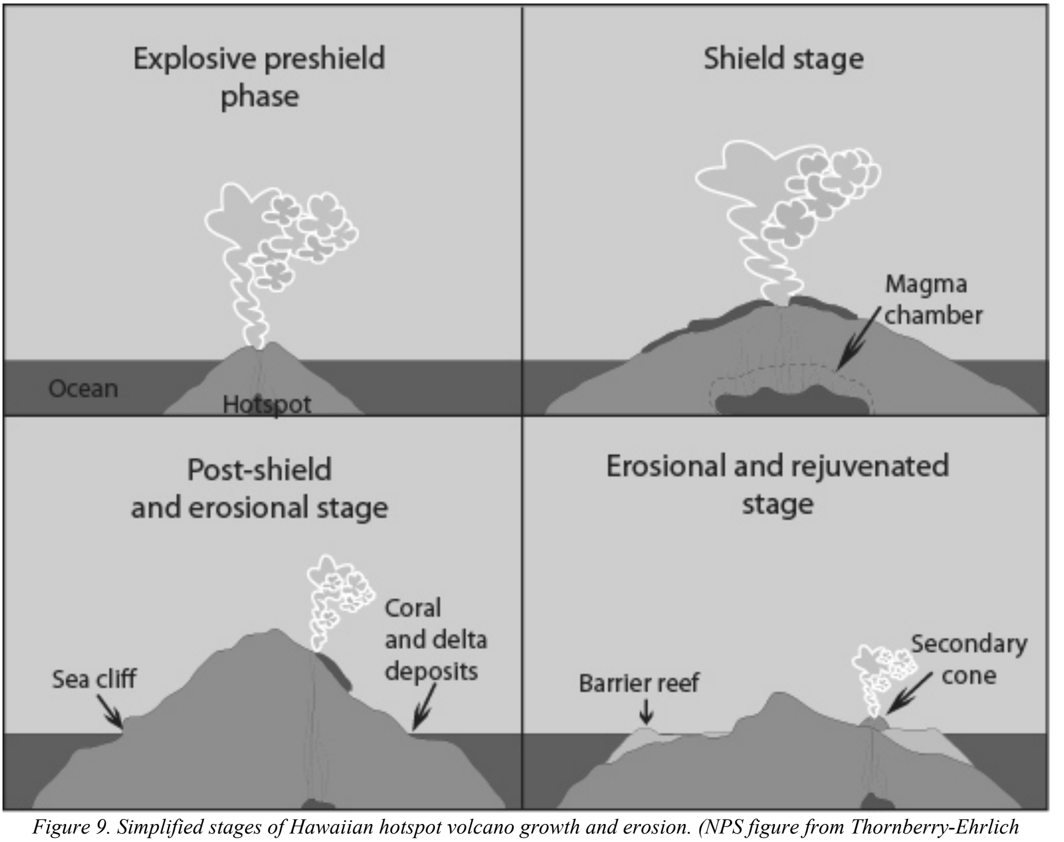

Figure 9. Simplified stages of Hawaiian hotspot volcano growth and erosion. (NPS figure from Thornberry-Ehrlich 2009).

Hawaiian-style eruptions are named after the typical eruptive behavior at Kīlauea and Mauna Loa, which generally involve passive lava effusion/flows, lava fountaining, and the more explosive cinder-cone building eruptions. They are eruptions of relatively low viscosity, high temperature basaltic lava. They may occur along fissures or at a central vent and tend to begin with lava fountaining where lava is shot high into the air, occasionally reaching over 200 meters high, before raining back down and flowing away in streams, often forming lava tubes. While effusive basaltic lava eruptions are often thought of as not being especially dangerous, when lava becomes channelized it can move rather quickly. Additionally, the onslaught of lava is relentless. Lava will cover and burn everything in its path.

Hawai'i has a relatively brief written history, going back only about 200 years, and relatively little is known about the eruptive history of Kilauea prior, though Hawaiian oral traditions document some of the earlier eruptions. Kilauea was erupting from its summit in the early 1800s and continued to erupt nearly constantly throughout early exploration of Hawaii by the western world. A great deal has been published about Hawaiian volcanism since western exploration began, and including all of those details would be outside the scope of this work (for further reading see: Babb *et al*. 2011; Poland *et al.* 2015 and references therein, Thornberry-Ehrlich 2009; Tilling *et al.* 2010 and references therein).

While the majority of recent activity has been passive and relatively harmless, explosive eruptions do occur at Hawaiian volcanoes (Swanson *et al.* 2011; Swanson *et al*. 2012; Swanson *et al*. 2014). In 1790, during the century of mostly passive summit eruption, Kīlauea exploded and killed at least eighty, but possibly hundreds, of people as a group of Hawaiian warriors and their families were overtaken by a pyroclastic surge as they passed Kīlauea's crater (Swanson *et al.* 2011). This was the deadliest known volcanic eruption in what is now the United States of America. Deposits of thick ash on the island of Hawai'i are proof that other powerful explosive eruptions have occurred from both Kīlauea and Mauna Loa in the past (Swanson *et al.* 2011). Studies indicate that Kīlauea experiences explosive events with similar frequency to the eruptions of the Cascade Range stratovolcanoes such as Mount St. Helens and Mount Rainier (Swanson *et al.* 2011).

With an estimated volume of approximately 75,000 cubic kilometers (Kaye and Trusdell 2002; Robinson and Eakins 2005), Mauna Loa is the most massive mountain in the world. Base to summit, Mauna Loa is also one of the tallest mountains in the world, second only to Mauna Kea. Though the summit elevation is only 4,710 meters above sea level, its total height from the ocean floor to its summit is approximately 17,000 meters, which is over 8,000 meters higher than Mount Everest. Mauna Loa is 700,000 to 1,000,000 years old and cut by two active rift zones—the Southwest and the Northeast—that intersect at the summit caldera Moku'âweoweo. These rift zones are marked by open fissures, cinder cones, spatter cones, and pit craters. The most recent eruptions at Mauna Loa were a summit eruption in 1975 that lasted about one day and a summit-flank eruption in 1984 that lasted approximately three weeks. The 1984 eruption threatened the city of Hilo with lava flows that ceased a mere six kilometers from the city on 15 April 1984 (Tilling *et al.* 2010; Babb 2011).

While smaller than Mauna Loa, Kīlauea has been much more active in recorded history. Kīlauea is one of the most active and best-monitored volcanoes in the world. It has been erupting from its east rift zone nearly incessantly since 1983. Kīlauea has a history of long-lived eruptions. Before 1924, it experienced approximately a century of nearly continuous eruptive activity at its summit crater, Halema'uma'u. Kīlauea also has frequent eruptions from its southwest and east rift zones (Tilling *et al.* 2010; Babb *et al.* 2011).

On 3 January 1983, Kīlauea began erupting from fissures along its east rift zone, and months later localized at a single vent. For the next three years, intermittent lava fountains at the single vent formed the Pu'u 'Ô'ô spatter and cinder cone. At the time of this writing (2017), this eruption has been ongoing since 1983 with the majority of the eruption taking place from the Pu'u'Ō'ō vent, though several periods have involved activity shifting down-rift and up-rift.

In March 1990, the ongoing eruption of Kīlauea's East Rift Zone began its most destructive phase. Lava flows erupted from the Kupaianaha vent and buried the community of Kalapana in fifteen to twenty-five meters of lava. The lava flowed all the way to the ocean, burying the popular black sand beach at Kaimū and filling Kaimū Bay with lava that extended the shoreline 305 meters. Late in 1990, the flows changed direction and flowed back toward the west and into Hawaii Volcanoes National Park. In 1992 the eruptive focus shifted from the Kūpa'ianahā vent back to Pu'u 'Ō'ō where it continued until 2007, during this phase lava flows remained mostly within the national park. Between 2005 and 2010, the lava flowed into the ocean almost continually (Orr *et al.* 2012).

In 2008 Kīlauea began erupting from a new vent within its summit crater. Activity began with an increase in sulfur dioxide emissions and with vigorous gas fumes issuing from an area near the base of the east wall of Halema'uma'u Crater. An explosive event blasted hot debris out of the crater wall, forming a new vent on 19 March 2008. Subsequent collapses enlarged the summit vent from 35 meters in 2008 to more than 145 meters in diameter by the end of 2011 (Orr *et al.* 2012; Poland *et al.* 2014). The summit activity has been occurring simultaneously with eruptive activity from the Pu'u 'Ō'ō –Kupaianaha eruption since 2008. The 2008 to present Halema'uma'u activity is both the longest summit eruption since 1924, but is also the longest concurrent summit and rift activity known to have occurred at Kīlauea. At the time of this writing (2017), an active lava lake exists within the Halema'uma'u crater and lava is erupting from the East Rift Zone and entering the ocean at Kamokuna, providing the visitor to Hawaii Volcanoes National Park the opportunity to witness the birth of new land.

4.3 Monitoring of Hawai'i Volcanoes National Park

The Hawaiian Volcano Observatory was set up in 1912 to study Mauna Loa and Kīlauea volcanoes on a permanent basis. The observatory was the brainchild of geologist Thomas A. Jaggar from MIT and has been managed at different times by the Hawaiian Volcano Research Association, the U.S. Weather Bureau, the U.S. Geological Survey, and the National Park Service. In 1935 the operation of the Hawaiian Volcano Observatory was temporarily transferred to the National Park Service due to funding issues. As a result, Jaggar changed agencies from the U.S. Geological Survey to the National Park Service to continue as director until his retirement in 1940. In 1947, the U.S. Geological Survey was put in charge of the Hawaiian Volcano Observatory once again, and it has remained under the authority of the U.S. Geological Survey since.

Hawaiian Volcano Observatory scientists have helped to develop and test many of the volcano monitoring techniques and equipment that are currently used at volcano observatories elsewhere in the world. Both Kīlauea and Mauna Loa are very thoroughly monitored volcanoes. They have been historically monitored by ground-based surveys using electronic tiltmeters, electronic distance measuring, seismometers and are now also monitored using satellite-based technologies including the global positioning system (GPS) and interferometric synthetic aperture radar (InSAR). GPS technology, electronic tiltmeters, seismometers, web cams, and gas sensors are continually monitoring both Kīlauea and Mauna Loa volcanoes. Both gas emissions and air quality is also being continuously monitored by Hawaiian Volcano Observatory scientists (Elias *et al*. 1998; Elias and Sutton 2002; Elias and Sutton 2007; Babb *et al*. 2011; Elias and Sutton 2012; Poland *et al.* 2014). Seismic monitoring is the backbone of monitoring Hawaiian volcanoes and the island of Hawai'i contains more than 60 seismic monitoring stations that continuously telemeter data to the Hawaiian Volcano Observatory and the observatory provides near real-time earthquake maps on their website (https://volcanoes.usgs.gov/observatories/hvo/hvo_earthquakes.html).

5. KATMAI NATIONAL PARK AND PRESERVE

Katmai National Park and Preserve, Alaska was established to preserve the deposits of the violent 1912 Novarupta eruption, the most voluminous eruption in the twentieth century. This eruption created the infamous ash flow-filled 'Valley of Ten Thousand Smokes', named for the steam rising from countless rootless fumaroles in the ash flow deposits for several years after the 1912 eruption. Additionally, the park contains over twenty other volcanoes, many of which are active. Originally designated Katmai National Monument on 24 September 1918, it was later converted to Katmai Park and Preserve 2 December 1980. It now contains 16,564 square kilometers, most of which is designated wilderness area. Katmai preserves a wide variety of natural features including volcanoes, lakes, forest, mountains, glaciers, wild rivers, marshes, salmon, and bears.

5.1 Early history and founding of Katmai National Park

Prior to the historic 1912 eruption, the Katmai area had been visited briefly by U.S. Geological Survey scientist Josiah Edward Spurr and topographer William Schuyler Post along with camp hands Oscar Rohn and George Hartman. They arrived in what is now the Valley of Ten Thousand Smokes on 14 October 1898 and camped for two nights there. They crossed Katmai Pass on 16 October and arrived at Katmai village on 17 October. Spurr's descriptions were the first by a scientist and he noted hot springs at Trident Volcano, while William Schuyler Post made the first topographic map of their route. They spent less than a month in the area, and left Katmai Bay via steamer 31 October 1898 (Hildreth and Fierstein 2012).

The afternoon of 6 June 1912 marked the beginning of the twentieth century's most powerful volcanic eruption. An eruption column rose thirty-two kilometers into the sky, burying nearby areas in meters of ash and shooting ash so high into the stratosphere that it depressed temperatures worldwide (Hildreth and Fierstein 2012). The eruption had major effects on Kodiak Island (Figure 10) 170 kilometers to the south, where ashfall left the village in darkness and caused the collapse of many roofs. Falling ash and sulfuric gasses left the inhabitants with respiratory problems and sore eyes. Water became so full of ash that it was undrinkable and radio communications were disrupted (Fierstein and Hildreth 2000). Even after the eruption was over the effects continued. Many species of plants and animals were annihilated by the ashfall, which also clogged streams—killing aquatic life. Southwestern Alaska's salmon-fishing industry was devastated for nearly a decade following the eruption (Fierstein and Hildreth 2000).

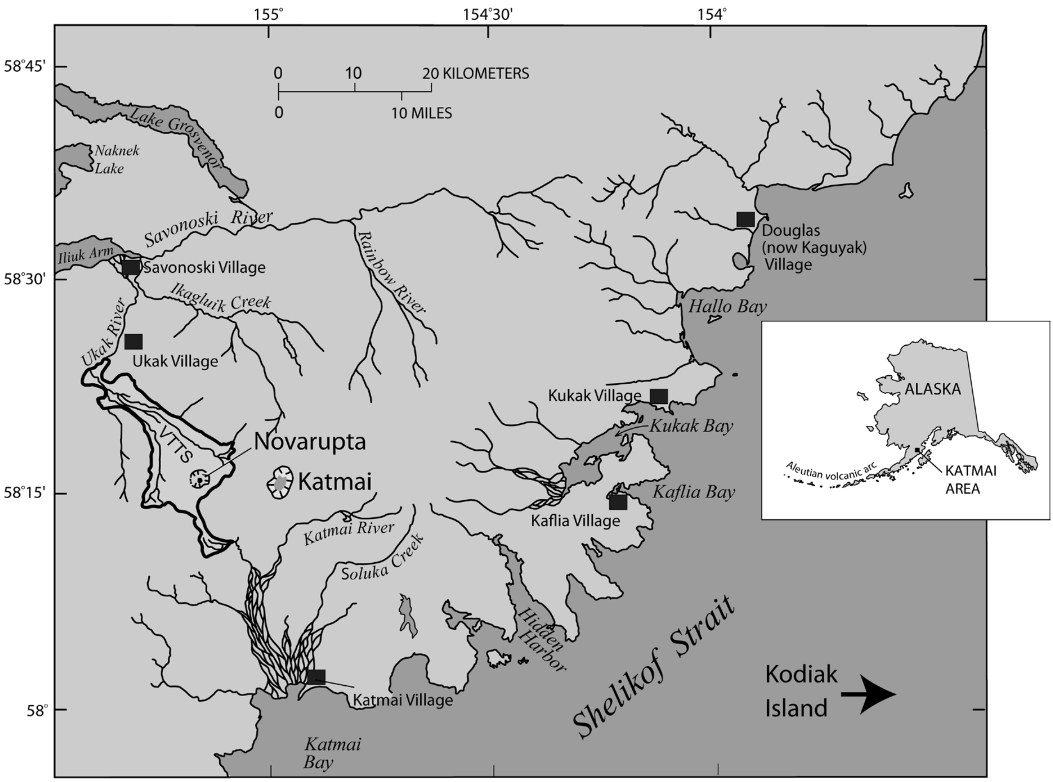

Figure 10: Locations of the populated areas near Katmai in 1912. USGS Alaska Volcano Observatory figure modified from Adleman 2002.

The eruption was witnessed from afar by the eighty-six passengers and crew on the *SS Dora*, a small steamship, which had the dubious luck to be passing through the Shelikof Strait at the time of the eruption. The eyewitness accounts provided by these people were crucial to identifying the timeline for the eruption as well as the size of the ash cloud. In fact, the captain of the *Dora*, C. B. McMullen, identified where the eruption came from at the time.

> Left Uyak at 8:45am, June 6; strong westerly breeze and fine clear weather. At 1 o'clock pm, while entering Kupreanof Straits, sighted a heavy cloud of smoke directly astern, raising from the Alaska Peninsula. I took bearings of the same, which I made out to be Katmai Volcano, distance about 55 miles away. The smoke arose and spread in the sky, following the vessel, and by 3pm was directly over us, having traveled at the rate of 20 miles an hour (Martin 1913, p. 152).

George Archibald Clark wrote a brief article about the eruption in 1912. He was on a ship about 800 kilometers to the southwest at the time of the eruption. He did not personally see the eruption, but did notice rafts of pumice floating in the ocean the following day. He also read and summarized the official reports from Captain Perry and Lieutenant Keester of the *Manning*, which was moored in Kodiak bay at the time of the eruption and collected a few photographs from several unnamed persons who were on those same boats (Clark 1912). Those reports indicated that many people who lived in Kodiak took refuge on the *Manning* and the tugboat *Printer*. They discussed attempting to flee by boat, but the darkness created by the eruption made that impossible (Clark 1912). Captain Perry described part of his experience in Kodiak as follows:

> At 2pm, pitch darkness had shut in; heavy static disturbances were observed, and our radio was dumb. A few refugees were on board, and the night of the 7th was spent in anxious watching. We got little sleep and the dawn of the 8th, which we anxiously awaited, failed to appear (Griggs 1922, p. 9).

The overwhelming darkness was mentioned by many of the eyewitnesses, and many stated that it was "impossible to see a lantern at arm's length" (Griggs 1922, p. 10). J. E. Thwaites, mail clerk on the *Dora*, described the disorienting nature of his experience thus

> . . . and now the real rain of ashes; it fell in torrents; it swirled and eddied. Gravity seemed to have nothing to do with the course of its fall. The under side of the decks seemed to catch as much ash as the sides or the decks under our feet. Bright clusters of electric light could be seen but a few feet away and we had to feel our way about the deck . . . lurid flashes of lightning glared continuously round the ship, while a constant boom of thunder, sometimes coinciding with the flash, increased the horror of the inferno raging about us. As far as seeing or hearing the water, or anything pertaining to earth, we might as well have been miles above the surface of the water. And still we knew the sun was more than two hours above the horizon (Martin 1913, p. 154).

All told, the people of Kodiak were subjected to two days and three nights of continuous darkness (Griggs 1922). The native fishing station in Kaflia Bay, approximately 47 kilometers from the volcano, was also heavily affected by the eruption, but there appears to be but one record of their experience, recorded in this letter:

> Kaflia Bay, June 9, 1912.
> My Dear Wife Tania:
> First of all, I will let you know of our unlucky voyage. I do not know whether we shall be either alive or well. We are awaiting death at any moment. Of course do not be alarmed. A mountain has burst near here so that we are covered with ashes in some places 10 feet and 6 feet deep. All this began on the 6th of June. Night and day we light lamps. We cannot see the daylight. In a word it is terrible and we are expecting death at any moment and we have no water. All the rivers are covered with ashes. Just ashes mixed with water. Here are darkness and hell thunder and noise. I do not know whether it is day or night. Vanka will tell you all about it. So kissing and blessing you both good bye. Forgive me. Perhaps we shall see each other again. God is merciful. Pray for us.
> Your husband Ivan Orloff.
> The earth is trembling; it lightens every minute. It is terrible. We are praying
> (Martin 1913, p. 148).

In early July 1912, George Curtis Martin of the U.S. Geological Survey arrived at Kodiak and compiled a more thorough account of the eruption by interviewing witnesses. He sailed along the coast for two weeks and visited the site of Katmai village on 13–16 August, but did not actually go to the area where the eruption took place. During his visit, Martin described a column of steam ascending through the clouds above Mount Katmai, created a localized isopach map of tephra fallout around Kodiak, and described three main layers of distal ashfall (Hildreth and Fierstein 2012). In 1913, George B. Rigg and Dr. Robert F. Griggs studied the impacts of the eruption on kelp and algae, and onshore vegetation. The same year, William A. Hesse of Cordova and Mel A. Horner of Seldovia attempted a photographic expedition to the site of the eruption, but were unable to get all the way to Mount Katmai, though they did take photos of a previously unmapped volcano now named Mount Martin. Griggs returned in July 1915 to continue his vegetation studies and upon being surprised by the rapid regrowth along the coast, decided to investigate areas closer to the volcano. During this trip, Griggs and his companions Bentley B. Fulton and Lucius G. Folsom took the first photograph of the new truncated silhouette of Mount Katmai, made note of the Katmai River debris flow, and saw steam plumes on Martin, Trident and Mageik volcanoes, but they were unable to cross Katmai River and thus did not access the site of the eruption (Hildreth and Fierstein 2012).

Scientists visited the actual Novarupta vent area for the first time 31 July 1916 during a National Geographic Society funded expedition led by Griggs. When this expedition arrived at what is now called the Valley of Ten Thousand Smokes, they discovered an ashy landscape filled with tens of thousands of steaming fumaroles (Figure 11). Many of these fumaroles were so hot that they cooked meals on them in later expeditions (Griggs 1922).

> The sight that flashed into view as we surmounted the hillock was one of the most amazing visions ever beheld by mortal eye. The whole valley as far as the eye could reach was full of hundreds, no thousands—literally, tens of thousands—of smokes curling up from its fissured floor. From our position they looked as small as the little fumaroles nearby, but realizing something of their distance we knew many of them must be gigantic. Some were sending up columns of steam which rose a thousand feet before dissolving. After careful estimate, we judged there must be a thousand whose columns exceeded 500 feet. A dozen miles away the valley turned behind a blue mountain in the distance. Plainly the smokes extended that far. How much farther we could not tell . . . It was as though all the steam engines in the world, assembled together, had popped their safety valves at once and were letting off surplus steam in concert (Griggs 1922, p. 191).

Figure 11. Top: The Valley of Ten Thousand Smokes when Griggs visited in 1916. National Geographic Society photograph by Robert Griggs (Griggs 1922, p. 234). Bottom: The Valley of Ten Thousand Smokes in 2013, note that the mist in the background of the bottom photo is fog, not steam from fumaroles. (AVO-UAF Geophysical Institute photograph by Taryn Lopez).

These expeditions continued for five years, after which Griggs and Clarence Norman Fenner, a petrologist at the Geophysical Laboratory established by the Carnegie Institution, published a number of works on Katmai, making the 1912 eruption famous. Their description of lava domes, lakes, and thousands of steaming fumaroles helped persuade the Department of

Interior Secretary Franklin Lane, a friend of Griggs, to urge President Woodrow Wilson to designate Katmai National Monument in order to preserve the landscape for future generations and for scientific study (Guffanti *et al.* 2000). The text of the presidential proclamation establishing the Katmai National Monument specifically refers to the "importance in the study of volcanism," the fresh eruptive deposits, and the excellent opportunities they provide for studying the causes of the catastrophe and its results and affording a conspicuous object lesson in volcanism to visitors interested in the operation of the great forces which have made and still are making America (Griggs 1922).

The famous 'Glacier Priest', Father Bernard Rosecrans Hubbard, S.J., made several expeditions into the Katmai region in the 1920s and 1930s. Father Hubbard was a Jesuit priest and then a professor of geology and theology at Santa Clara University in California until the mid-twentieth century. He had particular interests in both volcanoes and glaciers and led regular expeditions to Alaska from 1927 to 1962. In 1929, he and a group of students, mostly football players, arrived in the Valley of Ten Thousand Smokes. They brought a video camera and recorded their observations (Hubbard 1932a, 1932b).

Despite being declared a national monument in 1918, Katmai was not staffed by rangers until 1950. The monument was—and still is—extremely remote and difficult to access. Until the 1930s, few visitors, the majority of whom were scientists, visited the national monument. The first ranger station, the Brooks River Ranger Station, was not completed until July 1955. Interestingly, the Valley of Ten Thousand Smokes served as a unique training ground for United States astronauts preparing to land on the moon from 1965 to 1966. It was wrongly assumed that the ashy landscape devoid of plant life was similar to that of the moon (Clemens and Norris 1999).

5.2 Volcanic history of Katmai National Park and Preserve

Katmai National Park and Preserve contains more than twenty major volcanoes: Kejulik, Alagogshak Volcano, Mount Martin, Mount Mageik, Mount Cerberus, Falling Mountain, Novarupta, Trident Volcano, Mount Katmai, Snowy Mountain, Mount Dennison, Mount Steller, Kukak Volcano, Devils Desk, Kaguyak, Fourpeaked Mountain, Mount Douglas, Mount Griggs, the Savonoski River Cluster, Gertrude Creek Cone and the Saddlehorn Creek cluster (Figure 12). Four of these have erupted within the last century: Mount Katmai in 1912, Novarupta in 1912, Trident from 1953–1964, and Fourpeaked Mountain in 2006. Additionally, Mount Mageik, Mount Martin, Trident Volcano, and Mount Griggs all contain active fumaroles (Hildreth *et al.* 2003). The lakes within the craters of Katmai, Mageik, and Martin are so sulfurous that they are yellow-green in color. Gases rising through the Mageik lake are so vigorous that it appears to be boiling (Fierstein and Hildreth 2000).

The violent volcanic eruption at Novarupta in June 1912 is one of the five largest eruptions in recorded history. The eruption spanned approximately sixty hours from 6 June 1912 to 8 June 1912 (Figure 13). It involved three explosive episodes, producing seventeen cubic kilometers of tephra and eleven cubic kilometers of ignimbrite, which together indicate a magma volume of approximately thirteen-and-a-half cubic kilometers (Hildreth and Fierstein 2012).

The first sixteen hours of the eruption involved a sequence of geochemically distinct ash-flows ranging from rhyolite to andesite known as the Valley of Ten Thousand Smokes ignimbrite. Several years after the event, the area in which this ignimbrite is emplaced still contained thousands of active fumaroles—giving the area and rock unit its name. Throughout the eruption sequence, a large amount of banded pumice was ejected from the vent. The banded pumice resulted from the presence of multiple compositions of magma (rhyolite, dacite, and andesite) mingling together at the time of the eruption, and three lava domes were emplaced after the pyroclastic episodes (Hildreth and Fierstein 2012).

Figure 12: Map of Katmai National Park and Preserve showing the locations of all Quaternary volcanoes (NPS figure from Hults and Fierstein 2016).

Approximately eleven hours into the eruption the summit of Mount Katmai ten kilometers to the east collapsed to form a caldera. During its caldera collapse, Mount Katmai experienced several phreatic eruptions of mud and breccia, which were deposited simultaneously with, and are thus interbedded with, the coeval plinian tephra layers from Novarupta. No new magmatic material was erupted from Mount Katmai during the caldera collapse. However, a small dacite dome formed on the caldera floor shortly thereafter (Hildreth and Fierstein 2012).

Many earthquakes—ten with magnitudes between 6.0 and 7.0, much larger than is typical for volcanic earthquakes—accompanied the Novarupta eruption and caldera collapse at Mount Katmai. Even after the eruption ceased, earthquakes continued to rock the region. Between 9 June 1912 and 17 June 1912, four earthquakes with magnitudes between 6.0 and 6.9 were recorded and small shocks continued for months after the eruption ended.

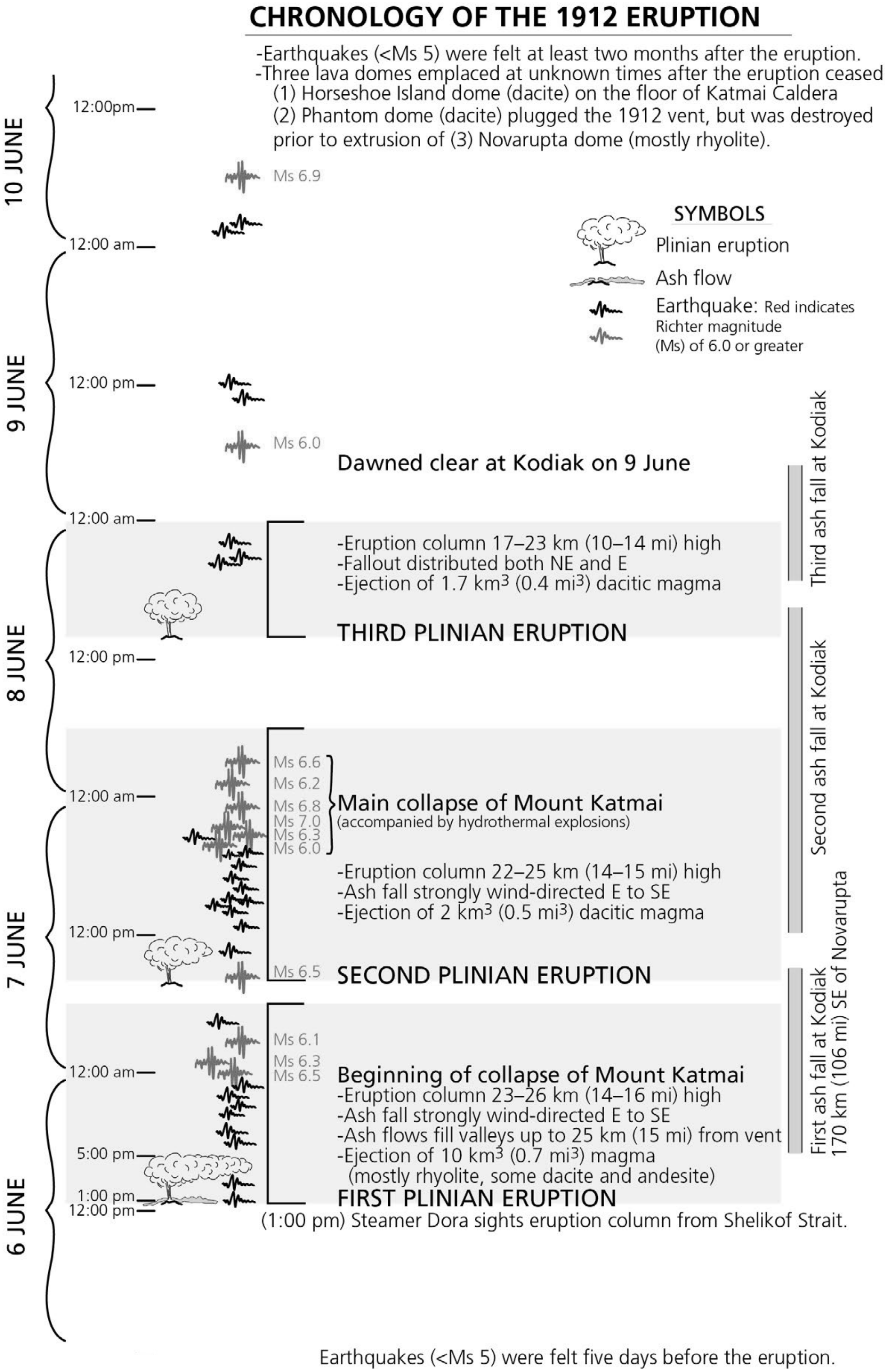

Figure 13. Chronology of the 1912 eruption. There was only one seismograph operating in Alaska in 1912 when the eruption occurred, but many of the earthquakes generated during this eruption were large enough that they were recorded by instruments elsewhere in North America, as well as in Asia, Europe, Hawaii, Japan, and North Africa (NPS figure modified from Hults and Fierstein 2016).

During the 1912 Novarupta event, thirty centimeters of tephra fell in Kodiak village, 170 kilometers away from the vent, and immobilized the town for three days and continued to disrupt lives for months (Fierstein and Hildreth 2000). Other villages were permanently abandoned. The ash fallout also affected local wildlife, both by killing them directly and by obliterating food sources.

Multiple moderate-sized lahars were associated with the 1912 eruption. One lahar at the southern foot of Mount Katmai was probably triggered by earthquakes generated during caldera collapse at Mount Katmai. Flooding and lahars occurred in Martin Creek due to an avalanche from Mount Mageik triggered by the seismicity. Soon after the eruption, lahars rushed across the surface of the Valley of Ten Thousand Smokes. They were caused by a combination of meltwater from hot ash blanketing glaciers and by the sudden release of a lake formed when deposits from the 1912 eruption temporarily dammed upper Knife Creek. These lahars combined with excess sediment from easily eroded pyroclastic deposits caused the burial of the old Savonoski village site (Fierstein and Hildreth 2000).

A landslide triggered by shaking from the 1912 eruption dammed the Katmai River in Katmai Canyon. The dam remained for three years after the eruption but in 1915, rapid snowmelt overwhelmed the dam, and an enormous flood broke out as the dam failed. As the water rushed down the riverbed, it picked up massive amounts of debris, transforming into a debris flow. The flow snapped large trees for several kilometers downstream and deposited huge boulders and other sediment in the river valley. The ten-kilometer wide valley was flooded up to a depth of ten meters. Katmai village, which was abandoned in 1912 when the earthquakes began, was destroyed, and stretches of the riverbed were transformed into quicksand from the great volume of deposited material. The flow choked the river mouth at Katmai Bay, nearly thirty kilometers downstream of Katmai Canyon, to the point that it was too narrow to navigate even by rowboat. Prior to the event, the mouth of the river was wide enough that it could be navigated by a ten-meter schooner (Griggs 1922).

The Novarupta event was extraordinary both for what it was and because it was initially misinterpreted. For example, it was long considered that all of the fallout came from Mount Katmai when the summit caldera was formed. The ash flows were assumed to have erupted through fissure vents in the Valley of Ten Thousand Smokes and a large magma body was proposed to underlie the entire valley (Griggs 1922).

The remote area was not actually inspected by modern volcanologists until 1953 when Howel Williams and Garniss Curtis visited the area. They concluded that the abundant banded pumice was produced by syneruptive magma mixing, not assimilation of wall rock material as Fenner had proposed. They also determined that the fumaroles were not the result of degassing of a large magma chamber located directly below the Valley of Ten Thousand Smokes ignimbrite as Griggs had thought. Later, Curtis measured thicknesses of the fallout deposits and showed that they thickened and coarsened toward Novarupta, not Mount Katmai (Curtis 1968). This discovery was evidence that eruptive column collapse from an eruption at Novarupta was the cause of the ash flows.

The idea that pyroclastic flows could be caused by the collapse of a vertical eruption column had been recognized from the 1929 eruption of Komagatake, Japan (Kozu 1934), but was not widely acknowledged until decades later. Early on, it was assumed that a pyroclastic flow resulting from column collapse would mean the eruption column had ceased to exist. Therefore, the tephra lying on top of the tuff in the Valley of Ten Thousand Smokes was enigmatic. Later fieldwork showed that the nine ash flows and many tephra layers were intercalated, and thus must have erupted synchronously (Fierstein and Hildreth 1992; Fierstein and Wilson 2005).

The discovery by Hildreth and Fierstein that very little material and no juvenile components, had erupted from Mount Katmai during the caldera collapse was puzzling and required explanation. It is now thought that there is some sort of kilometers-long subterranean connection between Novarupta and Katmai through which magma drained. In this case, the withdrawal of magma removed support from the Katmai edifice and allowed for caldera collapse without providing eruptive materials to the summit of Mount Katmai (Hildreth and Fierstein 2012).

In addition to Mount Katmai and Novarupta, Katmai National Park and Preserve contains numerous other volcanoes, briefly summarized in Table 3.

Table 3. Names, ages, and eruptive status of Quaternary volcanoes within Katmai National Park and Preserve. 'Active' is defined as volcanoes with historical eruptions, marked fumarolic activity, earthquake swarms, or volcanic deformation (Madden et al. *2014). NPS table from Hults and Fierstein 2016.*

Volcano	Active	Historic	Last eruption (yr BP)	History and Notes
Douglas	Yes	No	<11,700	Ice-clad stratovolcano with a small crater lake and active fumarole field on north side of crater.
Fourpeaked	Yes	Yes	CE 2006	17 September 2006 eruption formed a 6,100 m high plume from phreatic explosions. Steam was observed through 2007.
Kaguyak	No	No	1,060	A stratovolcano with a 3 km wide caldera and lake with CO_2 bubbling up. Pyroclastic flows from the caldera-forming eruption filled surrounding valleys to over 30 m thick.
Iron Trig Cone	No	No	88,000±27,000	Mafic scoria cone of the Savonoski River Cluster of volcanoes.
Cone 3110	No	No	235,000±30,000	Partly erupted under a glacier.
Cone 3601	No	No	132,000±27,000	Mafic cone of the Savonoski River volcanic cluster.
Knob 1000	No	No	Unknown	Remnant of a volcanic cone and part of the Savonoski River cluster of volcanoes.
Rainbow River Cone	No	No	390,000±39,000	Small basaltic volcano of radially dipping stacks of thin lavas and breccia that is part of the Savonoski River cluster of volcanoes.
Devils Desk	No	No	<11,700	Ice-clad volcanic neck of a stratovolcano.
Kukak	Yes	Yes?	CE 1889	Ice-clad stratovolcano that contains a vigorous fumarole field near the northern summit. Report of an eruption in 1889.
Steller	No	No	<11,700	Ice-clad stratovolcano.
Denison	No	No	<11,700	Ice-clad stratovolcano.

Snowy	Yes	No	<11,700	Ice-clad stratovolcano with fumaroles on the peak.
Folsoms Bluff	No	No	Unknown	Andesitic vent complex with curving glassy lava columns indicative of ice-contact emplacement.
Griggs	Yes	No	<11,700	Numerous fumaroles. 10 km behind (NW) the volcanic front defined by Martin, Mageik, Trident, Katmai, and Snowy Mountain centers.
Katmai	Yes	Yes	CE 1912	A stratovolcano with a 10km diameter caldera formed by collapse during the 1912 Novarupta eruption (VEI 3).
Novarupta	Yes	Yes	CE 1912	Vent source of the 1912 eruption – plugged with a 400m diameter dome.
Trident	Yes	Yes	CE 1953–1974	Volcanic complex consisting of four stratovolcanoes and numerous domes. 1953–1960 intermittent eruptions formed numerous lava flows and a volcanic dome. Numerous steam eruptions until 1974.
Cerberus	No	No	114,000±46,000	Andesite to dacite peripheral dome of Trident.
Falling Mountain	No	No	70,000±8,000	Andesite to dacite peripheral dome of Trident.
Mageik	Yes	No	Unknown	A stratovolcano with a phreatic crater on the northeast side containing a crater lake. Has vigorous fumarolic activity.
Martin	Yes	No	<11,700	A stratovolcano with a 300 m diameter crater that has intense fumarolic activity, and an ephemeral lake.
Alagogshak	No	No	2,600,000–11,700	Several eruptions spread intermittently over at least 600,000 years.
Kejulik	No	No	Unknown	Heavily eroded remnant of a stratovolcano.

5.3 Monitoring of Katmai National Park and Preserve

The Alaska Volcano Observatory is responsible for monitoring many volcanoes in Alaska, including those within Katmai National Park and Preserve. The Alaska Volcano Observatory operates nineteen seismic monitoring stations within the Katmai region (Fierstein and Hildreth 2000). Volcanic unrest is also monitored by daily satellite observations, volcanic gas measurements, ground deformation studies, fumarole temperature measurements, and water chemistry measurements.

6. SUMMARY

This is but a glimpse of the rich history of a few of the volcanic parks in the United States. The National Park Service manages lands that contain nearly every conceivable volcanic resource, from rocks containing evidence of a fiery past to single volcanoes to large volcanic complexes with numerous vents to active geothermal features. At the time of this writing, the National Park Service includes over four hundred national parks and monuments, of which at least seventy-six contain some form of volcanic resource, and at least sixteen contain volcanic edifices. This report highlights four of the nation's important volcanic parks, including two which have had major and scientifically significant eruptions during the twentieth and twenty-first centuries. Many parks were specifically set aside to preserve their volcanic attributes, and many more have scenery or cultural significance that is dependent on the rock types they contain. In addition, many significant advances in the science of volcanology have been made as a direct result of studies in national parks.

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