AN ABSTRACT OF THE THESIS OF

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Title: A Dynamic Landscape Formed by the Power of Volcanoes: Geology Training Manual for Interpretative Rangers at Hawai'i Volcanoes National Park.

Abstract Approved:

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Time spent as a ranger-naturalist at Hawai'i Volcanoes National Park (HAVO), coupled with field observations and library research, provides a basis to develop a geology training manual for the park's Interpretation staff. During my stay in Hawai'i, I led guided hikes, interpretive programs, and worked in the visitor center interacting with the public, other ranger-naturalists, and scientists at the Hawaiian Volcano Observatory (HVO) in order to experience the types of situations rangers face every day on the job. Geological expertise varies among rangers, from no background to degrees in geology. This document provides a base so that new rangers can communicate the geologic story of HAVO to park visitors and pursue and understand certain aspects of research conducted within the park at HVO. HAVO is a challenging park for interpretation because the average visitor spends very little time in the park, often not venturing far from the 11-mile (18 kilometer) Crater Rim Drive. This geology training manual provides ideas on how rangers can inspire visitors through concise theme statements, demonstrations, visitor participation, and simple animation.

The manual begins with basic geology and how Hawai'i fits into the global perspective and then progressively explores ideas down to the specifics of lava flow structure and textures. The first two chapters are intended for every interpretive ranger so they can grasp or refresh themselves on geology basics and gain ideas on how to explain

concepts to the general public. Chapter 1 examines the whole Earth, plate tectonics, hotspots, the various ways to generate molten Earth material, and the formation of the Hawaiian Islands. Chapter 2 is more specific to HAVO, focusing on Kīlauea Volcano and its internal and external anatomy. It includes discussion and illustration about the processes that create the landscape we see today. The complex rhythm of Kīlauea Volcano reveal ideas from how the plumbing system operates within the body of the volcano to the birth of surface features. Processes discussed during ranger programs might include topics such as Kīlauea's shape, how Kīlauea Caldera formed, or why it is currently erupting out of the side of the volcano. Because HVO is housed within the park, it is important for rangers to emphasize why Kīlauea is well studied and how predictive models may tell about future volcanic hazards. Chapter 3 is an in-depth look at the observations and ideas researchers have recently published on lava flow structure and textures. It contains more advanced ideas about the formation of pāhoehoe, 'a'ā, and lava tubes. A significant amount of the research constrains the intrinsic and extrinsic processes such as crystallization, viscosity, temperature, slope, eruption duration, and eruption volume that create smooth, ropey, jagged, or clumpy lava flow textures. The development of technology coupled with the longevity of the Pu'u 'Ō'ō-Kūpaianaha eruption provides opportunity to study lava flow dynamics and confirms that lava flows may transition from a pāhoehoe flow to an 'a'ā flow and vice versa based primarily upon temperature, viscosity, and shear strain. Ranger-lead programs help facilitate understanding by taking visitors out into the field to demonstrate how ideas such as crystallization, viscosity, and shear strain affect a lava flow.

Geology interpretation in HAVO provides opportunity to create a variety of programs. From this training manual, rangers can develop a concise theme for the specific program, know the terminology, and build a story with visitor interaction to help reveal how Hawaiian volcanoes and lava flows create the dynamic landscape we see today.

A Dynamic Landscape Formed by the Power of Volcanoes: Geology Training Manual for Interpreters at Hawai'i Volcanoes National Park

by

Rebecca H. Ashton

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APPROVED

Major Professor, representing Geology

Chair of the Department of Geosciences

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Rebecca H. Ashton, Author

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This is dedicated to my father, Thomas G. Ashton. With Love, Rebecca.

Preface

"Others breathed a blue flame with regular pulsations of sound louder than that from the valve of any engine of man's making. The solid lava trembling with the throes of the monster confined within."

- *George A. Howard, Los Angeles, January 3, 1891*

(On the Rim of Kīlauea: Excerpts from the Volcano House Register)

Imagine you are a white-tailed tropical bird, the Koa`e kea, soaring and catching the up currents of wind along Hilina Pali. You are traveling from the ocean to the summit of Kīlauea volcano, or to one of the craters along its flanks. As a Koa`e kea, you get a chance to view the entire volcano from the summit to the sea, as well as the snow-capped peaks of Mauna Loa, Mauna Kea and beyond. The ancestors of the Koa`e kea probably witnessed the formation of Kīlauea and generations have watched the landscape evolve over time. But, you don't need to be a tropical bird or live millions of years to see the geologic change of Kīlauea. Hawai`i Volcanoes National Park (HAVO) stands on a landscape that evolves with each pulse of volcanic activity – events that can be perceived on a human timescale. Even if you do not see change when you first visit, the landscape will probably be different when you arrive the next time - it already has changed significantly in the course of writing this manual!

A Dynamic Landscape Formed by the Power of Volcanoes:
Geology Training Manual for Interpretative Rangers at
Hawai'i Volcanoes National Park

Introduction

As a dynamic landscape, Hawai'i Volcanoes National Park (HAVO) is special. It is one of the few places where a person can see dramatic geologic change during his/her lifetime. HAVO displays and protects aspects of Hawaiian culture, native plants, and animals found nowhere else in the world, as well as the ever-changing geologic landscape on a human timeframe. The focus of this manual is the importance and pulse of a landscape constantly created and destroyed by the most active volcano in the world. One of the greatest assets of the park is geologic change on a human timescale that allows people to witness the process of geology. Watching a landscape evolve over our lifetimes in Hawai'i creates a measure of how small and powerless we are against the geologic processes of volcanoes and the dynamic power of the planet.

Hawai'i Volcanoes National Park

Hawai`i Volcanoes National Park is located on the Big Island of Hawai`i at approximately 19°N latitude and 155°W longitude, 2,400 miles (3,900 kilometers) west-southwest of Los Angeles. Thomas A. Jaggar recognized the uniqueness of the active volcanoes and established the Hawaiian Volcano Observatory (HVO) in 1911 to conduct research on the island. Before Hawai`i became a state, the United States government realized there was a gem right in the middle of the Pacific Ocean. The key advocates were Jaggar and L.A. Thurston, who had lobbied congress to get the land set aside for research of the active volcanoes. National park status would also allow the public to easily access and learn on the flanks of an active volcano. So in 1916 Hawai`i National Park was established as the $13^{th}$ national park. In 1961 it was divided into two separate parks, Haleakalā (HALE) on Mau`i and Hawai`i Volcanoes (HAVO) on the Big Island of Hawai`i. HAVO today preserves land that includes parts of Mauna Loa and Kīlauea volcanoes. The park protects land from the mountain tops to the sea, and all the precious resources in between.

This training manual focuses mostly on Kīlauea Volcano, because interpretive rangers deal with visitors in the most accessible region of the park, Crater Rim Drive and the coastal areas. In Hawaiian, Kīlauea means "spewing" or "much spreading," in reference to the lava that flows across its surface. Kīlauea rises 4,190 feet (1,280 meters) above sea-level and spans 552 square miles (1,430 square kilometers), which makes up 13.7% of the Big Island. But these numbers keep changing -- an important aspect of the park that constantly reminds us that the Earth is dynamic!

What is Interpretation?

Freeman Tilden set up principles and paved the way for interpretation as it is known today. Tilden's principles are as follows:

I. *Any interpretation that does not somehow relate what is being displayed or described to something within the personality or experience of the visitor will be sterile.*

II. *Information, as such, is not interpretation. Interpretation is revelation based upon information. But they are entirely different things. However, all interpretation includes information.*

III. *Interpretation is art, which combines many arts, whether the materials presented are scientific, historical, or architectural. Any art is in some degree teachable.*

IV. *The chief aim of interpretation is not instruction, but provocation.*

V. *Interpretation should aim to present a whole rather than a part, and must address itself to the whole man rather than any phase.*

VI. *Interpretation addressed to children (say, up to the age of twelve) should not be a dilution of the presentation to adults, but should follow a fundamentally different approach. To be at its best, it will require a separate program. (Tilden, 1957)*

It is the job of the interpretive ranger to *translate* the complex language of geology or other topics, find *meanings* in geological observations, and *connect* the visitor to the landscape of HAVO. And it should be done in such a way that visitors will *discover* their own meanings and connections to the landscape. It is important that interpretive rangers not delve into the nuts and bolts of geologic details that likely would bore visitors during a program. Know the terminology but, gauge the visitors as you progress through your program and adjust your presentation accordingly. Interpretive rangers should spark excitement about active volcanism at HAVO and how it might relate to other physical, biological, and cultural aspects of the park.

> *"I suppose that any one of nature's most celebrated wonders will always look rather insignificant to a visitor at first, but on a better acquaintance will swell and stretch out and spread abroad, until it finally grows clear beyond his grasp – becomes too stupendous for his comprehension ... I was disappointed when I saw the great volcano of Kilauea (Ke-low-way-ah) today for the first time."*
>
> *- Mark Twain's Letters from Hawaii (Day, 1966)*

This manual contains facts that rangers can use as tools for interpretation as well as a bag of tricks to help connect a visitor's heart and mind to the geological landscape. Park visitors are a non-captive audience; they are not required to take an exam after your ranger program. It is your job as an interpreter to inspire them and retain the attention of the audience through the use of good factual information and provocative interpretive techniques. Interpretation should be enjoyable, relevant to the person and landscape, organized, and thematic. Sam Ham's <u>Environmental Interpretation</u> book is an excellent source for guidance (Ham, 1992). As Ham says, "No topic is inherently boring or interesting. There are only people who make them that way."

<u>How do I use Interpretation?</u>

> *"The greater part of the vast floor of the desert and us was black as ink, and apparently smooth and level; but over a mile square of it was ringed and streaked and striped with a thousand branching streams of liquid and gorgeously brilliant fire! It looked like a colossal railroad map of the State of Massachusetts done in chain lighting on a midnight sky. Imagine it – imagine a coal-black sky shivered into a tangled network of angry fire!"*
>
> *- Mark Twain's Letters from Hawaii (Day, 1966)*

You are a better interpreter if you present the landscape in ways that are meaningful to visitors. If a visitor is emotionally connected to the park, they will appreciate the Earth and ultimately take better care of it. The best way to present interpretive programs is through the use of <u>themes</u>. A theme commonly can be stated as a one – sentence, "take home message". Visitors tend to remember themes rather than facts. Theme's ultimately make an interpreter's talk organized, easy to follow, and meaningful. Here are a few examples of potential geological themes for Hawai'i Volcanoes National Park.

- *"The Hawaiian Hotspot has created an island chain isolated from other landmasses."*
- *"HAVO provides visitors the opportunity to contemplate the awesome power of the planet through active volcanism."*
- *"Hawai'i's continuous geologic change creates spectacular scenery, a mosaic landscape of volcanic features."*
- *"Only the rim remains of a caldera that collapsed upon itself and filled with lava; not just once, but many times."*
- *The remains of explosive eruptions that visitors survived can be seen in every direction from the summit region of Kīlauea."*
- *"The sacred home of Pele is a birth of land and upwelling of spirits."*
- *"Discover the secrets hidden beneath the surface of 'Ai La'au, the forest eater, who holds history within the rainforest."*
- *"The new landscape of Kīlauea Iki; so fresh you can imagine the churning lava lake, hear the roar, and feel the heat of the 1,900-foot lava fountain that arose during the 1959 eruption."*
- *"The seemingly barren Ka'ū desert provides clues to the explosive past of Kīlauea."*
- *"Glance at the remains of magma that extruded at sheets of fiery lava through the most active rift zone of Kīlauea volcano."*
- *"Kīlauea, the "tamest" volcano in the world conceals its hazardous secrets away from the inexperienced lava viewer."*

Compelling stories are a great way to provoke excitement and connect visitors to HAVO's incredible landscape. And the only way to develop good, compelling stories is to get out and *experience* the resource yourself! But rangers need factual information to provide substance to their stories, so that the stories are accurate and grounded in the real world.

This manual is designed to be your guide to some of the geology related to Hawai'i Volcanoes National Park. Not everything is in the manual. Anatole France once said, *"Do not try to satisfy your vanity by teaching a great many things. Awaken people's curiosity. It is enough to open minds; do not overload them. Put there just a spark. If there is some good inflammable stuff, it will catch fire."* A ranger program that tries to cover all of the geology of Kīlauea is doomed to fail. Focus on a theme based on your location and then develop a story that can be told during the time you have to share with the visitor. Let the story be the spark that visitors can take with them to ignite their own fiery images of the Earth beneath Kīlauea. The story is the hardest part of an interpretive ranger's job and it will not be perfect the first time out. It is something developed over time with a lot of practice and revision.

What is geology and why is it important?

Geology is the scientific study of the Earth, its origins, the materials that make it up, and the processes that constantly change it. Everything in our lives is literally built on geology, the Earth. One reason geologists study the Earth is to protect human lives. After catastrophic events like earthquakes, tsunamis, mudflows, volcanic eruptions, and landslides, the public wants to know the what, when, why, and how. Geologists are scientists on a never-ending journey to answer these important questions.

Visitors come to Hawai'i to see new Earth formed right before their eyes as hot, bubbling lava flows into the ocean, adding land to the Big Island. Since 1983, 524 acres (~1 square mile) have been added to the island (US Geological Survey, 2002) and people get very excited about the prospect of seeing actual molten, flowing lava. But it is not always possible to see flowing lava. Or, there might be a line of cars 3 miles long just to see the hot stuff burning the asphalt. It is an interpretive ranger's job to draw on that excitement, to help visitors appreciate how the Earth operates.

This manual focuses on aspects of geology that are important at HAVO: volcanic eruptions and their resulting rocks and landscape. Rangers need to master certain concepts not only to present programs focused on geology, but also to help visitors contemplate how Hawaiian culture and biology are so closely tied to the landscape.

How do I use this manual?

There are a plethora of interpretive opportunities within the park. Most visitors explore the park for one to two hours and do not venture far from Crater Rim Drive. It makes sense to be intimately familiar with material in the summit area. Before you can dive into details of the park, it is important to learn about the foundation that the local geology is built on. The manual thus starts with the big picture geology and gradually works toward more local details. Throughout the manual there are suggestions on ways to inspire people. The best interpretive rangers learn from others' programs and also develop their own. There are many publications on the geology of Hawai'i. But they are often written for audiences well-versed in specialized areas of geology. Someone with little background in geology might feel overwhelmed and discouraged from incorporating much in-depth geology into their programs. As an interpretive ranger with a background in geology, I love learning about the geologic details of the park, but mastering the plants and cultural history has been a daunting task. Thanks to some rather articulate experts in those areas, I overcame some boundaries. This manual will be a resource for you to develop a strong base in Hawaiian geology and further provoke your interest in the subject.

Chapter One

The Basics of Geology: Hawai'i's Role in the Global Perspective

"The surprise of finding a good hotel in such an outlandish spot startled me considerably more than the volcano did."
- Mark Twain's Letters from Hawaii (Day, 1966)

A few questions from curious visitors ...

- *How deep to the magma chamber?*
- *What fills the void, or what happens if there is a void in the Earth when the magma empties?*
- *Where does lava come from?*
- *How is there a continuous flow of lava?*

The Grand Scheme

Sometimes we get caught up in the details of our daily lives and get upset when the smallest of detail fails to go our way, even when, in the larger picture, things are fine. If you walk around Hawai'i and only look at the rock and disregard the overall setting, you may be missing perspective that makes these rocks meaningful.

The Earth

Interpretation conveys inspiration, feeling, and meaning. It connects the visitor's heart and mind to the landscape. Before diving into the geology of Hawai'i Volcanoes National Park (HAVO), an interpretive ranger should understand the broader scope of the Earth and how it relates to Hawai'i's landscape. Even though you will not want to go into long, excruciating conversations about the interior of the Earth, that knowledge is the fundamental base to understanding the processes that form the Hawaiian Islands and their amazing volcanic landscape.

Earth's interior is like a giant spherical layer cake with different physical and chemical properties (Figure 1.1). From a chemical point of view (left side, Figure 1.1), the Earth can be compared to a hard-boiled egg. The crust, mantle, and core of the Earth are the eggshell, egg white, and yoke, respectively. Just make the egg a bit more round and you almost have the Earth. When the Earth formed 4.6 billion years ago, it was a homogenous, molten sphere. As gravity pulled material inward, the heavier elements sank towards the center, while the lighter elements floated towards the outer portions. The heaviest material, iron and nickel sank inward and formed the core. The lighter materials in the outer portion of the Earth consist mostly of compounds of silicon and oxygen, known as silicates. The heavy silicates, those containing iron and magnesium, comprise the mantle, whereas lighter silicates containing aluminum, calcium, potassium, and other elements are in the crust. Of course these are generalities; there is quite a bit of iron in the Earth's crust, but most has long settled into the mantle and especially the core.

Brain Thinking …
Most people probably never think much about what is below their feet. It is about 4,000 miles (6,300 kilometers) from Earth's surface to the very center. If you could drive non-stop from the Earth's surface to the core at 60 miles per hour (about 100 kilometers per hour), you would arrive in about 2 days and 19 hours. That would require a lot of coffee! Here is another perspective; it is about 2,400 miles (4,000 kilometers) as a crow flies from New York City to Los Angeles. In order to go from the surface of the Earth to the center would require a crow to fly from Los Angeles to New York City and back to Denver. If you are not savvy enough with the continental United States, let's think about flying to Hawai'i since most, if not all of you, took an airplane to Hawai'i. It is about 2,400 miles (4,000 kilometers) from Los Angeles to Hawai'i. You would have to fly almost round trip to cover the same distance as traveling to the center of the Earth in an airplane.

As you travel deeper into the Earth; temperature and pressure both increase. The combination of chemical composition, temperature, and pressure determine the physical state of portions of the Earth. According to physical state, the Earth is divided into the lithosphere, asthenosphere, lower mantle, outer core, and inner core (right side, Figure 1.1). The lithosphere is a rigid and hard outer shell that consists of the crust and uppermost part of the mantle. Beneath the lithosphere is a warm, softer portion of the mantle known as the asthenosphere. Think of the lithosphere as a cold, brittle stick of butter just out of the refrigerator.

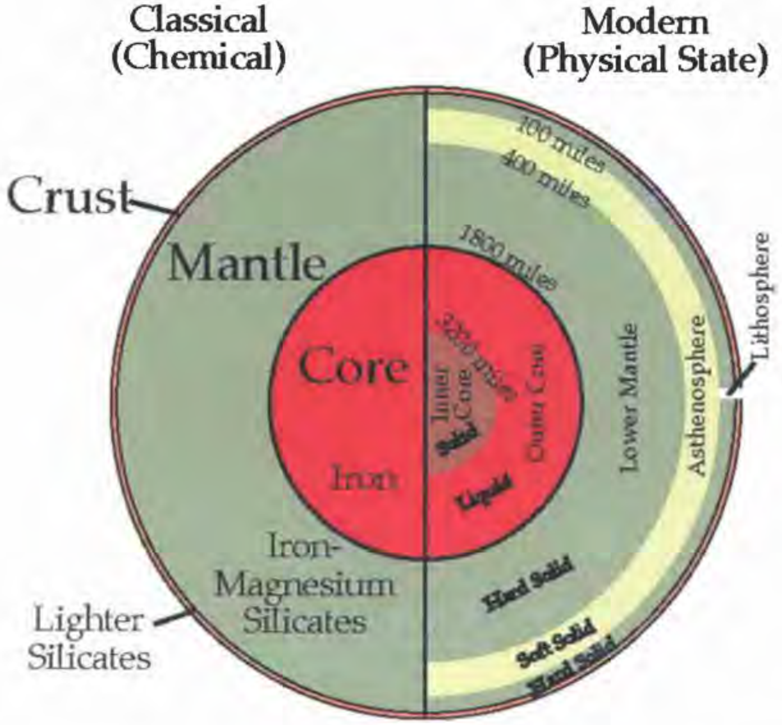


Figure 1.1 - *The Earth is a chemical and physical layer cake.* Left: *chemical divisions* - It is chemically divided into the crust, mantle, and core. The core consists of heavy elements, iron and nickel; the mantle, silicates rich in iron and magnesium; and the crust, lighter silicates. The most dense material, iron, is in the core, while the least dense materials, lighter (potassium, calcium, and aluminum) silicates, are in the crust. Right: ***physical state*** - The chemical layers actually exist in different physical states because both temperature and pressure increase with depth. The cold, rigid lithosphere consists of the crust and uppermost mantle. The warm, plastic-like asthenosphere is within the mantle. The lower mantle is another hard solid. The outer core is liquid, while the inner core is solid.

If you let it sit and warm up to room temperature, the butter will become more plastic and "flow" like the asthenosphere. The lower mantle is the same composition as the asthenosphere and even hotter, but the pressure is great enough to turn the material into a harder solid that can still "flow" over geologic time. The iron of the outer core is in a liquid state because it is so hot, but the extreme pressure on the inner core turns the iron located there into a solid.

Plate Tectonics

When you examine the physical properties of Earth's interior, a new perspective is brought forth that illustrates the idea of plate tectonics. And plate tectonics helps explain why there is an island chain in the middle of the Pacific Ocean, 2,000 miles (3,000 kilometers) from any other landmass. The Earth's hard outer shell, the lithosphere, is broken up into various chunks or plates. The plates are not stationary - they move away from each other at divergent plate boundaries, towards each other at convergent plate boundaries, or slip past one another along transform plate boundaries (Figure 1.2). Most tectonic activity, like earthquakes, volcanism, and the formation of mountain ranges, results from interactions along plate boundaries. If you choose to bring up plate tectonics with an audience, it would be helpful to have a map on hand that shows the boundaries (Figure 1.3). It is then easy to show that there are no plate boundaries even close to the Hawaiian Island Chain, to emphasize that the islands are the result of another important dynamic feature, a hotspot.

How is all of this motion going on inside the Earth? As stated earlier, the asthenosphere is a soft solid that results in *ductile flow* that allows the Earth to release heat by convection. It is easy to imagine convection if you think about a pot of boiling water. When you create a strong rolling boil, it is mimicking convection within the Earth. The hot water at the bottom of the pot, closest to the burner, rises so that heat can be released at the water's surface. Where the asthenosphere rises and parts, it rips apart the Earth's rigid outer shell, creating a divergent plate boundary. Where the asthenosphere descends, it causes pieces of the rigid shell to collide, producing a convergent plate boundary.

How fast do plates move? Geologists can determine the rate of motion of the Pacific Plate relative to a fixed hotspot by using the distance between islands and seamounts and considering their respective ages. If you look at the Hawaiian-Emperor Seamount Chain, there is a bend in the chain that occurred about 40 million years ago when the Pacific Plate changed its direction of motion (Clague and others, 1989). The Pacific Plate was moving northward about 3.3 inches (8.5 centimeters) per year during the formation of the Emperor Seamount chain. The current plate motion for the Hawaiian Chain is about 3.6 inches (9.3 centimeters) per year to the northwest. That is about the rate your fingernails grow! During a program, I *always* told visitors to watch their fingernails grow and then lead into a discussion about plate motion over the Hawaiian hotspot. Can you really see them grow? Visitors enjoy when geology is placed in perspective with daily life. More recently, it is suggested that the Hawaiian hotspot may move southward at speeds of 1-2 inches/ year (30-50 millimeters/year) (Tarduno and others, 2002).

Turning Up the Heat – Volcanism

> *"Occasionally the molten lava flowing under the superincumbent crust broke through – split a dazzling streak, from five hundred to a thousand feet long, like a sudden flash of lightning, and then acre after acre of the cold lava parted into fragments, turned up edgewise like cakes of ice when a great river breaks up, plunge downward and were swallowed in the crimson cauldron."*
>
> *- Mark Twain's Letters from Hawaii (Day, 1966)*

The first question visitors often ask when they get to HAVO is, "Where is the lava?" They want to see hot molten rock exploding out of the volcano. First, Hawaiian volcanoes rarely explode (maybe every couple hundred years); they usually ooze lava or occasionally fountain like a busted fire hydrant (every couple of decades). Second, depending on the state of the eruption, a visitor will not always see flowing lava. But there are some important questions you might help visitors ponder. Why is there liquid rock coming out of the ground? What makes rock melt? Where is the lava going to come out of the ground next? And what are the rocks around the park made of?

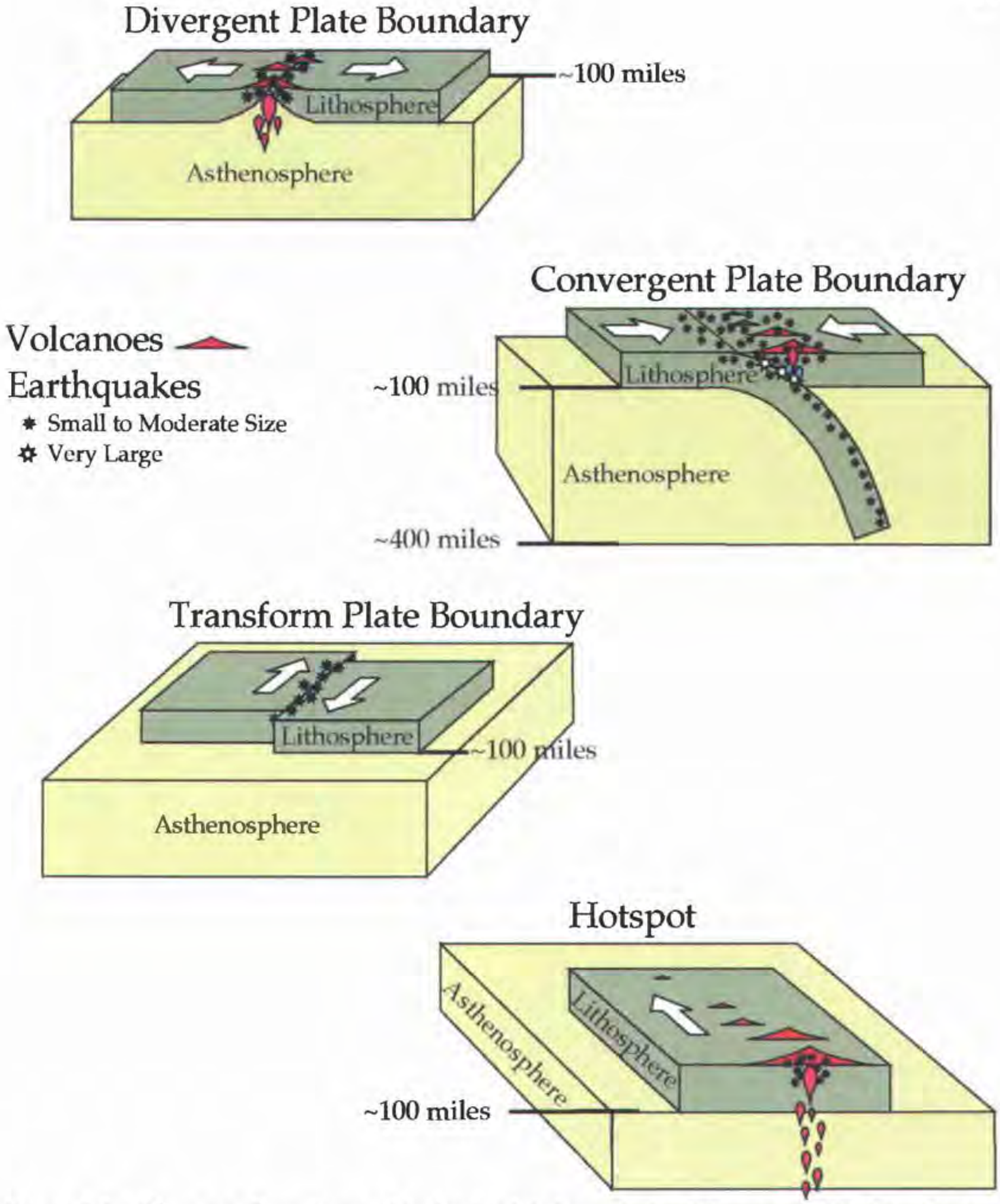


Figure 1.2 – *There are three types of tectonic plate boundaries.* Divergent plate boundaries create volcanoes and small, shallow earthquakes as the plates move away from each other. Convergent plate boundaries involve collision of plates, producing volcanoes on the overriding plate and earthquakes of all depths, including some that are very large. Transform plate boundaries are where plates slide parallel past one another; they produce earthquakes but lack volcanic activity. A hotspot is not a plate boundary, but it produces active tectonic processes such as volcanoes and earthquakes.

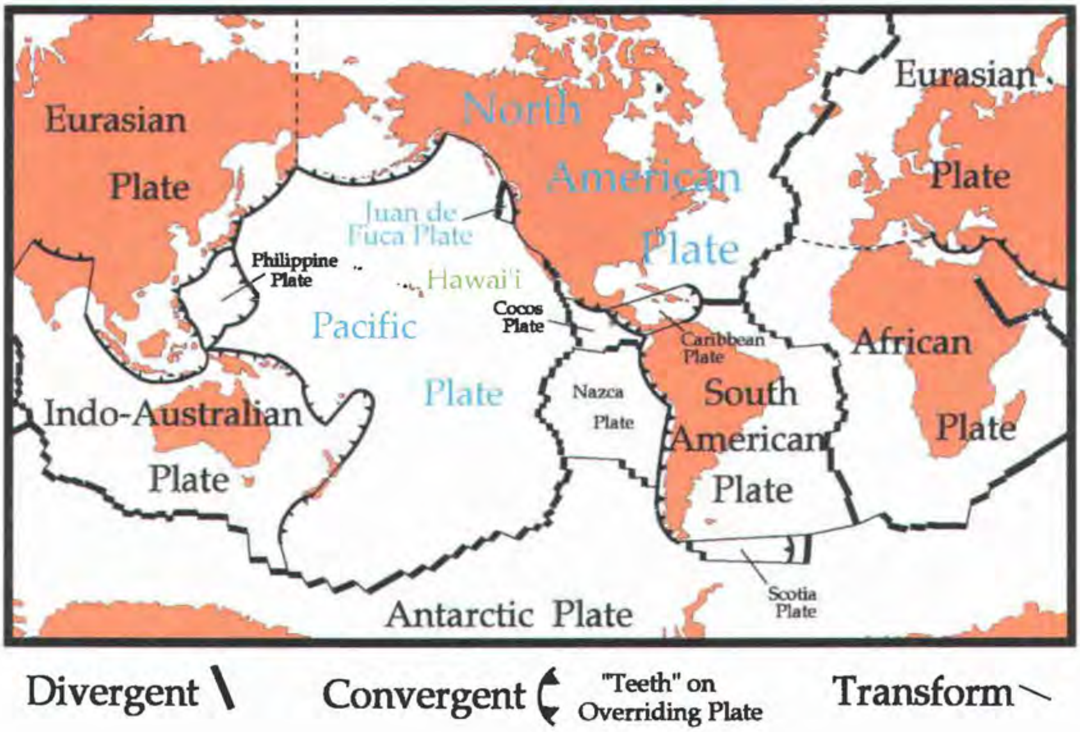


Figure 1.3 – *Plates and Boundaries.* This map outlines the various *tectonic plates* and *plate boundaries* around the world. Notice that Hawai'i is in the middle of the Pacific Plate, the volcanism is the result of a hotspot.

Why do rocks melt?

There are two important ingredients to the formation of the Hawaiian Island Chain: 1) molten rock erupting through 2) the moving ocean floor. Plate tectonics helps us understand that the ground is moving beneath our feet, but what makes rock melt?

There are three basic rock types, each formed by different processes. Igneous rocks cool and harden from *liquid* Earth material, called magma. Sedimentary rocks form from small particles of rock that are cemented together. Metamorphic rocks form where high temperature or high pressure (or both) alter, but do not melt, existing rock.

Let's stick with talking about igneous rocks because that is pretty much the only rock type found on the Hawaiian Islands, especially the Big Island. Rocks are made up of various minerals. Minerals are compounds of elements such as oxygen (O), silicon (Si), aluminum (Al), iron (Fe), calcium (Ca), sodium (Na), magnesium (Mg), and potassium (K), to name a few. Not all minerals melt at the same temperature; magma often contains some solid, crystallized minerals in addition to the liquid melt – and some gases.

Park Ranger Allyson Mathis Analogy
People often write poems based on landscapes. *Volcanoes, eruptions,* and *landforms* can be thought of as poems. Poems are composed of words. *Composition of rocks, temperature,* and *viscosity* are the words that shape the inspirational volcanic landscape. Finally, words are made up of letters. The *elements* making the *minerals* are similar to the letters making a word.

There are three ways to melt a solid rock. A rock can melt by (1) the direct addition of heat, (2) by lowering the pressure on a rock that is already hot, or (3) by changing the chemical nature of the system (Asimow, 2000). The first way, melting a rock by adding heat, is not a significant process that occurs in the Earth today to generate large amounts of melt. Simply, there are not many natural ways to turn on the burner to heat rocks and cause them to melt. The second way to melt a rock involves a hot, dry solid under intense pressure. When you decrease the pressure, the solid begins to melt. This is known as decompression melting, which is common where hot mantle material rises. Decompression melting results in a consistent feedback loop that can produce material for long periods of time once the process is started. It can create large volumes of magma and the eruption of a lot of material; for example, virtually all of the lava flows in Hawai'i are products of decompression melting. All of the land you see is made up of lava flow upon lava flow. Think about how much material was required to build an island from the ocean floor to the ocean's surface, not to mention the height of Mauna Kea at over 13,000 feet (~4,300 meters). That is a lot of material! A third way to melt rock is by changing the chemical composition of hot rock by adding water, which lowers the melting temperature of certain minerals. This process involving *hydration* of rocks occurs when rock is heated to the point where it produces "sweat", or dehydrates, just like you or I do when we get hot! As the water rises, it wets rock in its path causing some of the rock to melt (flux melting). Where do these different processes melt rock within the Earth?

At a convergent plate boundary like the Pacific Northwest, the ocean plate begins to heat up as it dives beneath North America at a subduction zone. When the plate heats up, it dehydrates, releasing hot, mineral-rich water. As the water rises it lowers the melting temperature of certain minerals and thereby melts some of the rock in its path, creating magma. Some of the resulting magma migrates upwards, leading to volcanic eruptions. Steep-sided, explosive volcanoes, like Mt. St. Helens in the Pacific Northwest, Mt. Vesuvius in Italy, Mt. Pinatubo in the Philippines, St. Augustine in Alaska, and Mt. Fuji in Japan, occur at subduction zones.

The mechanics of melting is very different at a hotspot, like Hawai'i, and at a divergent plate boundary, like the Mid-Atlantic Ridge. Hot, dry mantle rises, undergoing decompression that causes rock to melt. It is analogous to taking the lid off a pressure cooker, which suddenly releases the pressure of superheated water, causing it to flash to steam. At hotspots and mid-ocean ridges, the drop in pressure causes some of the hot, rising asthenosphere to "flash" from solid to liquid. The change is not instantaneous; only a portion of the solid rock melts, creating a small amount of liquid. Some of the partial melt (magma) rises and erupts on the surface of the Earth through cracks and pores.

Hotspots

People see the features created by hotspot volcanism in various parts of the world, not just in Hawai'i. For example, volcanic landscapes in the Yellowstone National Park region, the Galapagos Islands, the Canary Islands, Iceland, and the southern portion of India (Deccan Traps) all result from hotspots (Figure 1.4). But why are there hotspots, and how do they form? Geologists do not have completely satisfying answers to these questions. But, what they do understand can be related to park visitors and perhaps compel them to contemplate how the Earth's internal processes affect the landscape in places like Hawai'i or Yellowstone.

The Global Perspective

Plate tectonics suggests that volcanic activity should occur at plate boundaries. Why are some spectacular volcanoes right smack in the middle of the Pacific Plate? In 1963, J. Tuzo Wilson proposed that there was a spot of deep mantle that brought magma to the surface in the middle of the plate. As the plate moved over the stationary "hotspot", a line of volcanoes formed. A little later, Jason Morgan (1972), the man who put many of the first pieces of plate tectonics together, suggested that the Emperor Seamount Chain was an ancestral extension of the Hawaiian chain that displayed a different trend because the plate at the time moved in a different direction. Since the hotspot proposal, there has been an explosion of study related to the Hawaiian Islands. Age determinations have confirmed that volcanic features become progressively older to the northwest. Furthermore, it was shown that the chemistry of the rocks of the Emperor Seamounts closely matches that of the Hawaiian Chain (Dalrymple, 1979, McDougall and Duncan, 1979). In 1993, Tackley and Stevenson put forth a way that magma production by decompression melting could continue to feed itself, leading to more magma production in the upper mantle. As a rock melts, a further decrease in density of magma causes it to continue to rise, which perpetuates more melting, creating balloon-like diapirs. As diapirs rise through the Earth, there is a natural downward drag of cooler surrounding rocks to renew the magma source

(Weinberg, 1997) (Figure 1.5). If we think back to our boiling pot of water, the hot water that rises has to be replaced, so water from the top of the pot circulates to the bottom and the cycle begins all over. This is analogous to the natural downward drag of rocks to renew the magma source. The question today revolves around what gives rock the first boost of upward velocity to *initiate* a hotspot? Geochemists believe that hotter locations in the mantle begin to rise, overcoming some viscous forces that become a hotspot (from plumes). The heating occurs from the radioactive decay of potassium (K), thorium (Th), and uranium (U) in the mantle. At about 60 miles (100 kilometers) depth, the pressure on rising hot mantle is so low that decompression melting can occur. A hotspot may originate deep within the Earth with a diameter of about 600 miles (1,000 kilometers) in order to produce the large volume of basalt that initially erupts on the surface of the Earth (Griffiths and Campbell, 1990). If the source area were shallow or not very wide in diameter, insufficient material would melt by decompression - far less than necessary to produce the large volumes that erupt from hotspots through Earth's surface.

Rising blobs from ... where?
To interpret Earth's deep interior; let's look at a lava lamp! Think about the light as the heat source that initiates the hotspot. The light is analogous to the bumps on the core that heat up the mantle and cause it to begin to rise. Let the wax be the "hotspot" of rising solid mantle, and the oil represents the rest of the mantle. As the light heats up the wax, it expands and becomes less dense than the oil. When the wax rises it creates a balloon-like diaper on top and stem on the bottom that displays the continuous supply of magma from deep within the Earth (Figure 1.6). The hotter the wax becomes, the more mixing occurs.

Let's follow the upward journey of a hotspot. First, there are the bumps on the core that heat up the lowermost mantle. Second, the hot mantle expands and rises as a ductile, but still solid state. This movement at a few inches per year creates convection or stirring. Third, at about 60 miles (100 kilometers) depth decompression melting occurs, forming diapers of liquid magma (Figure 1.7). Fourth and finally, magma from the rising diapirs may sit and cool in the Earth 2-5 miles (3-7 kilometers) beneath the surface, and erupt at a volcanic summit or along a rift zone.

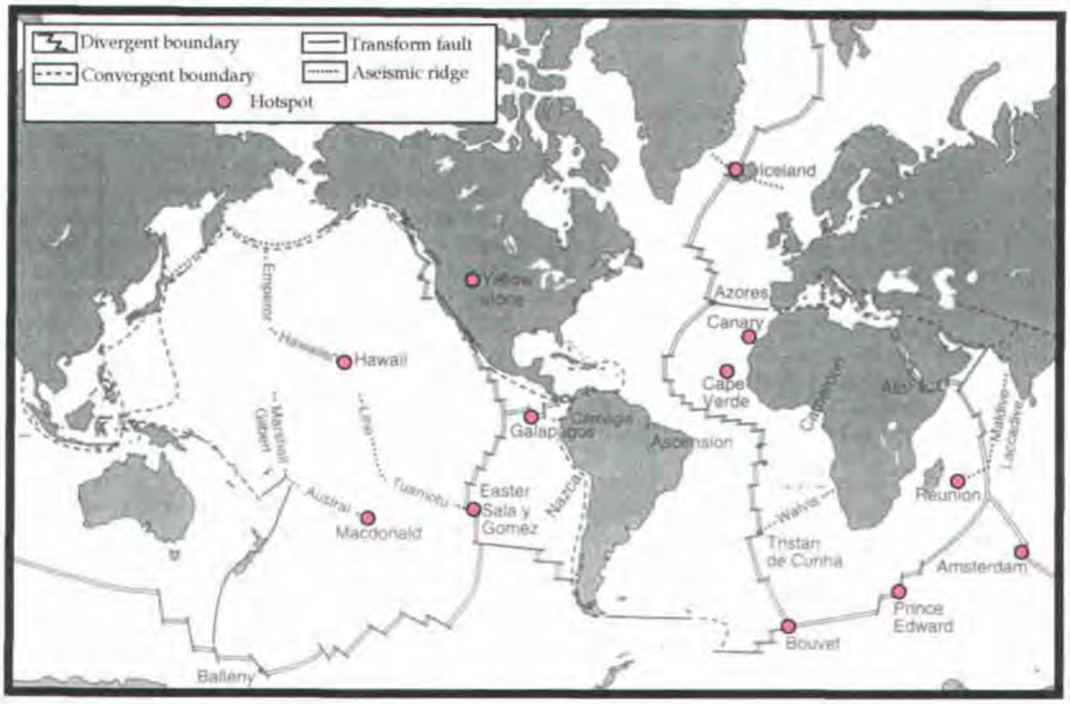


Figure 1.4 – *Hotspots* (Map modified from Moores and Twiss, 1995). Hawai'i and Yellowstone are the best known hotspots in the United States, but there are many other active hotspots in the world. An aseismic ridge is a chain of low islands and submerged volcanoes that results from a hotspot. A seamount is an underwater mountain (commonly a submerged volcano that formed above a hotspot).

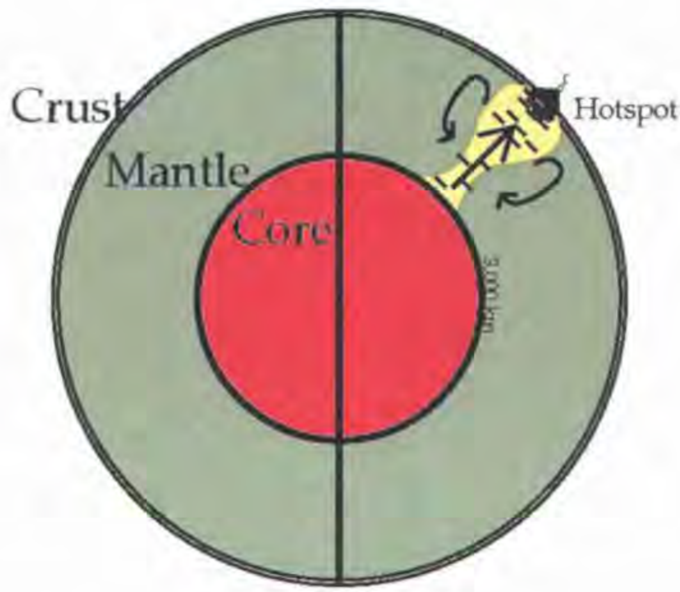


Figure 1.5 – ***Liquid Rock??*** *Decompression* is one method of melting a solid. As hot solid material rises through the Earth, it experiences less pressure and begins to melt between 40-100 miles (60-160 kilometers) beneath Earth's surface. Just as a reminder, material in the Earth travels at VERY slow velocities. It takes more than 10 million years for material to travel about 1,800 miles (3,000 kilometers) from the Core-Mantle boundary to the surface of the Earth (Lambeck and Johnston, 1998). A person lives for about 0.001% of the time required for material to travel from the Core-Mantle boundary to the surface of the Earth!! Melting of material by decompression occurs between 40-100 miles (60-160 kilometers). The yellow represents the region that produces partial melt … the yellow is NOT all liquid. The black specs indicate movement of material. The circular arrows indicate convection of material.

It is interesting to note that the diapirs of rising material are not entirely liquid. There are no large pockets of churning liquid in the mantle (only the chore contains liquid iron). Melt is more on the order of a grain-size scale. How big is that? If you look at a grain of green olivine in a rock on the Kīlauea Iki trail … that is a *large* grain! So I am talking about an extremely small scale! Researchers have done whole PhD theses on experimental studies about movement of liquid along grain boundaries. Even though the average visitor is looking at the broader landscape, it is amazing how something so small is of great importance to researchers trying to understand how the Earth works. Liquid moving along grain boundaries is probably more how magma flows through the shallow portions of the Earth. Near the top of Earth's mantle, magma can be thought of as a mushy blob of mostly solid and a small fraction of liquid rising through the small pore spaces in the Earth (Asimow and others, 1995). By the time a diapir rises to the base of the crust, immediately before eruption, there is probably significantly more liquid in the blob of mush due to decompression melting.

The Hawaiian Islands

The Hawaiian Islands and HAVO provide visitors an opportunity to contemplate the awesome power of volcanic activity generated by a hotspot. How and why does a hotspot result in such incredible sculptures? The Hawaiian island chain is created from a deep source that rises and eventually causes the mantle to melt partially. The liquid melt buoyantly rises (like a "hot-air balloon") and erupts onto Earth's surface. Plate tectonics helps explain why there is a chain of islands instead of one massive island in the middle of the Pacific Ocean. The constant motion of the Pacific Plate eventually transports the island off the hotspot, and a new island forms behind it, leaving a line of volcanoes known as the Hawaiian Ridge-Emperor Seamount Chain (Figure 1.8). The Hawaiian Ridge-Emperor Seamount Chain displays an age progression of older volcanoes to the north-northwest, and younger volcanoes to the south-southeast, further supporting the hotspot idea.

Figure 1.6 – *Geology with a lava lamp!* After your kids outgrow their lava lamp (or you still have yours from the 1960's and 1970's), pull it out of your closet and put it to good use as a hotspot demonstration. (a) Wax sits at the bottom of the lava lamp before the heat is turn on. (b) As the wax begins to heat up, it becomes less dense than the oil and starts to rise. (c) The hot wax forms a balloon-like diaper with a stem that is analogous to the formation of a hotspot.

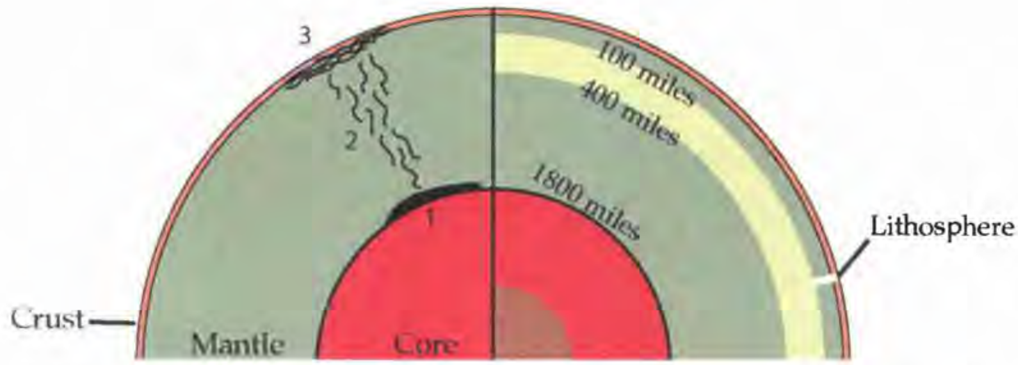


Figure 1.7 – *Journey from the Center of the Earth.* Place yourself inside the Earth at the Core/Mantle boundary, 1,800 miles (2,900 kilometers) beneath our feet. (1) You are a bump about 10 miles (16 kilometers) high and 600 miles (1,000 kilometers) wide. You are hot core material and you make the nearby mantle heat up, expand, and rise in a solid state (2). As you leave the boundary you creep towards Earth's surface at less than a snails pace (a few inches per year), as you *convect* upward. After a long, arduous journey you begin to melt by decompression about 60 miles (100 kilometers) from Earth's surface (3). As trickles of magma migrate the remaining 60 miles, "diapirs" of liquid collect and prepare for eruption (too small to fit in diagram!).

(a)

(b)

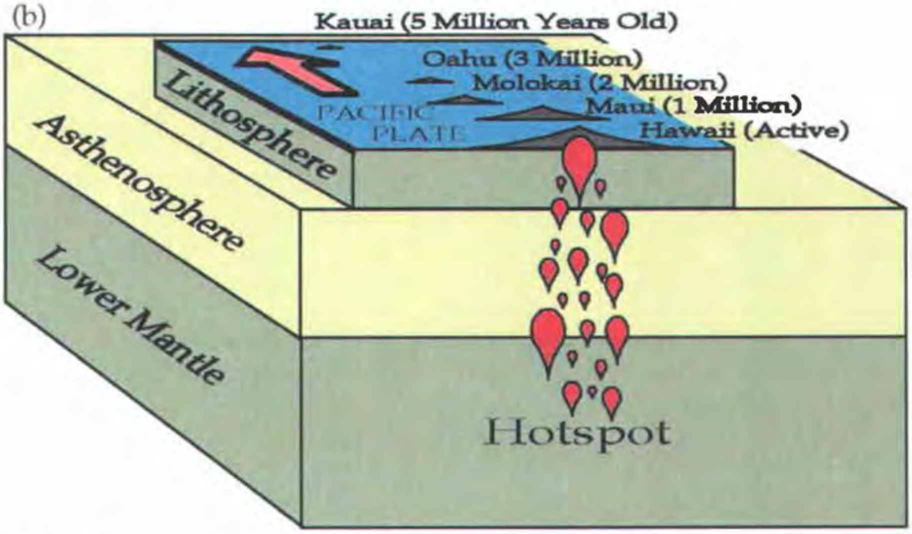


Figure 1.8 – *A Noticeable Scar.* (a) The Hawaiian Hotspot has created the Hawaiian Ridge-Emperor Seamount chain, a 2,200 mile (3,500 kilometer) chain of *active* and *ancient* volcanoes extending from the Aleutian Islands to the Big Island of Hawai'i (from National Geographic Society Physical Globe). (b) Block diagram showing the relationship between a hotspot and the lithospheric plate moving over the asthenosphere (Modified from Whole Earth Geophysics, by R.J. Lillie, ©1999, Prentice Hall., New Jersey).

The Big Island, there HAVO is located, is a conglomeration of five volcanoes. From northwest to southeast, the volcanoes are Kohala, Hualalai, Mauna Kea, Mauna Loa, and Kīlauea. The Big Island is truly big; at over 4,000 square miles (10,500 square kilometers), it is one of the largest volcanic islands in the world, second only to Iceland. The area of the Big Island is greater than that of all of the other Hawaiian Islands put together. Yet you can drive around it in 4 hours!!

What makes one volcano, Mauna Loa or Kīlauea, look like an inverted plate or chocolate Vanilla Wafer™, while another, Mt. St. Helen's, look like a cone or a Hershey's Kiss™ (Figure 1.9)? People of the Pacific Northwest are very concerned with volcanic eruptions. Mt. St. Helen's erupted violently on May 18, 1980. But that volcano is vastly different from the volcanoes in Hawai'i, not only in the way the rocks melt but also, in the size and shape of the volcano. The chemical differences in the material that melts at a hotspot, compared to that at a subduction zone, result in different processes to produce different volcanic shapes (Figure 1.10).

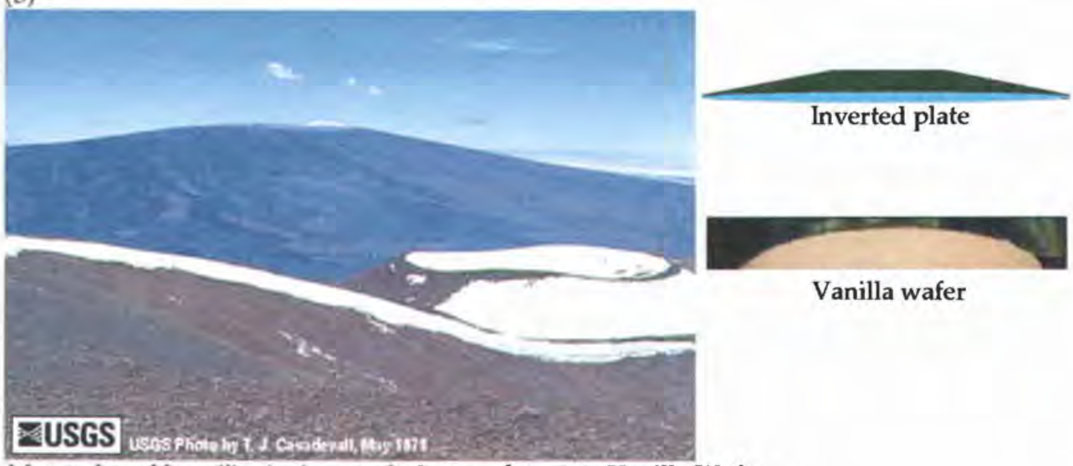
Igneous Rocks and Magmas

Igneous rocks are classified based on their chemical composition (% silica) and texture (size of mineral grains) (Table 1.1). Silicates are compounds of the elements silicon (Si) and oxygen (O). The percentage of silica in a rock influences many properties of magma and the igneous rock that forms. In Hawai'i there is basically one type of igneous rock, basalt, a relatively low-silica rock. Geologists study the subtle differences between rocks in Hawai'i leading to a plethora of names, but basically, the rocks are all basalt.

(a)

Cotopaxi, Mexico - A cone or Hershey's Kiss

(b)

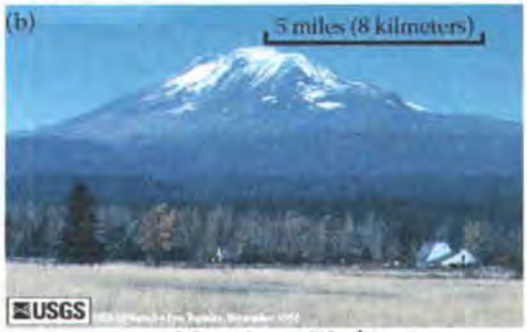


Mauna Loa, Hawai'i - An inverted plate or chocolate Vanilla Wafer.

Figure 1.9 – *Volcanism at a convergent plate boundary (subduction zone) compared to oceanic hotspot volcanism.* (a) Cotopaxi, Ecuador has the *steep-sided* cone shape developed where the Nazca Plate subducts beneath South America (Courtesy USGS). Lava that erupts out of a volcano at a *convergent plate boundary* is much *higher* in *silica,* causing it to be *stickier.* Because lava does not flow downhill very well, it piles up to form a steep-sided composite volcano. (b) Mauna Loa, Hawai'i has an inverted plate or Vanilla Wafer shape developed at an oceanic hotspot (Courtesy T.J. Casadevall, USGS). Lava erupted out of an *oceanic hotspot* is *lower* in *silica* and therefore *very fluid.* The lava can flow great distances creating a broad, gently sloping *shield volcano.*

Composite Volcanoes

Mt. St. Helens, Washington

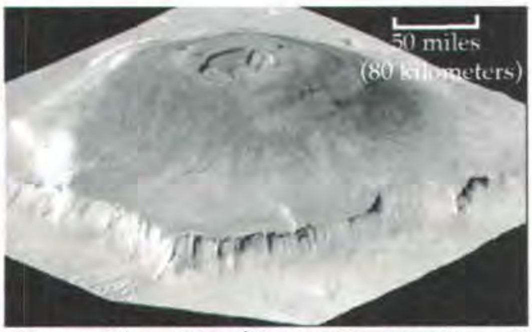


Mt. Adams, Washington

Popocatépetl, Mexico

Shield Volcanoes

Mauna Loa, Hawai'i



Olympus Mons, Mars (Vertical Exaggeration = 2X)

Figure 1.10 – *Examples of composite compared to shield volcanoes.* (a) Mt. St. Helens, Washington (Photo courtesy L. Topinka, USGS), (b) Mt. Adams, Washington (Photo courtesy of L. Topinka, USGS), and (c) Popocatépetl, Mexico (Photo courtesy J.W. Ewert, USGS), are all composite volcanoes that develop at subduction zones from *high-silica* material. The black lines on Mt. St. Helens represent the top of the mountain before the 1980 eruption. (d) Mauna Loa, Hawai'i (Photo courtesy D. Little, USGS) and (e) Olympus Mons, Mars (Photo courtesy NASA) are shield volcanoes that develop at hotspots from *low-silica* material. Notice the difference in shape, profile, and size of the composite volcanoes compared to the shield volcanoes.

Table 1.1 - CLASSIFICATION and PROPERTIES of IGNEOUS ROCKS and MAGMAS

		CHEMICAL COMPOSITION (% Silica)			
		40%	50%	60%	70%
TEXTURE	Glass				*Obsidian*
	Fine Grained (Volcanic)		*BASALT	*Andesite*	*Rhyolite*
	Coarse Grained (Plutonic)	*Peridotite*	*Gabbro*	*Diorite*	*Granite*
	Very Large Crystals			*Pegmatite*	
Common Minerals		Olivine	Pyroxene, Plagioclase-Feldspar	Amphibole	Quartz, Orthoclase-Feldspar
Viscosity of Magma			Low ⟷ High		
Extent of Lava Flows			Large Area ⟷ Small Area		
% Volotile Fluids			1% ⟷ 10%		
Type of Eruptions			Quiet ⟷ Explosive		
Types of Volcanoes			Shield ⟷ Composite Cinder Cone ⟷ Lava Dome		

*Basalt is the composition of almost every rock on the Hawaiian Islands.

Table 1.1 – Classification and Properties of Igneous Rocks and Magmas. Rocks that form from molten Earth material (magma) are igneous rocks. All volcanic rocks are igneous rocks, but not all igneous are volcanic (some are plutonic). The type of igneous rock depends on the types of minerals (compounds of different elements) found in the rock. Two of the key elements in igneous rocks are silicon and oxygen, forming silicate compounds. Window glass and the mineral quartz are made of pure silica (SiO_2). The only igneous rock type found in Hawai'i is basalt (~50% silica). The amount of silica influences viscosity, which in turn controls extent of lava flows, % volatile fluids, explosivity, and types of volcanoes (Modified from R.J. Lillie).

The higher the silica content of magma, the stickier or more viscous it tends to be. The amount of silica determines how well lava flows, which in turn controls volcanic mountain shapes and explosivity of the eruptions. High-silica lavas do not flow very well (more viscous), thus creating explosive and steep conical composite volcanoes. Low-silica magmas are less viscous and flow more easily, so the lava can travel farther away from the eruption site creating broader, more gently-sloping shield volcanoes (Figure 1.11). Compare old, crystallized honey and fresh honey. If you pour the crystallized honey onto a table, it will not flow as easily as the fresh honey. One way to make honey crystallize is to add sugar. Because crystallized honey does not flow as well as fresh honey, it is highly viscous. The thickening agent, sugar, in the honey is comparable to the thickening agent, silica, in igneous rocks. From this analogy, what process might increase viscosity? Hopefully you thought of the crystallization of mineral grains that occurs as molten Earth material cools and hardens into a rock.

High-silica magmas that erupt from Cascade volcanoes like Mt. Rainier and Mt. St. Helens in the state of Washington, and Mt. Hood in Oregon, pile up close to the vent to form steep, cone-shaped composite volcanoes. But low-silica magma that erupts from Hawaiian volcanoes flows easily down-slope far away from the eruption vents, resulting in broad, gently-sloping shield volcanoes.

Kaboom!!! Well ... maybe not.

Not only does silica affect the viscosity of magma, it ultimately controls the explosivity of a volcanic eruption. Think about when you make cranberry sauce for Thanksgiving. You simply add the cranberries, a lot of sugar and a bit of water. Once you heat it all up it is more viscous (sticky) than pure water. If you boil the cranberry sauce it will splatter and explode out of the pot and leave red drips all over the stove. When pure water boils, it releases the bubbles in a relatively calm manner, creating no mess on the stove. High silica magmas forming composite volcanoes are analogous to cranberry sauce, while low silica magmas that build shield volcanoes flow more like water.

Another way to think of the explosivity of a volcano compares to a can of Coca-Cola™. If you shake a can of soda and pop it open, it will explode like a high-silica, composite volcano, whereas if the gases are released slowly, it acts more like an effusive, low silica, shield volcano.

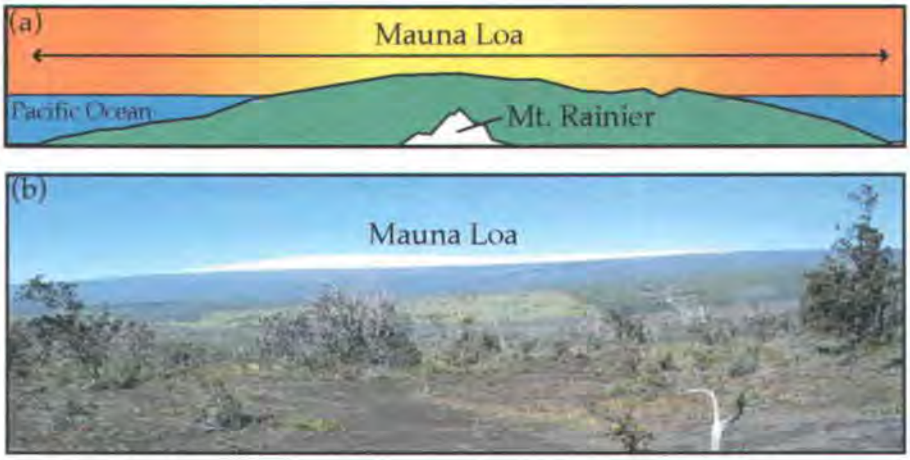


Figure 1.11 – *Sizing up the competition!* (a) The *size* and *profile* of a large composite volcano, Mt. Rainier in Washington state, compared to a large shield volcano, Mauna Loa, (Modified from NPS). The diagram illustrates that hotspots spew enormous amounts of volcanic material compared to subduction zones. From the base of Mauna Loa to the top of the mountain is about 32,000 feet (9,800 meters). Mt. Rainier is puny at ~14,000 feet (~4,300 meters). Mt. Everest, the highest elevation on land, is ~29,000 feet (~8,800 meters) above sea-level. (b) Photo of Mauna Loa (Courtesy D.A. Swanson, USGS).

Why do high-silica lavas erupt at convergent plate boundaries like the Cascade Mountains or continental hotspots such as Yellowstone, while low-silica lavas erupt from the Hawaiian hotspot? What makes the Yellowstone hotspot differ from the Hawaiian hotspot? There is a two-part explanation; mixing and fractionation. First, the entire mantle is composed of peridotite, an extremely low-silica rock. So, how does liquid that melts off the mantle rock produce magma with somewhat higher-silica content? Peridotite has about 40% silica. But the peridotite only partially melts, producing magma with about 50% silica (basaltic magma composition). Where magma rises through the crust, it melts and mixes with material along the way. Thin oceanic crust is composed of low-silica rocks (gabbro and basalt), whereas much thicker continental crust is usually made up of rocks with higher-silica content (granite, rhyolite, diorite, andesite). When a partial melt of peridotite (basaltic magma) travels through oceanic crust, it melts and mixes with gabbro and basalt; lava of the same low-silica composition (basalt) erupts from volcanoes. Low-silica rock, basalt, dominates at oceanic hotspots and mid-ocean ridges where the crust is thin and of basaltic composition (Figure 1.12). On the other hand, if a partial melt of peridotite (basaltic magma) travels through thick continental crust of granite or diorite, it melts and mixes with a lot of the silica in those rocks. The resulting magma is enriched in silica as it rises through the crust, producing rhyolite to andesite lavas at subduction zones (Pacific Northwest) and continental hotspots (Yellowstone). Even though Yellowstone is a region of high-silica eruptions, it does not display steep conical volcanoes because eruptions are so large and explosive that they scatter everything across the landscape; the last major eruption, about 600,000 year ago, created a caldera of ~40 miles (~60 kilometers) across.

High-silica rocks are also generated through a process known as fractionation. Fractionation is the separation of minerals and liquid. When magma begins to cool, low-silica minerals like olivine form first, causing the remaining liquid magma to be somewhat higher in silica. During eruption, different types of lava have different physical properties (temperature, density, viscosity) that affect how material flows and moves down-slope. If you think about common materials that you use every day you might be able to imagine some properties of lava. For example, if you compare ice-cold maple syrup and hot maple syrup, the hot syrup will flow and spread out faster than the cold syrup. The properties of hot and cold maple syrup thus differ depending on temperature. But not all maple syrups are the same. Some have more sugar, which also affects viscosity. Viscosity helps determine the temperature at which the magma will erupt. Table 1.2 is a break down of different types of magma and their eruption temperature, density, and viscosity, along with a comparison to water.

Table 1.2 - Physical Properties of Lava Flows compared to Water

	Eruption Temperature	Density @ Eruption Temperature(g/cm^3)	Viscosity @ Eruption Temperature* (Pa s)
Basalt (45-52 wt % SiO_2)	1920 - 2200°F (1050°-1200°C)	2.6-2.8	10^2-10^3
Andesite (57-63 wt % SiO_2)	1740 - 2140°F (950°-1170°C)	2.45	10^4-10^7
Rhyolite (>70 wt% SiO_2)	1300 - 1650°F (700°-900°C)	2.2	10^9-10^{13}
Water (at room temperature)	68°F (20°C)	1.0	10^{-3}

Kilburn, C.R.J, 2000

°C – degrees Celsius
°F – degrees Fahrenheit
g/cm^3 – grams per cubic centimeter
Pa s – Pascal seconds
* – Newtonian approximation at low shear rate

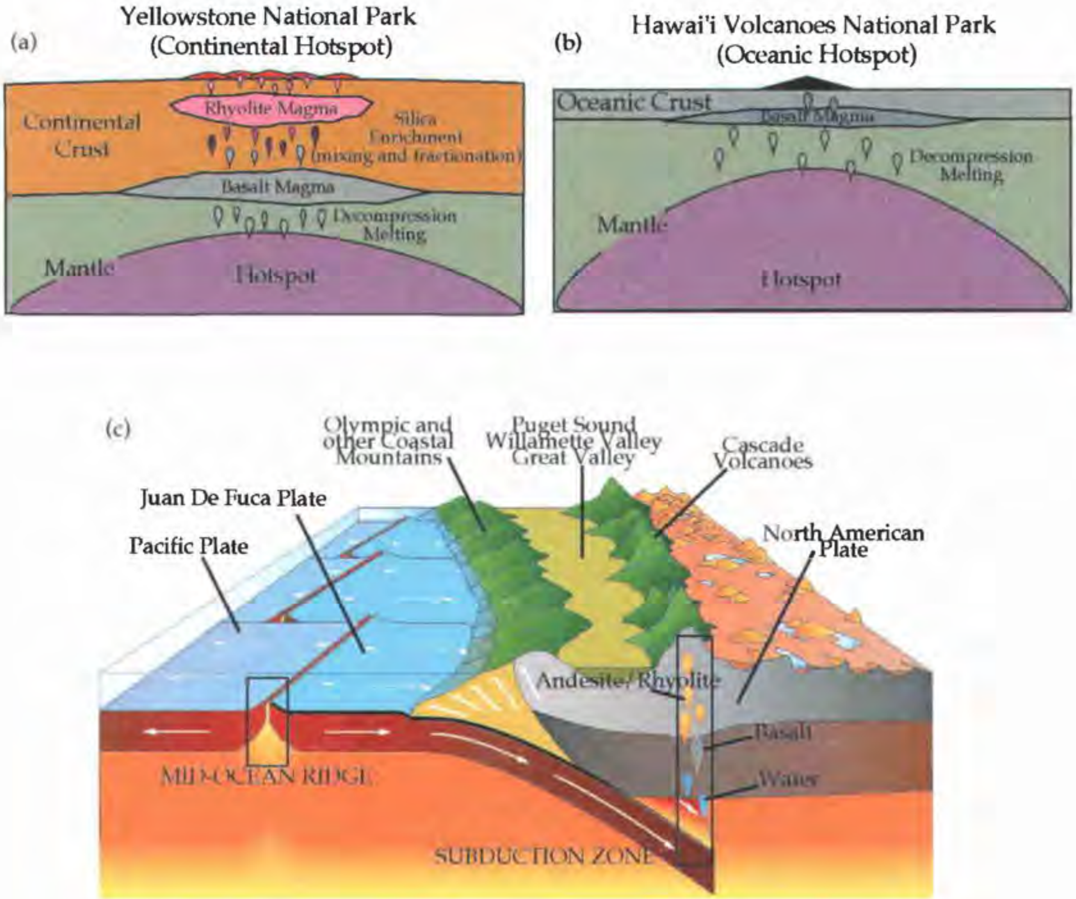


Figure 1.12 – *Development of crustal magmas from initial melting of Earth's mantle.* The mantle composition is peridotite, a very *low-silica* rock. As peridotite partially melts, basaltic magma is created in *both* hotspot and subduction settings. (a) If basalt travels through a *thick, continental* crust made up of *higher-silica* material in a continental hotspot setting, the basaltic magma will be *enriched* in silica to create rhyolite and andesite. (b) If basaltic magma travels through a *thin, ocean* crust made up of *low-silica* material in a mid-ocean ridge or oceanic hotspot setting, the magma will remain similar in composition to basalt. (c) Similar to a continental hotspot, if basaltic magma travels through a *thick, continental* crust made up of *higher-silica* material in a subduction setting, the magma will be *enriched* in silica to create andesite and rhyolite (Modified from R.J. Lillie).

Everyone is familiar with water and realizes that it flows freely – that is, it has *extremely low viscosity*. Increasing viscosity means that material gets thicker, and pastier, and thus does not flow as easily. According to Table 1.2, rhyolite magma is 10^7-10^{10} (10 million to 10 billion) times more pasty than basalt magma and 10^{12}-10^{16} (over 1 trillion) times more pasty than water! If you look at the temperature column, lava is hot stuff. 68°F (20°C) is about room temperature, so 2200°F (1200°C) is hotter than hot! In fact, it is about 5 times hotter than your oven on its highest setting. Depending on the color of flowing lava, you can estimate the temperature (Table 1.3). Determining the temperature of lava by color is similar to a gas stove. When you turn on the stove, the flame near the base is the hottest and displays a violet or blue color. As you look away from the base of the flame is goes from violet or blue (hottest), to yellow, orange, and then red (coolest, but still hot!). If you are in Hawaii, most of the lava you may catch a glimpse of is a reddish color, which is significantly cooler than when it first came out of the ground. Beware if you walk across fresh, black lava rock, it can melt through your shoes easily!

<u>Table 1.</u>3 - Temperature determines the color of a radiating body, like flowing lava.

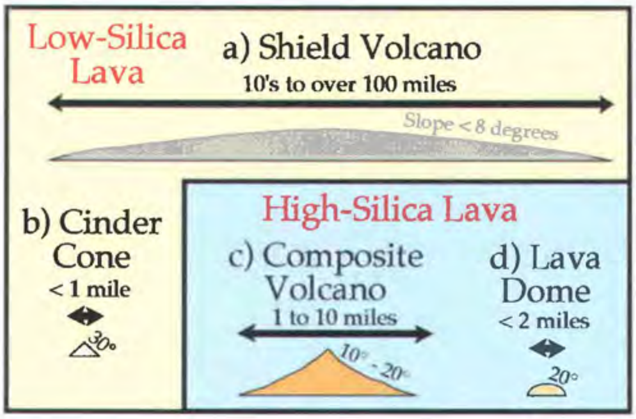
Temperature	Color of Lava Surface
2100°F (1150°C)	White
2000°F (1090°C)	Golden Yellow
1650°F (900°C)	Orange
1300°F (700°C)	Bright Cherry Red
1000°F (600°C)	Dull Red
890°F (475°C)	Lowest Visible Red

Kilburn, C.R.J, 2000

(a) Mauna Loa (Hawai'i) a shield volcano.

(b) Pu'u Pua'i (Hawai'i) a cinder cone.

(c) Mt. Rainier (Washington) a composite volcano.



(d) Novarupta (Alaska) a lava dome.

Figure 1.13 – *Low-silica and high-silica magmas produce different eruption styles and landscape features. Non-violent* eruptions at hotspots in Hawai'i and Iceland produce shield volcanoes and cinder cones made of *low-silica* lava (basalt). *High-silica* lava (andesite and rhyolite) produce *violent* eruptions that create composite volcanoes and lava domes such as those seen at subduction zones on the west coasts of North and South America, and in Japan, and the Philippines. Schematic courtesy of R.J. Lillie, (a) Photo courtesy of D.A. Swanson, USGS, HVO, (b) R.H. Ashton, (c) Photo courtesy of L. Topinka, USGS, (d) Photo courtesy of USGS.

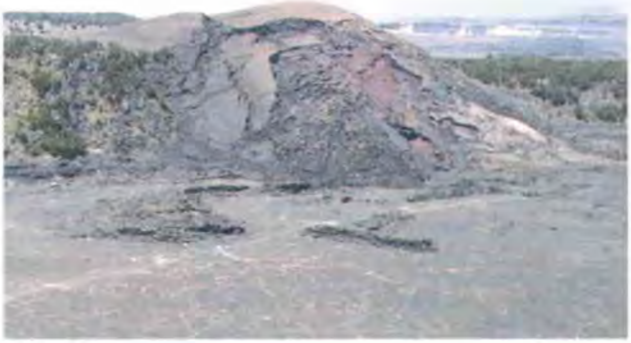
Types of Volcanoes

Volcanic landforms made out of low-silica rocks like basalt form broad shield volcanoes (Figure 1.13). A shield volcano can be over 60 miles (100 kilometers) in diameter, with gentle surface slopes typically less than 8°. The name relates to the low-profiled shape of a warrior's shield, especially apparent when viewing these features from the air.

> *Looks are deceiving!*
> If you drive around the base of a large shield volcano you would likely have to travel over 200 miles (300 kilometers)! That would take over 3 hours if you drive at 60 miles per hour! But the base of a Hawaiian volcano is typically not the shoreline. To get to the base of Kīlauea volcano, for example, you would have to swim 12 miles (20 kilometers) offshore and dive into over 16,500 feet (~5,000 meters) of water! Looking at another perspective, the Statue of Liberty spans 305 feet (93 meters) from the ground to the tip of the torch. It would take more than 54 statues on end to reach the ocean floor from sea level.

Another type of volcano produced by the eruption of fluid basaltic magma is a cinder cone. A cinder cone is different from a shield volcano in shape and eruption style. When basalt retains some gas, the eruption will be more like a lava fountain shooting up into the air. The resulting "cinders" rains down onto the ground creating a steeper-sided cone as opposed to the dribbling out of a vent that would produce a broad shield volcano. The slope of a cinder cone is about 30°. Pu'u Pua'i and Pu'u 'Ō'ō are the best known examples of cinder cones in the park. Pu'u Huluhulu is an older cinder cone that is now covered in vegetation because it formed about 400 years ago – old for landforms seen on Kīlauea, but relatively young by geologic standards (Figure 1.14).

> *What do cinder cones and hour glasses have in common?*
> As the sand pours through the hour glass, it piles up forming a cone with a slope of about 30° (Figure 1.15). Cinder cones will not become any steeper because the slopes will collapse back to a lower angle. In other words, the cinders pile up to a steeper and steeper angle until the friction can no longer hold the steep slope. If the slope was any steeper than 30°, cinders would slide downhill, decreasing the slope to 30°. As with the sand in the hour glass, the steepest stable angle is called the angle of repose.



(a) Pu'u Pua'i

(b) Pu'u 'O'o

(c) Pu'u Huluhulu

Figure 1.14 – *Cinder cones in Hawai'i Volcanoes National Park.* Pu'u Huluhulu, near Mauna Ulu supports vegetation because it is 400 years older than Pu'u 'Ō'ō and Pu'u Pua'i. Pu'u Pua'i developed during the 1959 eruption of Kīlauea Iki and Pu'u 'Ō'ō grew during the beginning stages of the current eruption of lava (between 1983 and 1986 and partially collapsed in 1997). (a) Photo courtesy of USGS, HVO, (b) Photo courtesy of USGS, HVO, (c) Photo courtesy of N. Nesvadba, USGS, HVO.

Figure 1.15 – *How can an hour glass explain the shape of a cinder cone?* (a) As sand filters through an hour glass it builds a cone with approximately 30° slope. A steeper slope is unstable and falls away, recreating the 30° slope. (b) A cinder cone forms from a "fountain" eruption of gaseous basaltic material that rains back down to build up a cone with a slope of about 30°. (c) Kīlauea Iki erupting and forming Pu'u Pua'i cinder cone in 1959 (Photo courtesy USGS, HVO). (d) A look inside a cinder cone showing the 30° slope and deposition of layers of cinder (Capulin Volcano National Monument, New Mexico, photo courtesy R.J. Lillie).

Higher-silica rocks create composite volcanoes (or stratovolcanoes) that generally have base diameters of up to about 10 miles (16 kilometers). Some prominent examples include Mt. Fuji in Japan, Mt. Shasta in the Cascade Mountains of the Pacific Northwest, and Arénal and Galèras volcanoes in Central and South America, respectively. If you notice, all of those volcanoes occur on top of thick continental rock. Recall that composite volcanoes are often a product of subduction and the sweating of hot water that rises, melting and fractionating the continental crust to produce magma with enriched silica content. When composite volcanoes erupt, they are sometimes explosive like Mt. St. Helens. There is commonly an eruption of ash and thick, pasty lava. Lava domes may form during an eruption of a composite volcano. They are commonly found inside summit craters and have base diameters less than about 1/3 the base size of the composite cones. As thick, pasty lava is extruded onto the ground, it cannot flow very far and will locally build up to form the dome shape.

Here is some "food" for thought:
A composite volcano may be represented by a Hershey Kiss™, while a shield volcano is like a chocolate vanilla wafer. Somewhat smaller cinder cones and lava domes may be thought of as chocolate chips and M&M's™, respectively.

Chapter Two

Volcanic Landforms in Hawai'i Volcanoes National Park

"This lava is the accumulation of ages; one torrent of fire after another has rolled down here in old times, and built up the island structure higher and higher. Underneath, it is honeycombed with caves ..."
- Mark Twain's Letters from Hawaii (Day, 1966)

A few questions from curious visitors ...

- *What is the difference between a caldera and a crater?*
- *How deep to the floor of Halema'uma'u crater and Kīlauea caldera?*
- *Can scientisits predict earthquakes in Hawai'i?*
- *Can you "feel" the volcano when it starts to erupt?*
- *Is there more steam in the caldera before a summit eruption?*
- *When was the last eruption?*
- *How much warning do you have before an eruption?*
- *How do you tell that there is going to be an eruption?*
- *What is Pele's hair?*

The internal anatomy of Kīlauea Volcano

Visitors converge at Hawai'i Volcanoes National Park to experience the landscape. The surface volcanic features that fascinate them are products of things happening deep beneath their feet. Magma originally melts from decompression of mantle rock about 40-100 miles (60-160 kilometers) below the surface. It migrates up towards the surface and usually sits in a shallow reservoir at 2-5 miles (3-7 kilometers) beneath the volcano before it erupts at the summit or travels down a rift zone (Tilling and Dvorak, 1993). Resulting landforms include collapse of the summit to form a caldera, lines of cinder and spatter cones along rift zones, and other effects the flowing lava has on the land. Rangers can spark visitors' minds as they venture out on a journey through the park experiencing spatter ramparts, cinder cones, twisted and tangled lava flows, Pele's hair, bombs, and other features telling stories through their shapes. For example, spatter ramparts display remnants from the process of a curtain of lava erupting from the ground. The twisted and knarled lava flows or volcanic bombs strewn about the ground may tell how much gas was trapped in the lava. The mere shaking of the ground (earthquakes) may indicate magma rising to shallow chambers, perhaps forecasting the onset of an eruption.

When the Earth Rattles ...

Earthquakes, along with lava flows, are a hazard concern in Hawai'i. During the course of a year, there are thousands of earthquakes. Many of them are so small that only instruments detect them (Figure 2.1). As Californians know, an earthquake's size can be measured by the Richter scale. An increase of one number on the Richter scale increases the amplitude of the wave on a seismograph recording by ten times. Most earthquakes in Hawai'i are related to the injection or movement of magma, although some are caused by the slumping of various parts of the island, such as the south side of Kīlauea. The probability of an earthquake increases with the length of time the rift zones remain active. However, it is impossible to predict the exact time and magnitude of an imminent earthquake. Even though most earthquakes are not felt or cause any damage, when a large one hits, the result can be devastating. Large earthquakes may create cracks in the ground and building structures, initiate landslides and mudflows, or break sewer, water, and power lines. If the conditions are right (size, depth of earthquake, and fault displacement), earthquakes may create a tsunami that will innundate coastal areas with water.

Geologists are constantly monitoring certain factors to determine when and where a volcanic eruption might occur. (1.) Earthquakes help predict volcanic eruptions. There are often earthquake swarms days to weeks before an eruption occurs that instruments detect even if humans cannot. (2.) Tiltmeters are key instruments that can also "feel" changes within the volcano and possibly forecast a volcanic eruption (Figure 2.2). (3.) Volcanic gas emissions such as carbon dioxide (CO_2) and sulfur dioxide (SO_2) usually increase before an eruption occurs.

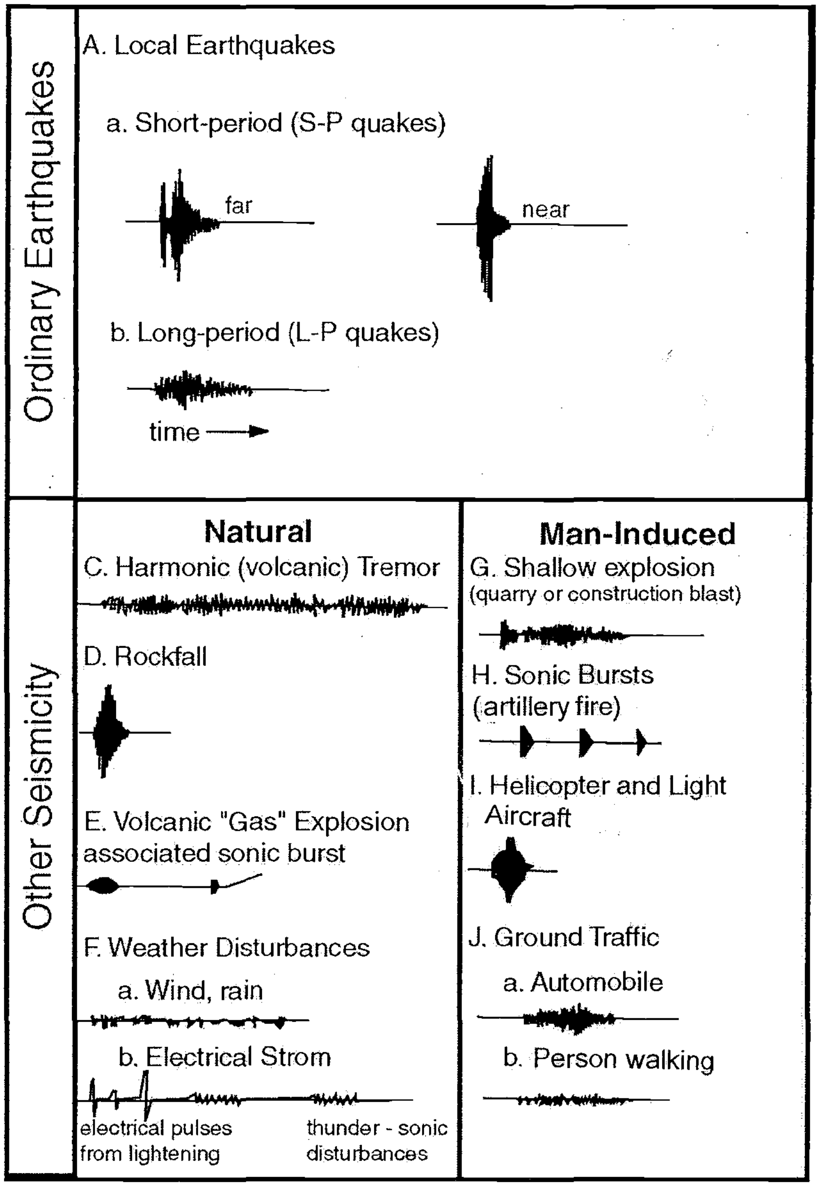


Figure 2.1 – *The feelings of sensitive instruments* (Figure from USGS, HVO). Seismometers detect the thousands of earthquakes that occur in Hawai'i. The figure displays different seismic signals produced by nature and man. Ground movements of all types and sizes are picked up on the instruments. Geologists then translate the type of disturbance and magnitude to decipher what is going on inside the Earth (or if someone is simply walking by the seismometer).

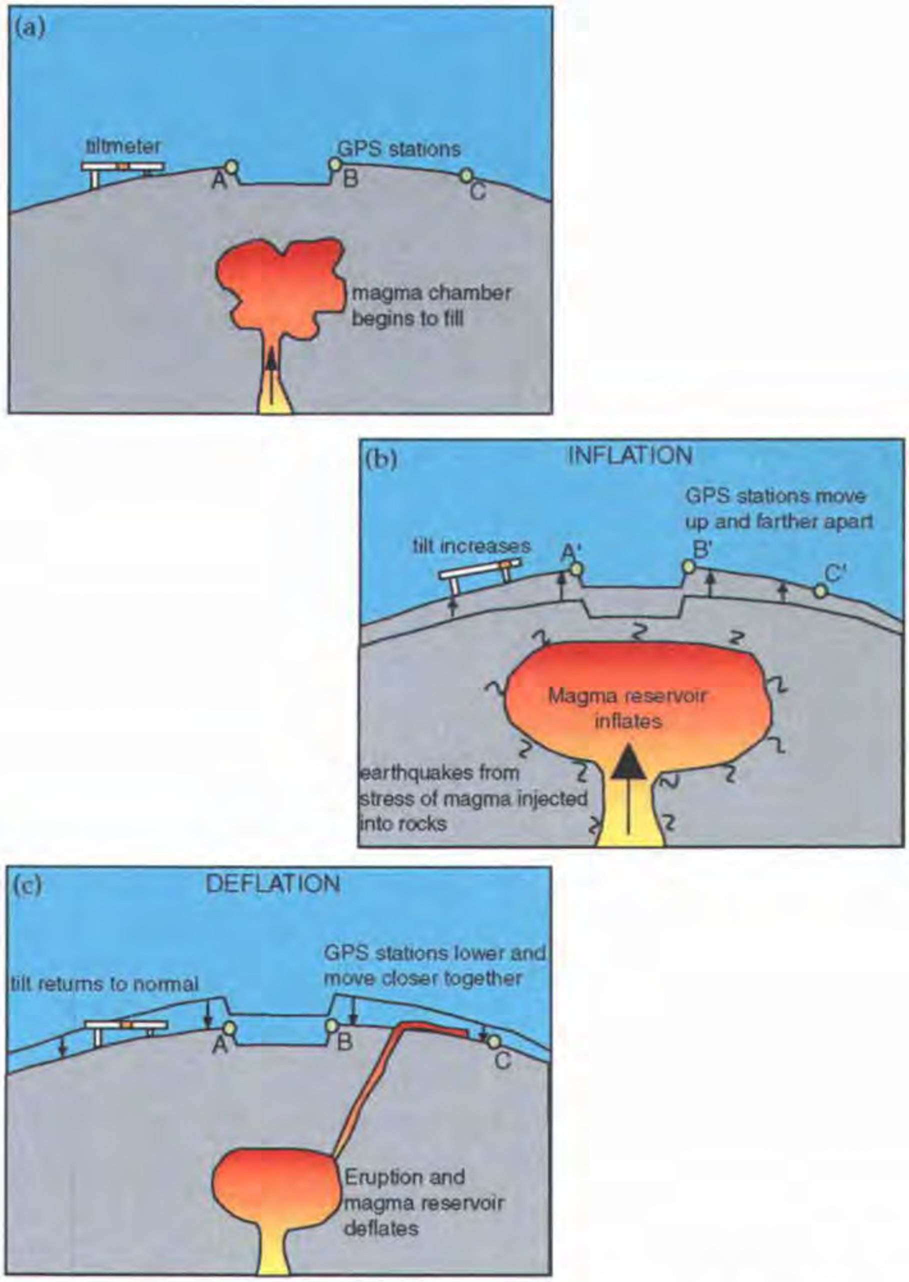


Figure 2.2 – *The tilt of the Earth.* (a) Tiltmeters and GPS stations are devices that "feel" what happens beneath Earth's surface. (b) As magma rises and fills the chamber, the volcano begins to inflate like a balloon. The *tilt* of the volcano *increases* and *GPS* (global positioning stations) move *apart* and *upwards*. (c) After an eruption or possibly without an eruption, the volcano will deflate, returning the *tilt meter* towards *level* and the *GPS* stations will move *closer* together and *downwards* in elevation (Modified from USGS, HVO).

Where is the summit? What lies beneath?

"I am passably good at judging heights and distances, and I fell to measuring the diameter of the crater. After considerable deliberation I was obliged to confess that it was rather over three miles, though it was hard to believe at first ... And when I came to guess at the clean, solid, perpendicular walls that fenced in the basin, I had to acknowledge that they were from six hundred to eight hundred feet high, and in one or two places even a thousand, though at a careless glance they did not seem more that two or three hundred. The reason the walls looked so low is because the basin inclosed is so large."

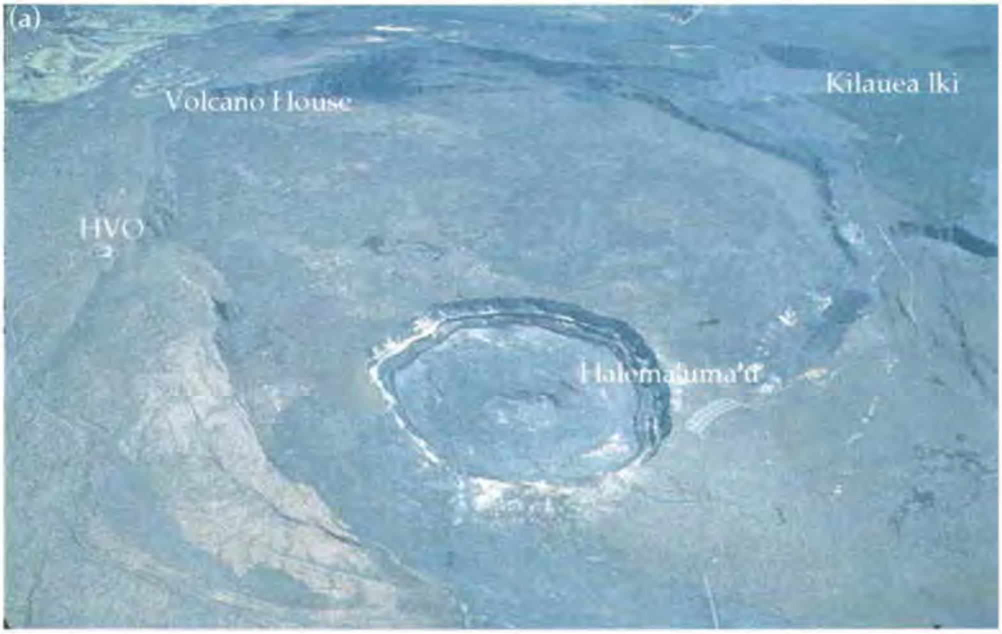
- Mark Twain's Letters from Hawaii (Day, 1966)

(Note: Mark Twain visited Kīlauea when the caldera was much deeper than the present day caldera; it has since filled with about 400 feet (~120 meters) of new lava.)

Only the rim of Kīlauea remains of the summit area of a shield volcano that collapsed upon itself and filled with lava - not just once, but multiple times. One of the main questions visitors ask when they arrive in the Visitor Center is, "Where is the volcano?" One reason they cannot see the "volcano" is the broad shield shape – their image of a volcano is a steep-sided form like Mt. Fuji in Japan or Mt. Hood in Oregon. Another reason is because vegetation covers much of Kīlauea, obscuring even fairly recent lava flows. Finally, rather than a true summit, there is a large caldera at the top of Kīlauea. A caldera is commonly a flat bottomed, bowl-shaped, depressed region of the ground at least 1 mile (1.6 kilometers) in diameter. Kīlauea Caldera is 2 by 3 miles (3 by 5 kilometers) in diameter and 395 feet (120 meters) deep (Figure 2.3).

The floor of the caldera has not always looked the same. Clues from the current topography can reveal some of the past history, but other events are covered up by younger lava flows (Figure 2.4). From the Volcano House, you can see some of the areas of recent lava flows, as indicated on the geology map of the region. There are no current eruptive events within the caldera. The last summit eruption occurred in 1982. The ongoing eruption on the East Rift Zone began in 1983. All we see in the summit are the remains of past eruptions. But eyewitness accounts reveal that there were many lava flows on the caldera floor during the past two centuries, including continuous caldera activity from 1823-1894 and 1907-1923 (Bevens, 1992) (Figure 2.5).

Kīlauea volcano not only erupts lava quietly, but has produced some burps in the past that might be considered "explosive". Basaltic (low-silica) magma mixing with water can trigger violent eruptions. But these burps are much less harmful than explosions from Mt. St. Helens or Mt. Pinatubo (in the Philippines), which involve andesite to rhyolite (high-silica) magmas. Remnants of explosive Hawaiian eruptions, such as large blocks, boulders and ash, are most notable on the south end of the caldera and in the Ka'u desert (Figure 2.6). Below are highlights of some of Kīlauea's activity that visitors observed and documented in the Volcano House Register before there was a volcano observatory.



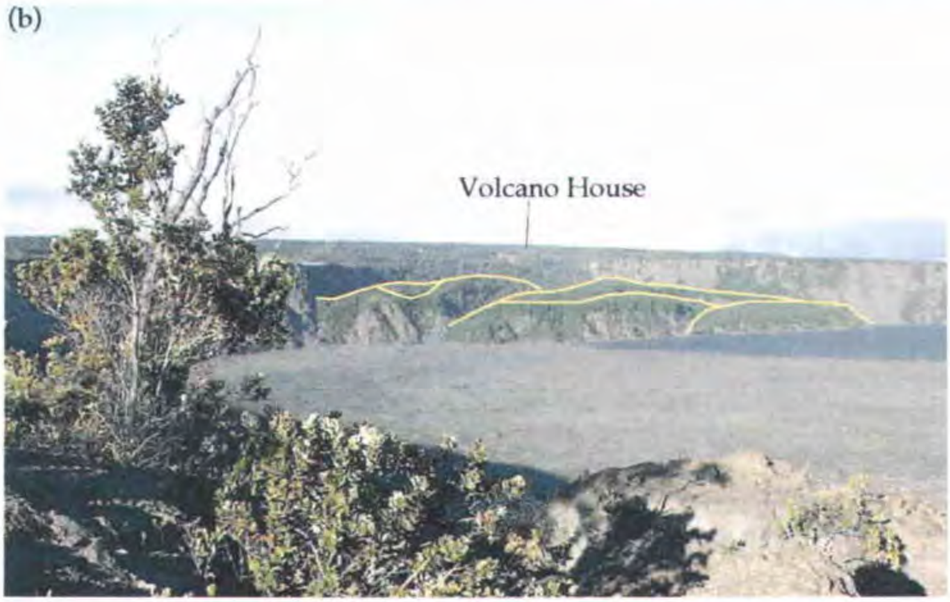


Figure 2.3 – *The hole on top of Kīlauea.* Kīlauea caldera is a bowl-shaped depression with dimensions of 2 by 3 miles (3 by 5 kilometers) in diameter. (a) Aerial view of the entire caldera (Photo courtesy USGS, HVO). (b) View from near Hawai'i Volcano Observatory, looking back towards the Volcano House (Photo courtesy S.R. Brantley, USGS, HVO). *Outlines highlight step-like, down dropped blocks.* These blocks are the result of *collapse* that helped form the caldera. *When hiking into the caldera on Halema'uma'u trail, look for other clues related to caldera collapse!*

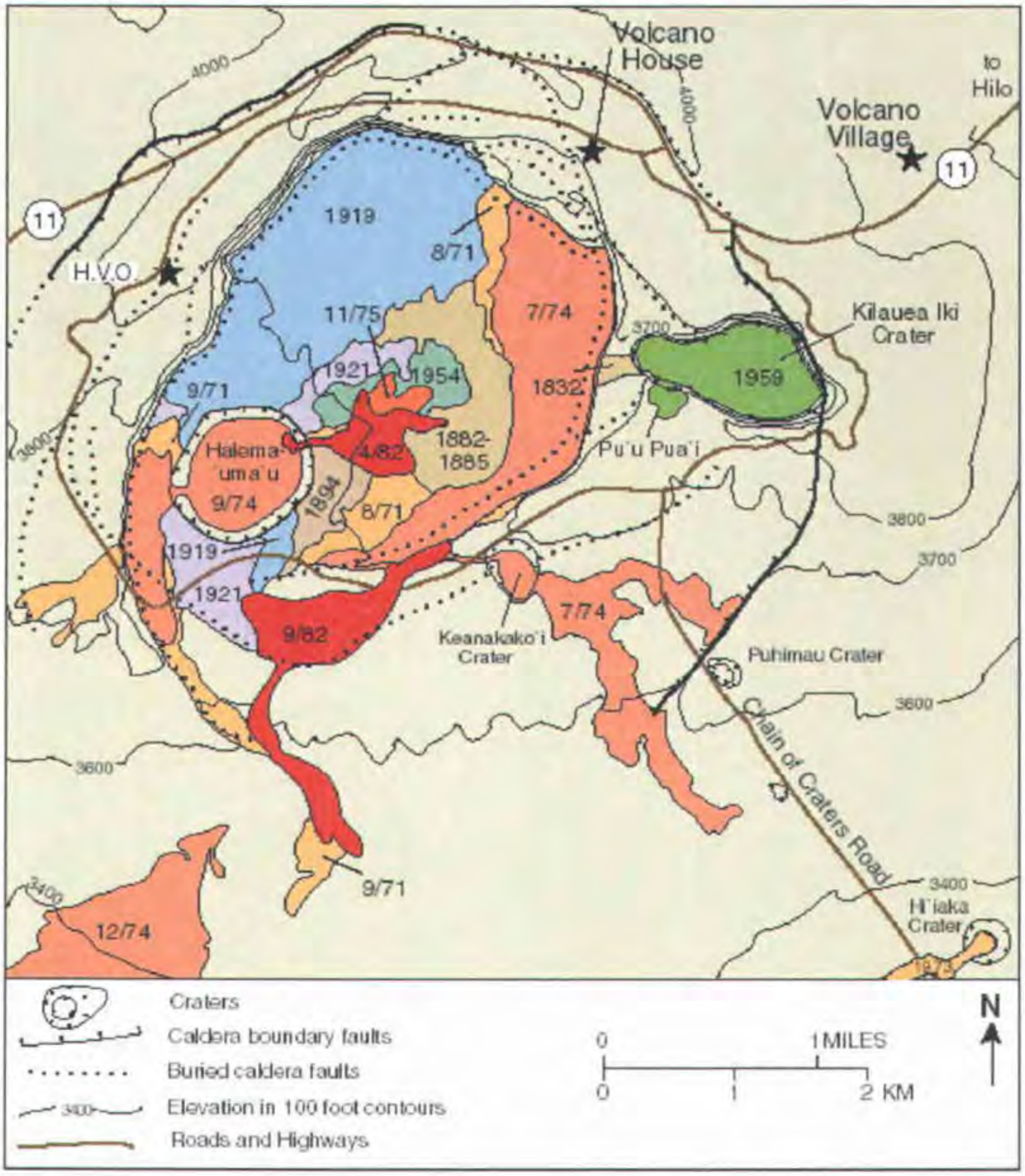
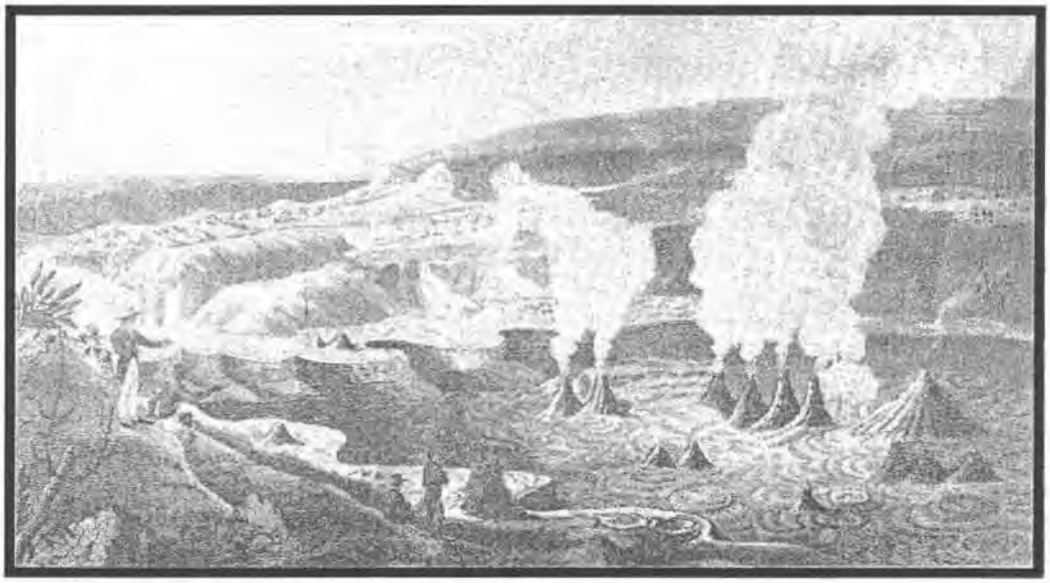


Figure 2.4 – ***Simplified geology map of the summit lava flows*** (Courtesy USGS, HVO). Even though there have not been many lava flows in the summit area in recent times, it is easy to pick out how the various flows have changed the landscape through time. How many flows can you identify as an observer from Volcano House, Jaggar Museum, or during a traverse on Halema'uma'u Trail? Can you match the edges of the flows with this map? About how often do major eruptions occur in the summit region?



I forgot to say that the noise made by the bubbling lava is not great, heard as we heard it from our lofty perch. It makes three distinct sounds - a rushing, a hissing, and a coughing or puffing sound; and if you stand on the brink and close your eyes it is no trick at all to imagine that you are sweeping down a river on a large low-pressure steamer, and that you hear the hissing of the steam about her boilers, the puffing from her escape pipes, and the churning rush of water abaft her wheels. The smell of sulphur is strong, but not unpleasant to a sinner.
- Mark Twain's Letter from Hawaii (Day, 1966)

Figure 2.5 – *Some of the first white man's perceptions.* Kīlauea caldera as viewed by Ellis in 1823 (Sketch courtesy of NPS, HAVO). Ellis was the first missionary to see Kīlauea and become captivated by its volcanic mysteries. Mark Twain visited Hawai'i in 1866 to capture the landscape in words.

(a)

(b)

(c)

Figure 2.6 – *Can Kīlauea be an explosive volcano?* Explosive eruptions leave markers like these large blocks in the south end of the caldera. The two most recent explosive eruptions occurred in 1790 and 1924. (a) Don Swanson, the head of Hawaii Volcano Observatory, explains that a boulder was thrown with such force from an explosive eruption that it broke through the top layer of a lava flow. (b) Large boulder from the 1790 eruption of Kīlauea. (c) Scattered debris from explosive eruptions of Kīlauea. Photos in (a) and (b) by R.H. Ashton; (c) Photo courtesy of S.R. Brantley, USGS, HVO.

History ...
Kilauea is dry, for the first time since 1840, when Kilauea emptied its liquid contents through subterranean conduits in the flow which reached the sea at Nanawali in Puna. This time it seems to have sent them underground a distance of forty miles to rise in the destructive eruptions at Kahuku in Kau. We have today made a full circuit of the crater and not found a trace of liquid lava, not a vestige of the incandescent lakes remaining, in place of them vast pits, with beetling toppling walls, of frightful desolation. At least two-thirds of the area of the crater towards W. and N. W. have caved in and sunk about 300 feet below the level of the remaining portion of the old floor. The bottom of Kilauea Iki, formerly covered in thick vegetation, is now floored with black lava which rose in it between 6 and 10 P.M. on April 4.
- William Hillebrand, 18 April 1868

(The events described above occurred after an earthquake and landslide on April 2, 1868. In addition to the draining of the lava lakes, there was an eruption on the southwest rift zone of Kīlauea and the southwest rift zone of Mauna Loa.)

When I first saw this crater (September 5, 1866) the action was confined to the North and South Lakes, but it increased gradually, till, just before the Great Earthquake of April 2nd, 1868, there were 12 lakes in active operation, beside many cones. On the night of the 2d of April the appearance of the crater was grand beyond description, nearly whole surface being covered with the liquid lava. For two weeks after the earthquake there was no fire to be seen in the crater, but it is again in action, and promises to equal its former grandeur – in time. The center of the crater has dropped all of 300 feet below its former level.
- Chas. E. Stackpole, San Francisco, 16 Aug 1868
(Volcano House Register, 1865-1872)

Confusion often enters one's mind when reading text about the history of eruptions and the various stages of Kīlauea. And the visiting public generally does not really care unless they can visualize how eruptions fit into the life of Kīlauea. A chronological tabulation, like Table 2.1, with an accompanying activity description, can help.

Table 2.1 – Chronology of Kīlauea Summit (and other) activity
Bold Italics indicates summit changes

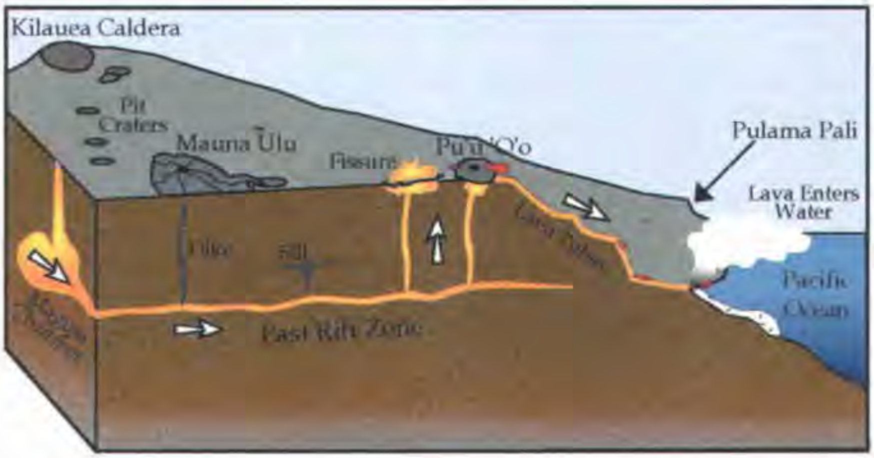
1823 – 1923 → Continuous summit lava lake	1955 – 1974 → Frequent ERZ eruptions
1823 – Southwest Rift Zone (SWRZ) eruption *1832 – Outbreaks near summit rim* 1840 – Lower East Rift Zone (ERZ) eruption destroyed Nanawale *1868* – SWRZ eruption, *outbreaks near caldera rim* *1877 – Outbreaks near summit rim* *1894 – 1907 – No continuous summit lava lake* 1919 – 1920 – Mauna Iki built	1955 – Eruption spanned 50 feet (15 meters) of mid to lower East Rift Zone ***ENDED 150 year repose of ERZ (no ERZ eruptions from 1840 – 1954)*** 1956 (July) – Modern seismic and ground deformation studies begin ****Big development for science**** *1959 (November – December) – Kīlauea Iki eruption* 1960 (January – February) – Kāpoho eruption *1961 – Lava lake in Halema'uma'u* 1961 -1969 – 9 small ERZ eruptions 1963 – SWRZ intrusion 1963 – ERZ intrusions 1965 – ERZ intrusion *1967 – 1968 – Lava lake rose to within 100 feet (30 meters) of crater rim* 1969 (May) – 1971 (October), 1972 (February) – 1974 (July) – Mauna Ulu eruptions - filled two pit craters and partially filled third *1971 (August) – Summit eruption* 1971 (September) – Small SWRZ eruption 1973 (May) – Pauahi and Hi'iaka pit crater eruption 1973 (November – December) – Pauahi eruption *1974 (July) – Summit eruption* *1974 (September) – Summit eruption* 1974 (December) – 1975 (January) – SWRZ intrusion
1924 – 1954 → Phreatic explosions followed by frequent summit extrusions	1975 – 1981 → Large Kīlauea earthquake followed by intrusions
- 13 foot (4 meter) subsidence along ERZ - *Withdraw of magma from Halema'uma'u leading to ollapse and enlargement of diameter from 1,300 feet (400 meters) to 3,000 feet (900 meters), and 1,300 feet (400 meters) deep.* *1924 (May) – Steam explosions from groundwater mixing with lower magma column.* *1924 (July) – Lava re-entered Halema'uma'u filling crater to depth of 750 feet (230 meters).* *1934 – 1952 – Inflation and deflation → no eruptions* *1951 (April) – 6.5 magnitude earthquake* *1952 (June) – Lava lake re-entered and filled crater to depth of 360 feet (110 meters).*	*1975 (July) – Summit eruption* *1975 (November) – 7.2 earthquake on south flank of Kīlauea* - Repeated intrusions into ERZ since 1955 made south flank susceptible to gravitational failure - Movement 10 feet (3 meters) down, 26 feet (8 meters) southeast - Shifted seismicity from summit area to summit and flank 1976 (January) – 1982 (May) – ERZ extended 2 feet (70 centimeters) and 3 feet (93 centimeters) 1977 – ERZ eruption 1979 (November) – ERZ eruption *1979 – 1980* – 7 ERZ intrusions; *two summit intrusions;* two SWRZ intrusions
	1982 (April-May, September) – Summit eruptions
	1983 (January) -? → Pu'u 'Ō'ō eruptions begin

From Dzurisin, D., Koyanagi, R.Y., English, T.T., Magma supply and storage at Kilauea volcano, Hawaii, 1956-1983

Engage the Public!!
A way to help convey the summit history to visitors includes engaging them in an activity where they become Kīlauea Volcano. Pick about five people and arrange them in a circle to represent Kīlauea Caldera. Pick another person to be Halema'uma'u and yet another to be Kīlauea Iki. Now pick four people to represent the southwest rift zone and eight people to represent the east rift zone. As you read through eruption history, the appropriate representative person will do an eruption dance to indicate any activity in their area. If there are visitors left over, make sure they pay as much attention as the participants by asking them questions. What do they notice about where eruptions take place? Do they mostly occur on the east rift zone, the southwest rift zone, or the summit? Do rift zones erupt when the summit erupts? In this exercise, you can include as many or as few people as you like. My suggested numbers are purely off the top of my head, so experiment to your liking.

The legs of Kīlauea – The Southwest and East Rift Zones

Kīlauea does not erupt only at the summit - it also erupts through rift zones out of the flanks, or sides, of the volcano. Summit and rift zone eruptions generally operate on their own cycles – rarely are there eruptions from the summit and flanks occurring simultaneously. The East Rift Zone and Southwest Rift Zone are lines of weakness where magma is injected and moves laterally down-rift. Not all magma that travels through a rift zone erupts on the surface as lava; the magma may cool and harden to form an intrusion. Long, vertical intrusions filling rift zones are called dikes. If the intrusion is more like a flat, horizontal layer, it is called a sill (Figure 2.7). The easiest place to find a sill-like feature, called a laccolith (which is more like a dome instead of a true sill), displayed in Hawai'i Volcanoes National Park is within the walls of Kīlauea Caldera on the north side beneath HVO/Jaggar Museum. I encourage you to look for dikes and sills as you stroll through Kīlauea Iki and other areas of the park. The injection of magma into rift zones pries the land apart and, along with gravity, contributes to the forces that move the south flank of Kīlauea about ~ 3/4 - 3 inches per year (2-7 centimeters per year) southward (Figure 2.8).



<u>Figure 2.7</u> – *Cross section of Kīlauea volcano* (Modified from J. Johnson, 2000, USGS, HVO). Most visitors spend the majority of their time exploring the summit of Kīlauea volcano. Beneath their feet is a complex, not fully understood, *plumbing system*. Below the summit caldera is a *shallow magma reservoir* at about 2-5 miles (3-8 kilometers) depth. From the shallow magma reservoir, magma either *erupts to the summit* or *travels down one of the rift zones*. Not all magma travels through the rift zone and erupts to the surface as <u>lava</u>; the magma may cool and harden to form an <u>intrusion</u>. Long, vertical, tabular intrusions filling rift zones are called <u>dikes</u>. A horizontal intrusion is called a <u>sill</u>. The injection of magma into rift zones pries apart the land and forces the south flank of Kīlauea 2-4 inches/yr (6-10 cm/yr) southward. Eruptions from Mauna Ulu (1969-1974) and Pu`u `Ō`ō (1983 - ?) on the East Rift Zone have provided spectacular lava viewing within the park.

Not only is Kīlauea growing by eruptions of lava at the surface, but the mountain is also growing because of lateral expansion (Dzurisin and others, 1984; Cayol and others, 2000). Lateral expansion occurs to the south because Mauna Loa is a large obstruction holding up the north side of Kīlauea. Over-steepened sides all around the Hawaiian Islands are created via piling material from volcanic eruptions and pushing it sideways from intrusions. The pali (stair-step cliffs) near the coast result from large-scale slumping of over-steepened sides as gravity takes its natural course of action that is facilitated by earthquakes (Swanson and others, 1976). Think about a bulldozer. Dirt from the top of the pile slides down due to gravity from over-steepening as the pile is pushed along. The over-steepened side collapses to form large landslides (Figure 2.9). Landslides resulting from the push of volcanic intrusions or the pull due to gravity are a hotly debated topic (Delaney and others, 1993, 1998; Denlinger and Okubo, 1995; Clague and Delinger, 1994; Swanson and others, 1976). On the surface of Kīlauea, you can see the battle going on as you drive to the coast. The series of pali are indicators that the south flank is on the move. At the onset of the current eruption of Pu'u 'Ō'ō in 1983, the middle East Rift Zone shifted 3 feet (1 meter) seaward, however the surface displayed a shift of 6-10 feet (2-3 meters). The difference was absorbed by non-seismic compression between the East Rift Zone and the coast (Hall-Wallace and Delany, 1995). Through geologic time these forces have created the series of pali seen on the flank of Kīlauea. Even though there are all of these forces influencing the south flank of Kīlauea, it does not necessarily mean that the entire south flank will slide into the ocean.

Surface Explorations

Hawai'i's continuous geologic change creates spectacular scenery, a mosaic landscape of volcanic features. Not all surface features in the park result from volcanic eruptions, even though they are found on a volcano. Calderas, pit craters, and grabens are features that do not necessarily involve eruption. But these features are definitely the products of the movement of magma below the surface.

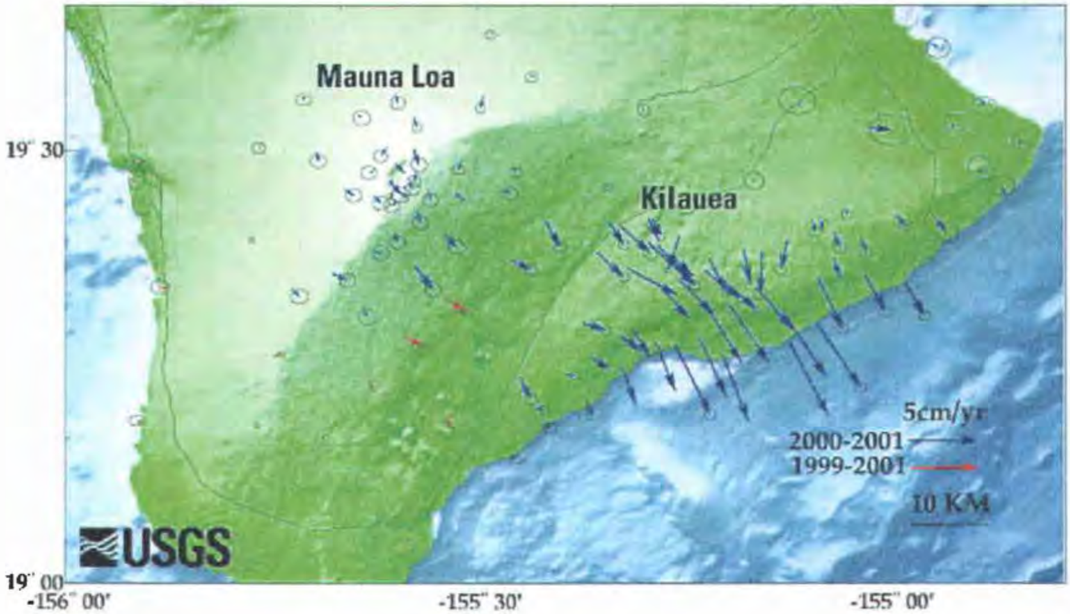


Figure 2.8 – *A volcano on the move!* Global Positioning System (GPS) data show that the south flank of Kīlauea moves southward at a rate of 2-4 inches/yr (6-10 cm/yr)! Long arrows mean that there is more movement compared to short arrows. The southward movement of Kīlauea's flanks creates an extensive fault system resulting in a series of pali's, or cliffs (Courtesy of USGS, HVO).

Figure 2.9 – *Is Kīlauea is sliding into the ocean?* Large landslides have been mapped off the coast of Hawai'i. The arcuate shape of the coastline is a clear indicator that land failed and slid into the ocean. Does this mean that Kīlauea will one day fall into the ocean? A landslide taking out the majority of Kīlauea is highly unlikely, even though the pali along the coast are reminders that active slumping is a prominent force on the south flank. Small landslides demolishing a few acres occur regularly where lava enters the ocean creating new, unstable land (Modified from Earth: Portrait of a Planet, by S. Marshak, ©2001, W.W. Norton & Comp., New York).

The Hawaiian Volcano Observatory resulted from a collaboration of efforts. In 1912 the observatory was established by the Department of Geology of the Massachusetts Institute of Technology (MIT). The financing came from Edward and Caroline Whitney, who in 1909 established the Whitney Fund in order to study, research, and teach seismology as a way to protect human life and property. The San Francisco earthquake in 1906 and loss of life from the 1902 volcanic eruption of Mt. Pélee in Martinique had prompted studies of active faulting and volcanic activity. Because Thomas A. Jaggar had investigated the subject, he was placed in charge of picking the location for a volcano observatory.

Jaggar picked Hawai'i for several reasons including:

- various activity in a relatively safe environment
- Kīlauea and Mauna Loa are isolated centers of activity, unaffected by other volcanic centers
- accessible location
- good locality for studying distant earthquakes
- constant climate
- frequent, small earthquakes
- hot and cold underground water
- territory belongs to the United States.

"The main object of all the work should be humanitarian – earthquake prediction and methods of protecting life and property on the basis of sound scientific achievement." (Bevens and others, 1988).

Jaggar envisioned detailed plans for a volcano observatory. The research building should be located on the edge of Kīlauea Caldera, with an attached museum for visitors to provoke interest and secure more funding. Other scientists and students could come and partake in research studies, while current HVO staff could visit other regions of the world to study volcanic activity. The first HVO building was constructed where the Volcano House resides today, while the Technology Station was built on the edge of Halema'uma'u in a very dangerous and vulnerable position. After construction of the necessary facilities, scientific research took off and continues today. HVO occupied several different localities before moving to its present location in 1948. HVO has also been run by several organizations. From 1919 to 1924 the US Weather Service controlled operations. From 1924 to 1935, the US Geological Survey took over, and from 1935 to 1947 the National Park Service ran operations before returning jurisdiction to the USGS as it remains today (Bonsey, 1999).

If your curiosity sparks your interest, the beginning of The Early Serial Publications of the Hawaiian Volcano Observatory, Volume 1, provides more detailed information.

Landforms, stages of eruption, characteristics, and materials

Pit craters form when there is a loss of support beneath the ground surface that results in collapse. The majority of the pit craters in the park line the upper segment of the East Rift Zone. Pit craters look like small calderas, with diameters less than 1 mile (1.6 kilometers). Halema'uma'u is a pit crater within the larger Kīlauea caldera. Halema'uma'u is 0.6 miles (1 kilometer) in diameter and 260 feet (80 meters) deep. Geologists hypothesize that magma flowing down the East Rift Zone leaves voids causing the land surface above to collapse. A pit crater has never actually been seen during formation, so their origin is still somewhat a mystery (Figure 2.10). Perhaps they form in a manner similar to <u>sinkholes</u> in Florida, even though the Earth materials involved are quite different. (Sinkholes form as limestone dissolves from interaction of the rock and groundwater.)

The Count
How many pit craters can you count as your drive through the park? Encourage visitors to look and identify pit craters as they explore. Just by doing this exercise will get visitors into the mode of *observing*. From there they might *explore*, then *interpret*, and *appreciate* for themselves. A visitor should be able to find at least seven pit craters during their exploration of the park by car. Challenge them to do so. As a ranger, how many pit craters can you discover on various maps or hiking through the park?

(a) Pit Crater Formation (Side View)

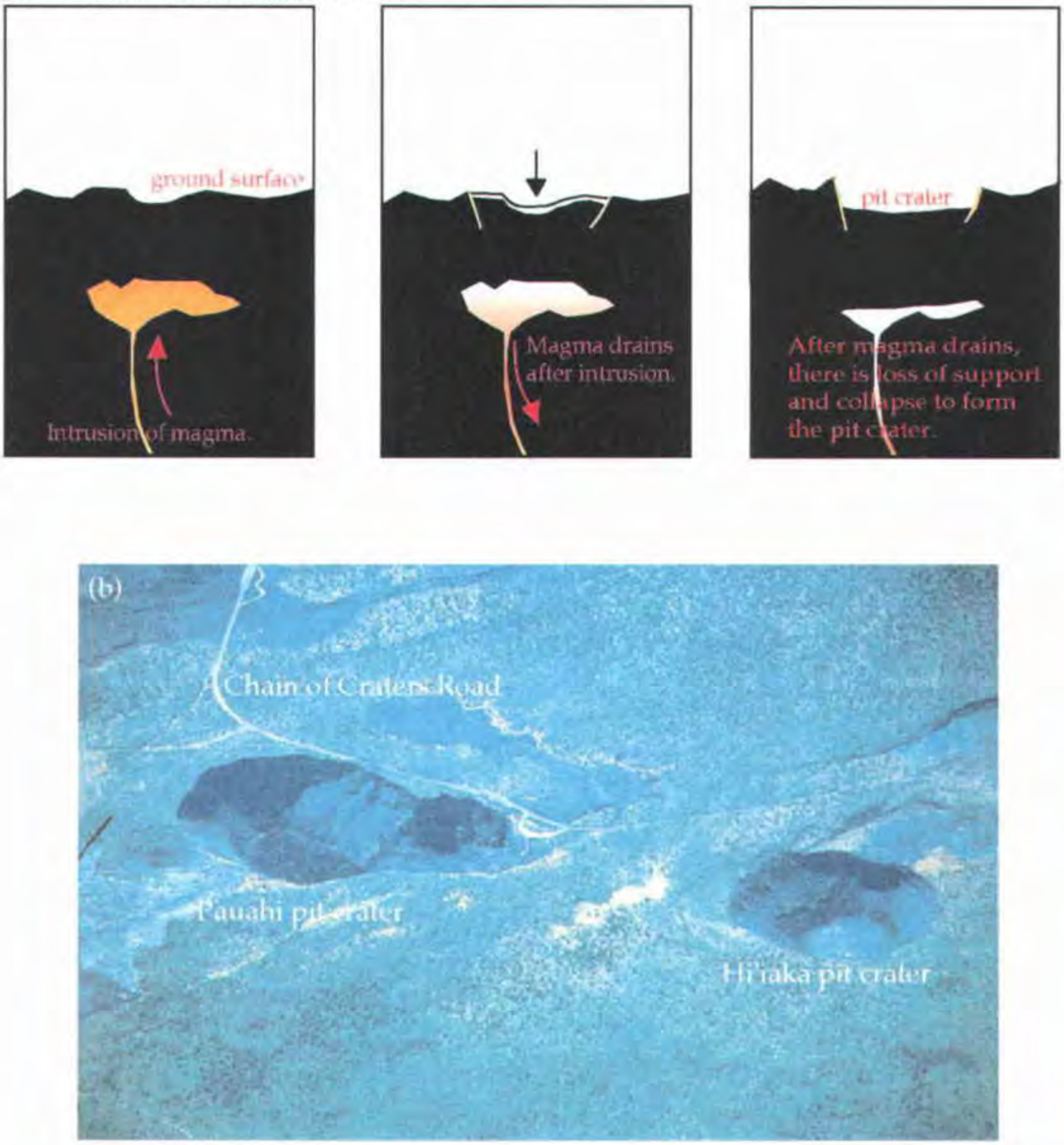


Figure 2.10 – *Why are there so many holes in the ground?* (a) Pit craters are features found on volcanoes that result from the *collapse* of the land generally without a significant eruption. The difference between a pit crater and a caldera is mostly *size*, a caldera having a diameter of at least 1 mile (1.6 kilometers). A graben forms much the same way as a pit crater, but is a more *elongated* collapse structure. Hi'iaka and Pauahi pit craters (Photo courtesy J.D. Griggs, USGS, HVO).

Puhimau Thermal Area - A pit crater in the making?
As you drive down Chain of Craters Road, you might notice an area lacking vegetation near Hilina Pali Road, known as the Puhimau Thermal Area (Figure 2.11). After a series of earthquakes near the region in 1938, T.A. Jaggar recognized the "hot region" along with collapse of the road near Devil's Throat. The thermal area consisted of a 15 acre region of dying vegetation due to the heating of the ground, possibly from the presence of magma below. By the fall of 1938 temperature measurements showed that the maximum temperature in the center reached 182°F (83°C), whereas normal ground temperature was 67°F (19°C). By 1985 the thermal area was approximately 29 acres. Today the affected vegetation extends to the east side of Chain of Craters Road. Several studies conclude that there is magma beneath the ground, but not much else is agreed upon. A proposal to drill an exploratory hole for research purposes by Sandia National Laboratories of New Mexico in 1985 was denied by the park to preserve the grounds. Puhimau Thermal Area thus leaves its mysteries to the imagination. Time will certainly let us know if a pit crater is created in this area.

Let's take a systematic journey through materials and features that result from volcanic eruptions. There are general stages to eruptions that have been identified in Hawai'i. The cycle commonly begins with an elongated crack, or fissure, in the rock that erupts in a curtain of lava. Such fissure eruptions last for a few hours to days. Features that result from the eruption include spatter ramparts and spatter cones. Spatter ramparts are elongated lines of lava that erupted out of a fissure, whereas spatter cones are more circular (Figure 2.12). Spatter consists of globs of lava that fly out of the ground and weld together to build features on top of the ground surface. Spatter is easy to imagine if you think about the last time you cooked spaghetti sauce. You get a nice spatter effect if you let the sauce come to a boil on your stove top (Remember, always wear a white shirt while cooking spaghetti sauce☺). Excellent spatter ramparts are found in Kīlauea Caldera as you continue on the Halema'uma'u trail beyond the Halema'uma'u overlook on the south side of the caldera, or across the road from Keanakāko'i Crater. Other places to explore spatter ramparts include Mauna Ulu and along the Southwest Rift Zone. Go and explore Mauna Ulu!

Figure 2.11 – *Why is the ground so hot here?!* Puhimau Thermal Area is a region along Chain of Craters Road where a *loss of vegetation* and *elevated ground temperature* has been recognized since 1938. The limited studies have left the area one of the many unresolved mysteries of Kīlauea Volcano. Geologists think that there is magma close to the ground surface near the Puhimau Thermal Area, resulting in the high heat flowing through the surface. But, will it turn into the next pit crater? (a) Photo courtesy of N. Nesvadba, 2001, USGS, HVO, (b) Photo courtesy of R.T. Holcomb, 1972, USGS, HVO, (c) Photo courtesy of D.A. Swanson, 2002, USGS, HVO.

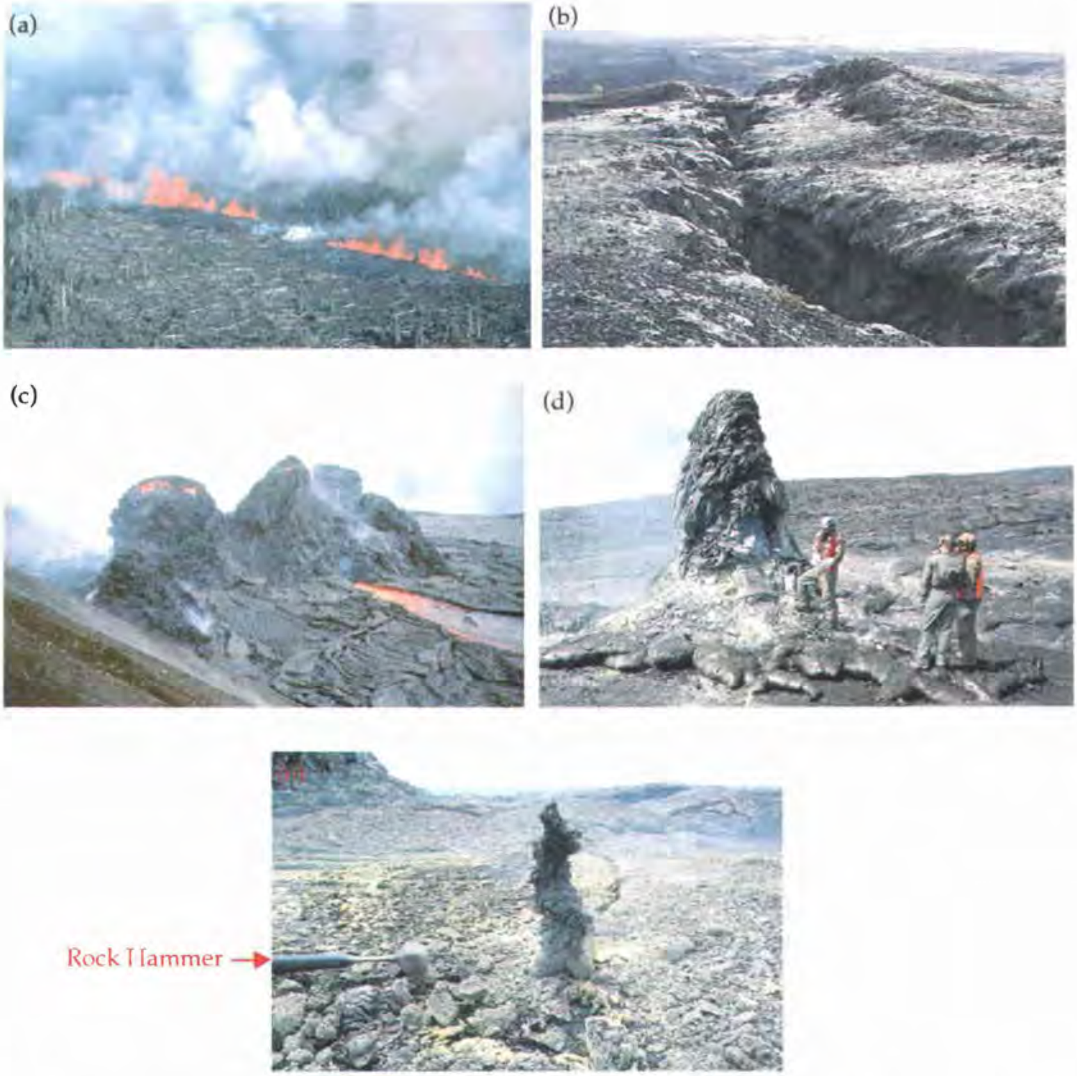


Figure 2.12 – *First sight of lava!* When a volcanic eruption begins in Hawai'i, it usually starts with a large crack or fissure splitting the ground to erupt a curtain of lava, known as a fissure eruption (a). Fissures usually erupt for a few hours to days. The remaining hardened lava leaves a ridge-like feature called a spatter rampart (b). If the spatter forms a cone shape, the resulting name is a spatter cone or hornito (Spanish word for "little oven") which may be of various sizes (c,d,e). (a) Photo courtesy of N. Banks, USGS, HVO, (b) Photo courtesy of S.R. Brantley, USGS, HVO, (c) Photo courtesy of C. Heliker, USGS, HVO, (d,e) Photo courtesy of USGS, HVO.

A plethora of colors!
Many visitors ask, "Why are there different colors in the basalt?" Reds and oranges form from the oxidation of iron in the rocks. The iron in the rocks form iron oxide (rust) during exposure to heat, wind, water, and air. Shininess results from the rapid rate of cooling of the rock, making it a bluish or purple glassy color. The rapid cooling creates a thin glassy coating that reflects and refracts light like a triangular prism. If you see green, you are probably looking at the mineral olivine. Larger olivine crystals are found at Kīlauea Iki (Figure 2.13), and smaller ones can be seen around Mauna Ulu if you look carefully.

After a fissure eruption, the vent usually shrinks to one localized spot to produce fountain eruptions (Figure 2.14). Fountain eruptions can last for years. They occur when volcanic gases that are under pressure expand and propel the magma out of the vent. The effect is much like shooting a fire hose straight upwards. Besides the most famous episodic fountaining of Pu'u 'Ō'ō in the 1980's, Kīlauea Iki in 1959 produced the highest fountain eruption on record in Hawai'i, reaching 1,900 feet (580 meters). A fountain eruption produces a cinder cone (see Chapter 1), composed of vesicular pyroclastic materials like cinders and Pele's tears. The word "pyroclastic" comes from combining the Italian words for "fire" and "broken". Scoop up some pyroclastic material near Kīlauea Iki and take a closer look. It truly looks broken and fractured - but make sure you return it to the ground; it is against the law to take objects from a national park! Cinder, a form of scoria, is fragmented, ejected volcanic material that commonly is pocked with holes. Pele's tears are differentiated from cinder because Pele's tears usually are still molten when ejected from the ground, so they take on a rounded, tear-like shape as pieces fly through the air. If Pele's tears get stretched out to long thin strands, then they are called Pele's hair. This type of eruptive material is hard to find as it is quickly carried away or broken down by wind and water. Your best bet is to look in the cracks of lava flows downwind of Pu'u 'Ō'ō to find the delicate hair preserved.

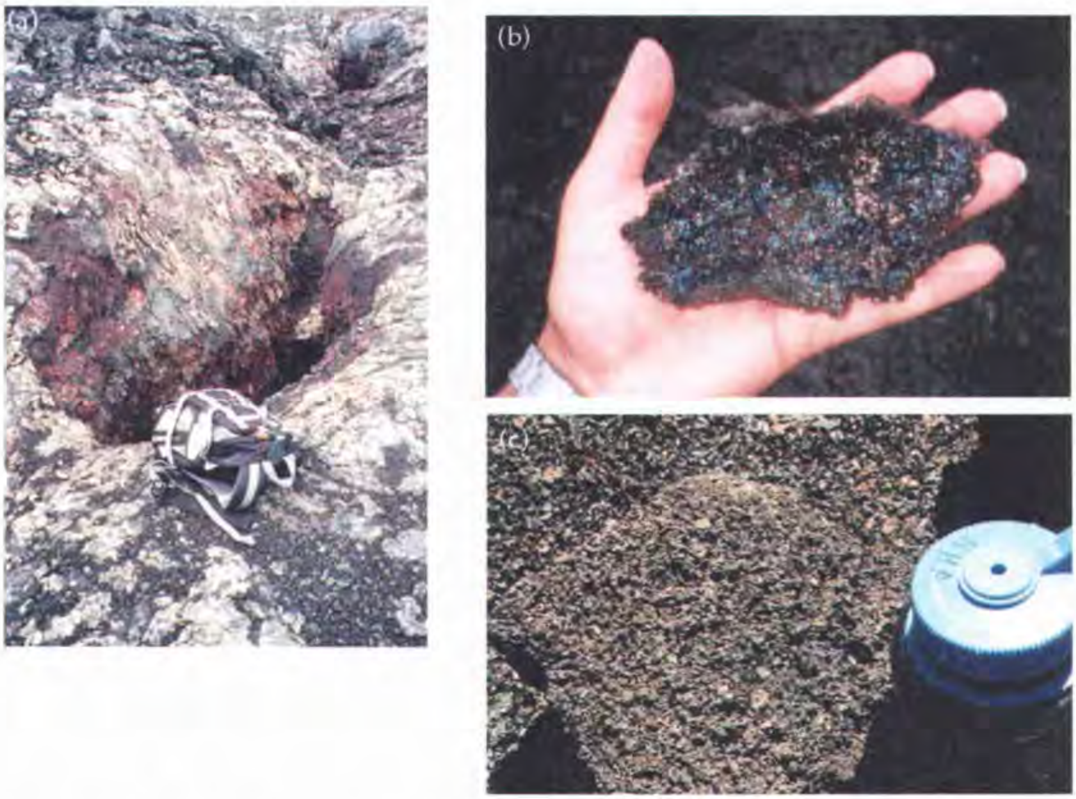
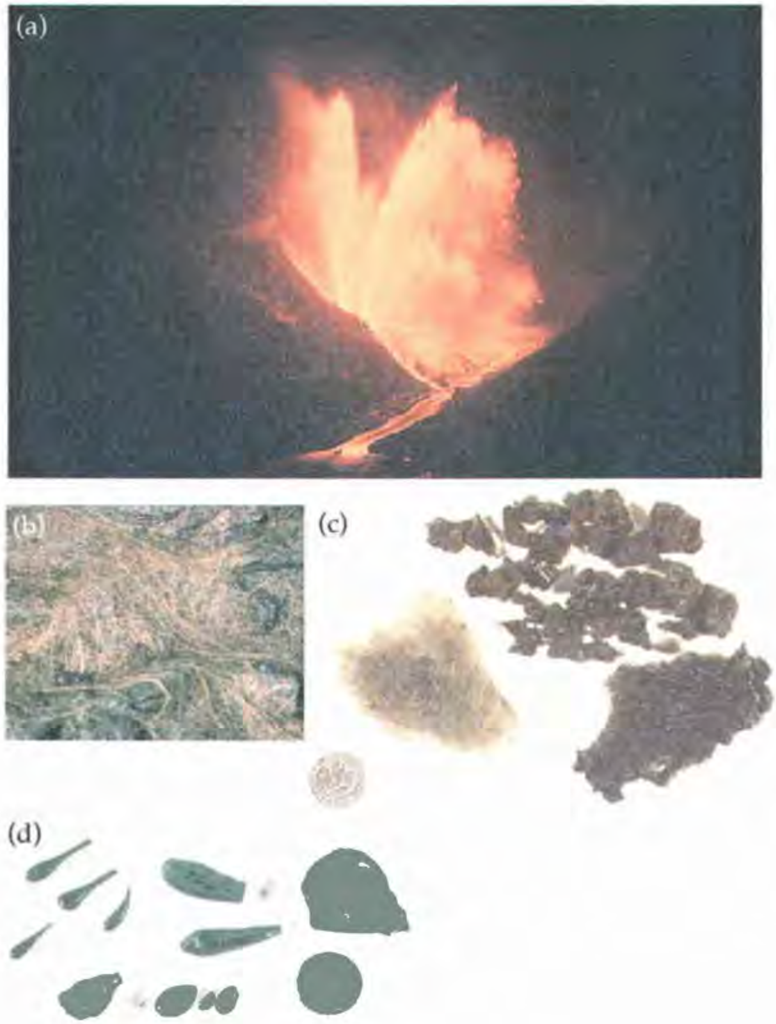


Figure 2.13 – *Hawai'i Black Basalt? Why there are various colors in the basalt?* Basalt is black, however, sometimes you will see reds, yellows, and oranges. These colors form from oxidation (a) of the iron minerals in the rock - the rock is *rusting*, just like your car. Yellow can also indicate sulfur. If you get a particularly glassy piece of basalt (b), there may be blues, purples, and reds. These hues are created from either slight impurities in the glass, or when the surface of the lava is *cooled* so *quickly* it quenches and forms glass with a variety of colors. A *green* color in basalt is the mineral olivine (c). Other minerals commonly found in basalt are plagioclase and pyroxene. Individual crystals are not usually seen in a hand sample, but when they are you may notice plagioclase as an off-white color, while pyroxene is black or dark green (Photos by R.H. Ashton).



<u>Figure 2.14</u> - *A closer look at the details.* After a curtain of lava erupts, the eruption usually confines itself to one spot to create a <u>lava fountain</u>. In 1959, the Kīlauea Iki fountain (a) reached a height of 1,900 feet (580 meters). Fountains can last for years. Pu'u 'Ō'ō produced fountains of lava from 1983 to 1986. During fissure and fountain eruptions, lava is hurled into the air. Some lava takes the shape of small, *tear-shaped droplets* known as <u>Pele's tears</u>. Other material called <u>scoria</u>, has *holes and vesicles.* Some material is caught in the wind and stretched out into *thin strands,* know as <u>Pele's hair</u>. At times huge explosive periods produce larger debris called <u>volcanic bombs</u>. This loose <u>pyroclastic</u> material, <u>scoria</u> (c), <u>cinders</u>, <u>pele's hair</u> (b, c), and <u>pele's tears</u> (d) piles up to create a cinder cone. Photo in (a) courtesy of USGS, HVO, (b) D.W. Peterson, USGS, (c) USGS, and (d) J.D. Griggs, USGS.

Once the trapped volcanic gases are released, eruptions consist of effusive eruptions of fluid lava that has been characteristic of Kīlauea more recently. An effusive eruption is not like a fire fountain that looks like a busted fire hydrant. Rather, it consists of lava bubbling, dribbling, and flowing out of the ground calmly to create lava shields and lava tubes (Figure 2.15).

Another Look at the East and Southwest Rift Zones

The East Rift Zone actually extends about 30 miles (50 kilometers) from the summit caldera to Cape Kumukahi on land, and about 50 miles (80 kilometers) offshore (Hawaiian Volcano Observatory, 2002). The onshore portion can be divided into three segments: an upper segment extending from the caldera to Napau, a middle segment from Napau to Heiheiahulu lava shield, and a lower segment from Heiheiahulu to Cape Kumukahi. Pit craters on the surface are common among the upper segment, while fissures, faults, and grabens dominate the middle and lower section. Faults are breaks in the land where one side slides past the other. Grabens (from the German word describing a "ditch" or "moat around a castle") are collapse features like pit craters, but elongated instead of circular. The fissures, faults, and grabens are features that contribute to the seaward movement of the land (Figure 2.16).

The Southwest Rift Zone is much shorter, about 20 miles (30 kilometers) long, and is not as distinctive as the East Rift Zone. The Southwest Rift Zone is divided into two sections: an upper section extending northeast of Yellow Cone and a lower section extending south-southwest from Yellow Cone to somewhere near Kamehame and Palima Point on the coast. The lower section mostly consists of the Great Crack region with a few cinder cones, while the upper section is scattered more widely with cinder cones, spatter ramparts, and a few small pit craters set in a graben-like structure (Holcomb, 1987).

Figure 2.15 – *A side by side comparison.* Pu'u 'Ō'ō was built during the early portion of the current eruption when gas was pressurized in the East Rift Zone to create fountain eruptions that formed a cinder cone. Today, lava dribbles out of the ground effusively creating shield-like shapes (Photo courtesy C. Heliker, USGS, HVO).

Figure 2.16 – *The Summit versus the Rift Zones - A map depicting the surface of Kīlauea* (Modified from R.T. Holcomb, 1987). The summit of Kīlauea volcano contains a caldera. The east and southwest rift zones are lines of weakness where magma is injected and travels laterally down-rift beneath the surface. The east rift zone is divided up into three segments, the *upper, middle,* and *lower* section. Each segment has a specific character. Pit craters are common among the *upper* segment, while fissures, faults and grabens dominate the *middle* and *lower* sections. The southwest rift zone is much smaller and divided into the *upper* and *lower* segments. The *lower* section mostly consists of the great crack region with a few cinder cones, while the *upper* section is scattered more widely with cinder cones, spatter ramparts, and a few small pit craters set in a graben-like structure.

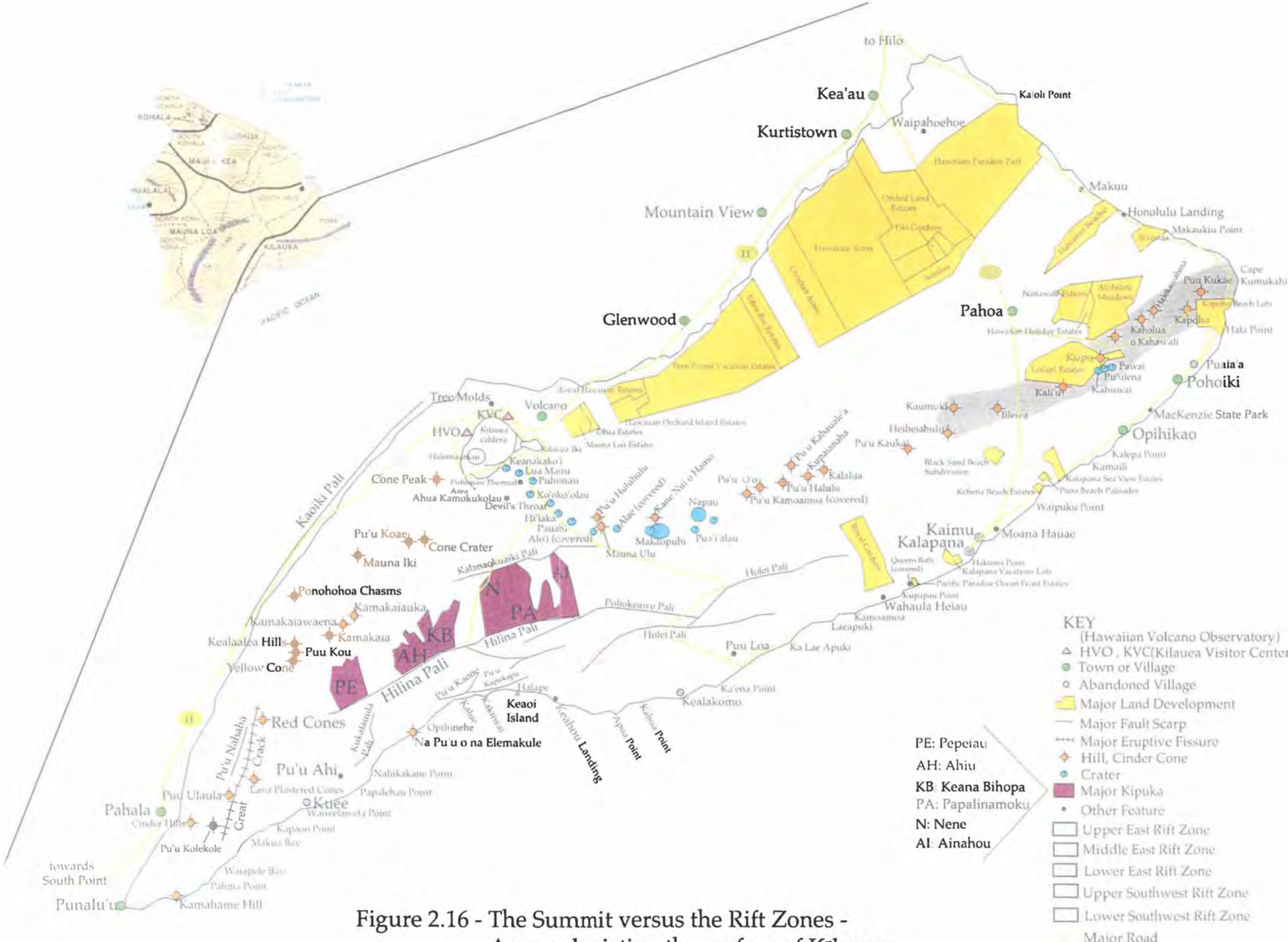


Figure 2.16 - The Summit versus the Rift Zones -
A map depicting the surface of Kīlauea

The Explosive Kīlauea

From the rim of Kīlauea Caldera, the remains of explosive eruptions, including places where visitors survived and perished, can be seen in every direction. Kīlauea did not experience a large explosive eruption in the 20th Century. But geologists study ash deposits from earlier eruptions at Kīlauea in order to protect lives in the future. Hawaiian volcanoes do not often erupt explosively because basalt allows slow release of gas, hence there is no fluid-pressure build up and kaboom. The occasional explosive eruption that does come from Hawaiian volcanoes requires the sudden interaction of hot rock or magma with water. An explosion at a subduction zone or continental hotspot occurs more frequently because of the high-silica rock type. The molecular structure of silicate traps the water molecules and does not release them slowly. If there is more silica in a rock, water will build-up within the crystal structure, lending to larger explosions. Once there is a large build-up of water, it violently expands and explodes like the 1980 eruption of Mt. St. Helen's.

So far, three ways Kīlauea erupts explosively have been identified (Figure 2.17). First, the hydrothermal system of the volcano can depressurize quickly (Decker and Christiansen, 1984). Second, there may be interaction between groundwater and magma or hot rock when magma withdraws from the magma column rapidly (Decker and Christiansen, 1984; Dvorak, 1992). And finally, lava may erupt through shallow bodies of water, creating fountains (Dvorak, 1992; Mastin, 1997).

Larger eruptions tap a fairly deep source and distribute rocks and ash over great distances. Such eruptions include the Uwēkahuna (800-100 B.C.), Kulanaokuaiki (1000-1400), and Keanakākao'i (1790) explosions. The most recent, 1924, explosive eruptions were mearly steam explosions of ash, dust, and hot gas that people observed from the rim of Kīlauea Caldera. The explosions were thought to have occurred when water (ground and surface) contacted hot rock or magma near a falling or rising/stationary magma column.

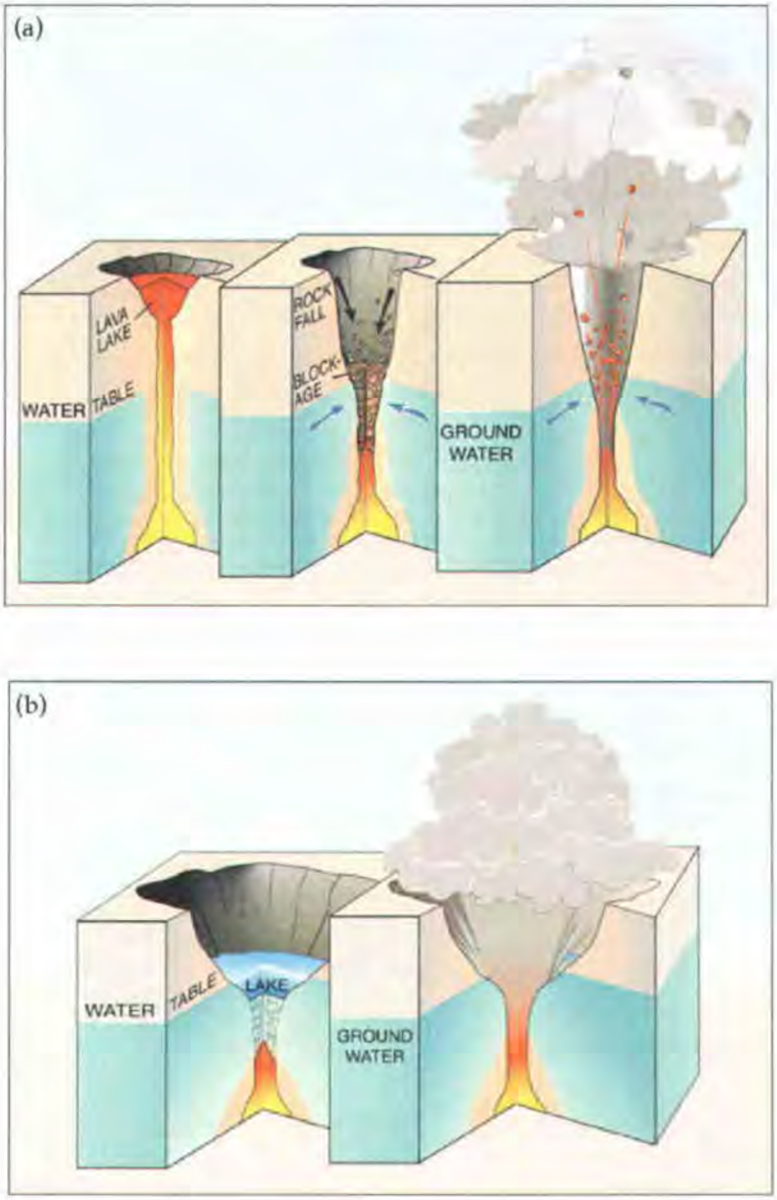


Figure 2.17 – *Silent sleeper?? Three causes of explosive eruptions at Kīlauea.* In the first way (not illustrated here), the hydrothermal system of the volcano can depressurize quickly (Decker and Christiansen, 1984). So much pressure can build up (like shaking or freezing a coke can) that it may simply pop to produce a dangerous explosive eruption. Second (a, Courtesy of USGS, HVO), there may be interaction of groundwater and magma or hot rock when magma rapidly withdraws from the magma column (Decker and Christiansen, 1984; Dvorak, 1992). Third (b, Courtesy of USGS, HVO), lava may erupt through shallow bodies of water creating fountains (Dvorak, 1992; Mastin, 1997).

Three large explosive episodes have been identified by studying ash deposits around Kīlauea. The rarely studied Uwēkahuna explosions between 800 and 100 B.C. left deposits scattered at least 6 miles (10 kilometers) in all directions from Kīlauea Caldera. The relatively symmetric distribution of deposits around Kīlauea suggests it was a large eruption that was directed upward rather than in a particular horizontal direction or easily blown by the wind.

The second identified large explosive episode, Kulanaokuaiki, occurred between 600 and 1400 AD. The resulting tephra deposits can be seen between lava flows near the top of Kulanaokuaiki Pali and traced upslope and correlated with deposits near the Tree Molds and the base of Uwēkahuna Bluff. These extensive deposits show several clues about the eruption. First, the wide distribution of deposits indicates that it was a large eruption. Second, the make-up of the fragmented material provides other interesting clues. The fragments include basalt and its coarse-grained equivalent, gabbro. The gabbro fragments are not 100% gabbro – about 1/3 of their composition is high-silica (glass) material. The fingerprint of gabbro with glass tells an interesting history. Gabbro is an intrusive igneous rock that forms within the Earth. Glass forms when magma cools extremely quickly at the surface, where it is in contact with air or water. Therefore, some of the Kulanaokuaiki fragments tell a two-fold story. The fragments came from magma that began to cool within the Earth, forming gabbro. The rest of the magma cooled quickly as it was suddenly brought to the surface during the explosive eruption, forming the glass co-mingled with the gabbro. Fragments as large as baseballs were found as far as 4 miles (6 kilometers) from the caldera, suggesting that the eruption cloud reached heights around 15-18 miles (24-29 kilometers) into the air. The Kulanaokuaiki eruption was large, as indicated by such large-sized deposits scattered great distances from the caldera. And the coarse-grained gabbro fragments suggest that a deep source was tapped (Fiske and others, 1999).

After the Kulanaokuaiki explosion that occurred between 600 and 1400AD, the caldera began filling and overflowed, creating what is known as the Observatory Shield in the western portion of the summit area. Today, if you stand near Keanakāko'i and look towards the Hawaiian Volcano Observatory, you can see the remnants of the shield from the gradual rise in the landscape (Figure 2.18). Co-existing with the Observatory Shield was the 'Ailā'au Shield in the region where Kīlauea Iki resides today (Figure 2.19). The 'Ailā'au (meaning "forest-eater") flow dating from between 1410 and 1460AD, covered the Puna region extensively with lava flows creating Thurston and Pua Po'o lava tubes. The collapse of Kīlauea Iki is thought to have occurred in the mid 1400's (Holcomb and others, 1986; Clague and others, 1999).

The date of the Observatory Shield collapse ranges between 1400 and 1500AD because the caldera wall cuts across flows formed as early as 1400, and because explosive eruptive material that dates at about 1500 is plastered on the walls of the caldera (Figure 2.20). The collapse of the Observatory Shield is thought to have created the shape of the caldera we find today, but the depth during the time of collapse is unknown. In 1823, Ellis estimated the depth of the caldera to be about 1,790 feet (546 meters). Today it is only 395 feet (120 meters) deep. This means that about 1400 feet (430 meters) of lava has partially filled the caldera in the last 180 years. The water table at Kīlauea is located about 2,000 feet (600 meters) below the Earth's surface. If the caldera collapsed close to that level, cold water could have contacted hot rock or magma, triggering the large explosive eruptions.

The third episode occurred after the caldera collapse in the 1400's, additional collapses could have placed the level of the caldera floor below the water table, creating explosive eruptions that scientists believe took place over a 300-year period that culminated with the deadly eruption of 1790. To say the least, Kīlauea may have been a key factor in historical events. The 1790 eruption, which produced the Keanakākao'i Ash Member, wiped out a portion of Keōua's Hawaiian army, rival to Kamehameha, who went on to become the first King of Hawai'i.

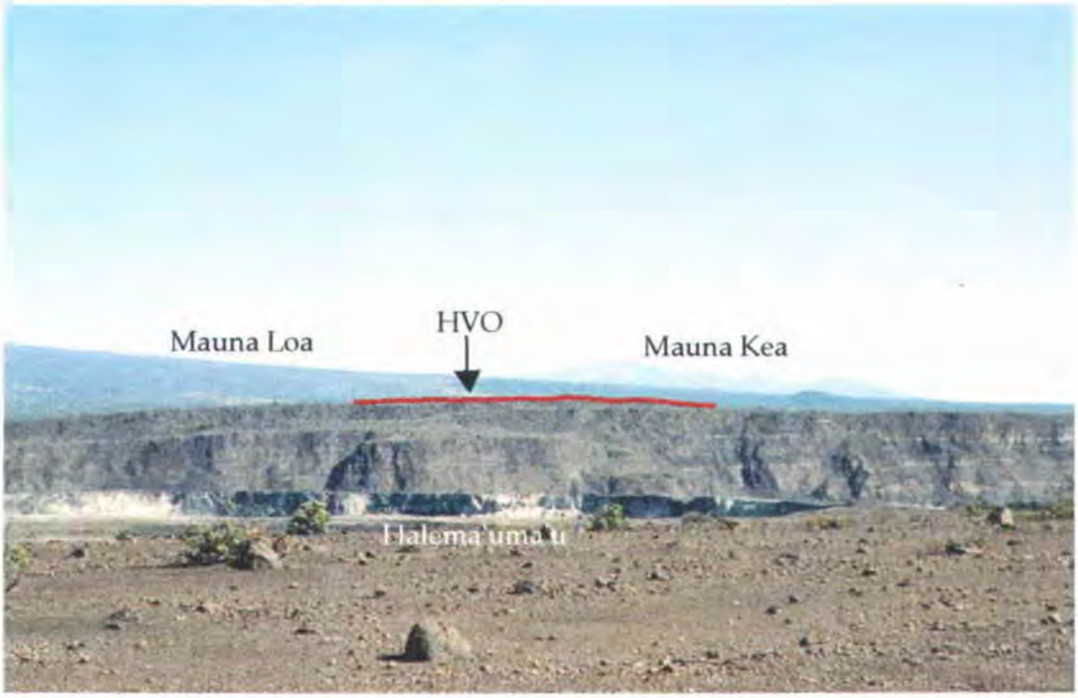


Figure 2.18 - *Read the landscape to learn the story.* It takes a lot of practice and patience to read the landscape and pick out hidden features. If you stand on the south side of Kīlauea Caldera and look towards the Hawaiian Volcano Observatory, you can see the remnants of the Observatory Shield from the gradual rise in the landscape, highlighted by the red outline (Photo by R.H. Ashton).

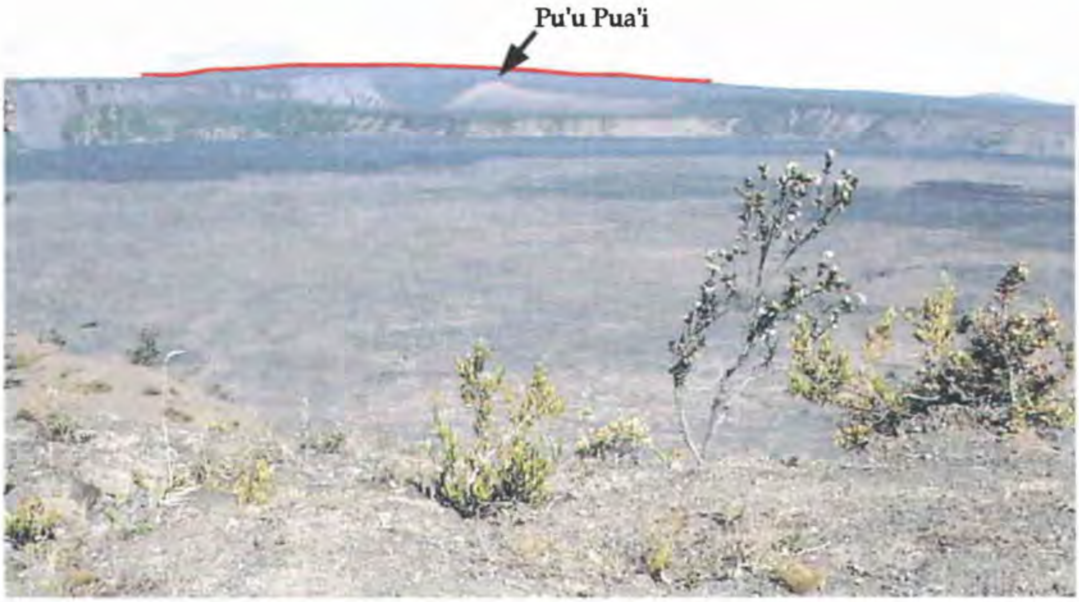


Figure 2.19 - *Read the landscape ... part II.* The remnants of the 'Ailā'au Shield can be observed while standing in front of the Hawaiian Volcano Observatory looking towards where Kīlauea Iki resides today (Photo courtesy S.R. Brantley, 1998, USGS, HVO). Notice the gradual rise in the landscape profile – typical of a broad, gently sloping shield. The red outlines the gradual rise of the remnant 'Ailā'au Shield.

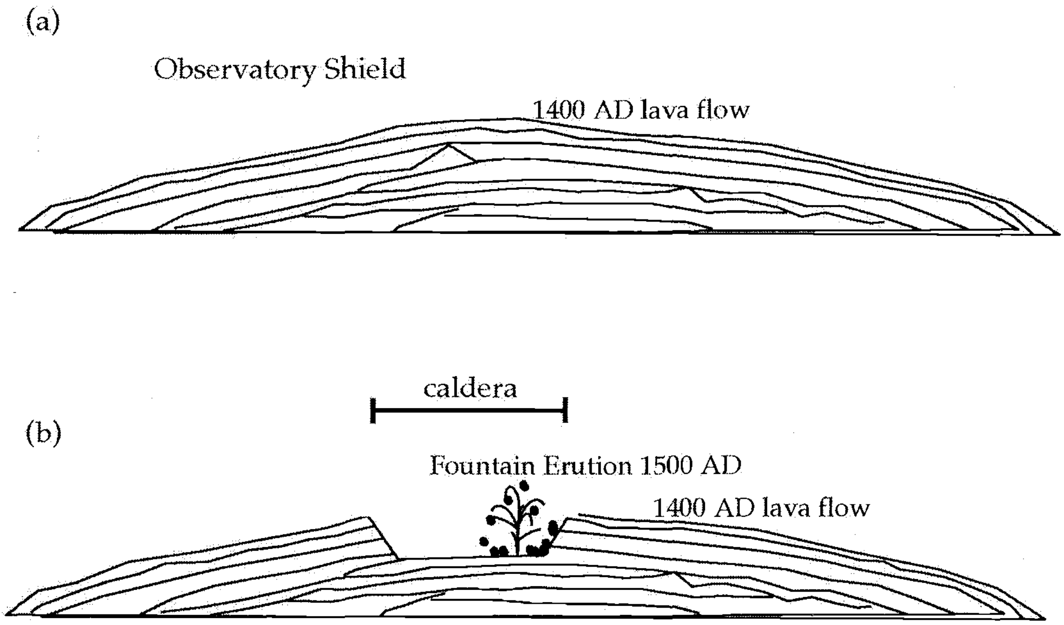


Figure 2.20 – *Piecing together the puzzle.* Piecing together geologic events is not always easy. Almost always, a geologist is given an incomplete record. It is like a book with some of the pages taken out - the rest of the story needs to be filled in from the clues. The date of the Observatory Shield collapse ranges from 1400-1500AD because the caldera *cuts* flows as young as 1400AD, and explosive eruptive material is *plastered* on the walls of the caldera probably from a fountain eruption dates at 1500AD. (a) The diagram demonstrates that the flow capping the Observatory Shield was 1400 AD. (b) The caldera collapsed shortly thereafter, and a fountain eruption occurred around 1500AD, plastering material on the wall of the caldera.

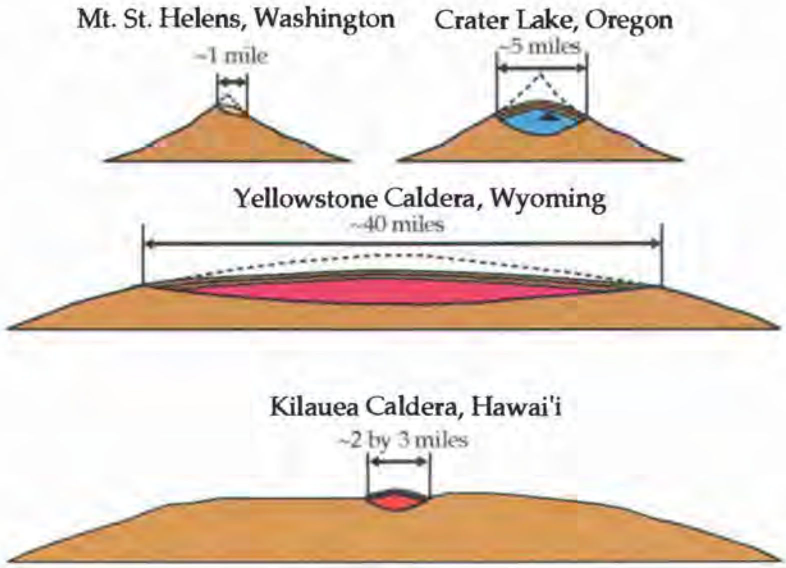


Figure 2.21 – *Sizing up the competition, again!* Calderas are common around the world. Various sizes relate to the size of an explosive eruption. For example, Yellowstone latest eruption (70,000 years ago) rarely erupts, but when it explodes, it expels a large volume of material; a caldera with a diameter of about 40 miles (64 kilometers) was created 600,000 years ago. Mt. St. Helen's erupts frequently and expels smaller amounts of material; the crater formed in 1980 was only about 1 mile (1.6 kilometers) across. Crater Lake and Kīlauea are mid-range with Kīlauea (1790 AD), erupting more frequently than Crater Lake (last major eruption ~7,700 years ago) with caldera sizes of 2 by 3 miles (3 by 5 kilometers) and about 5 miles(8 kilometers), respectively (Modified from R.J. Lillie).

Even though the 1790 eruptions proved deadly, they are considered smaller events than the Kulanaokuaiki and Uwēkahuna eruptions because material was distributed in a small area toward the southwest rather than in a large concentric region around Kīlauea. The evidence that suggests the explosions spanned 300 years lies within the ash layers. Three layers of charcoal between ash indicate that enough time (possibly a few years to decades) passed for vegetation to return to the land before another explosive eruption singed the land, depositing the charcoal marker and covering it up with more ash deposits.

How do Kīlauea's explosive eruptions size up to the competition? Let's take a moment to compare Kīlauea to Yellowstone and Mt. St. Helen's. Geologists realize Mt. St. Helen's and Yellowstone erupt higher-silica lava, creating more explosive eruptions by nature. Putting aside the silica factor, let's look at the frequency and size of volcanic eruptions at Yellowstone, Kīlauea, and Mt. St. Helen's. Yellowstone's latest series of eruptions occurred 160,000 to 70,000 years ago (U.S. Department of the Interior, 2003). Kīlauea had large explosive eruptions in 800-100 B.C., 1000-1400, and 1790. Mt. St. Helen's had eruptions in 1600, 1700, 1800 to 1802, 1831, 1835, 1842 to about 1844, 1847 to about 1854, 1857, and 1980 (USGS, 2002). If you compare crater and caldera sizes of these three prominent landmarks, they contrast as much as their eruptive frequencies (Figure 2.21). As a general rule, the greater the sizes of explosive eruptions, the less frequent the eruptions. The smaller the size of explosive eruptions, the more frequent the eruptions. Mt. St. Helen's has explosively erupted more frequently, but the eruptions are smaller events compared to Yellowstone, which does not erupt explosively very often. But when Yellowstone does erupt it is devastating, not just to the region, but globally. Kīlauea has been erupting effusively (calmly) since 1980 lending to the generalization, the more frequent the eruption, the smaller the eruption. When Kīlauea infrequently lets out a violent burp, it is moderate in size. Kīlauea's violent burps can be larger than Mt. St. Helen's that erupts violently relatively frequently, but smaller than Yellowstone that has colossal but infrequent eruptions.

There have been no deep caldera collapses in Hawai'i or nor devastating, violent eruptions since 1790. Kīlauea hides its explosive nature, making geologists wonder when Pele's temper will flare again.

Legend and Geology
It is thought that the 1790 explosive eruption may have inspired the Hawaiian Legend about Pele, her sister, Hi'iaka, and Pele's lover, Lohi'au. The story goes that Pele's spirit traveled to Kaua'i and fell in love with a young chief, Lohi'au. She decided to send her sister Hi'iaka, on the dangerous journey evading evils spirits to Kaua'i to fetch Lohi'au and bring him back to the Big Island. To dissuade Hi'iaka from intimate involvement with Lohi'au, Pele promised to watch over Hi'iaka's beloved groves of 'ōhia-lehua trees and ferns as well as her friend Hopoe. Once Hi'iaka fought her way to Kaua'i she found Lohi'au dead from grief of Pele's disappearance. Hi'iaka found his spirit and restored him to health and traveled back to the Big Island. When the allotted forty days for the journey had passed, Pele grew into a jealous rage for fear of betrayal. Pele took revenge and covered Hi'iaka's land with lava and killed Hopoe. Once Hi'iaka finally returned with Lohi'au and saw her land and friend destroyed, she made love to Lohi'au on the caldera's edge enraging Pele to a violent outburst (1790 explosion) killing Lohi'au. As Lohi'au spirit traveled across the water back to Tahiti, the homeland, Pele's brother, Kāne-milo-ha'i, captured the spirit and returned Lohi'au to form. Hi'iaka and Lohi'au reunited on O'ahu and returned to Kaua'i together.

In 1924 a small steam explosion from Halema'uma'u enlarged the crater to two times its previous area and deposited material up to a few hundred yards (meters) away. A cameraman perished when he tried to get the perfect shot. Otherwise, spectators watched in awe and fearlessness from Kīlauea's edge as ash, steam, and dust got blown into the air. During the 1924 event, geologists observed withdrawal of a long-lived lava lake and almost 300 ft (100 meter) subsidence of the pit crater before the explosion. Withdrawal and subsidence is thought to be associated with intrusion of magma into a flanking rift zone.

With the knowledge that geologists have collected over the years, Kīlauea appears to be much more dangerous than thought. The cycle of collapse, fill, collapse, explosion has been uncovered in the landscape of Hawai'i. What does the future hold for geologists and visitors alike? For humans it is hard to think on another timescale besides our own, but that is what geologists have to do everyday and it is certainly re-iterated in the history of Kīlauea volcano. Only time will tell and many precautions will be taken once activity looks imminent. Clues that Kīlauea may belch out a large eruption include rapid rise or withdraw of magma, or a sudden influx of water to trigger an explosive eruption. Kīlauea is so wired with instruments that a drastic change would be obvious to geologists.

Vegetation clues about eruptions

When visitors explore Kīlauea they want to see lava. But encourage them to slow down and read the landscape of vegetation and ask, "Why does it look like this?" There are a lot of clues about the volcanic history of Kīlauea if you observe vegetation closely. What follows are a few clues, but try to find your own vegetation hints as you explore the park as a ranger. For example, a visitor might just drive around Crater Rim Drive looking at the big hole in the ground and not think or realize that they are in a rainforest on the east side, and a desert-like landscape on the south and west. At Jaggar Museum there is 30-40 inches (75 -100 centimeters) of rain per year (Hazlett, 2002), on average, whereas across the caldera at Thurston Lava Tube there is more like 120-140 inches (300-355 centimeters). The park is right on the dividing line for the rain shadow effect, influencing landscapes on the east side of the park compared to the west. For the most part, weather patterns in Hawai'i show dominant trade winds blowing from the northeast to the southwest. As the air rises to get over the mountains of Hawai'i, the clouds usually release the bulk of their moisture before they reach the other side, dumping most of the rain on the east side of the island and park (Figure 2.22). Not only does this trend occur in the park, but the entire island displays the effects of the rainy side versus the dry side. The fact that there are deep ravines on the eastern, rainy side results from the effect of water. Dry conditions mean little erosion of the land, leaving the west side uncut and gently sloping (Figure 2.23).

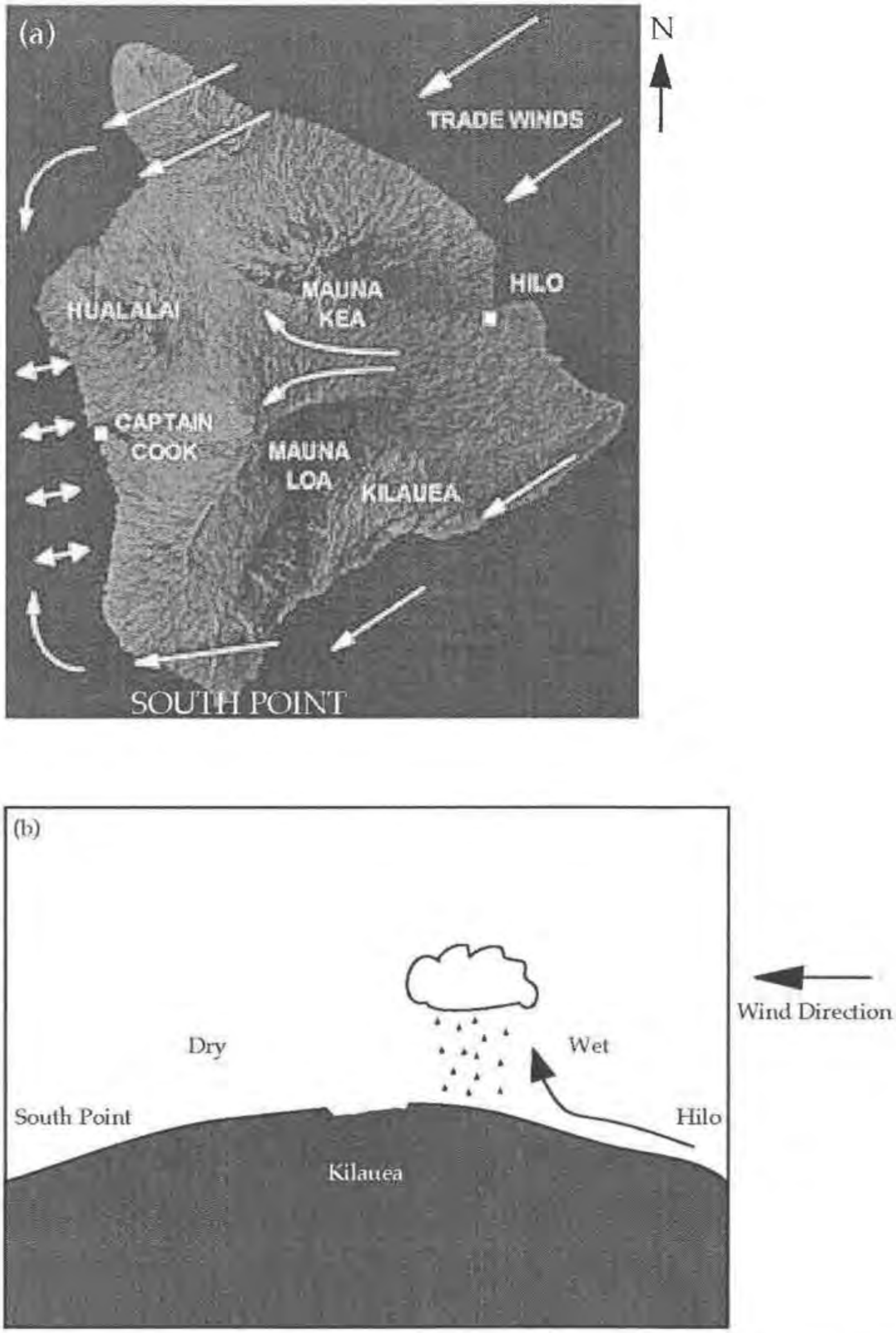


Figure 2.22 – *It is all in how the wind blows!* Wind patterns of Hawai'i generally show strong *trade winds* blowing from the *northeast* to the *southwest* (a). The strong trade winds result in more rainfall on the east and north side of the island (b). As the wind blows to the southwest and *rises* over the mountains of Kīlauea, Mauna Loa and Mauna Kea, the air *condenses* to form clouds that release the majority of their moisture on the *east* and *north* sides of the island.

Figure 2.23 – *Carved valleys and gently sloping sides all on one island.* (a) Waipi'o Valley on the northeast side of the island is the perfect example of a highly dissected valley cut away by the abundance of water on the east side of the island (Photo by R.H. Ashton). (b) The west side of Hualalai is an example of a drier region on the island where not much rain falls to erode away the landscape, so that deep valleys are not present (Photo courtesy J. Kauahikaua, USGS, HVO).

What controls how much vegetation grows? Rain is a key ingredient for plant growth, and the type of soil is another factor. But although the south and west sides of the caldera are a desert, a visitor from Arizona might think 30-40 inches per year is a flood! So, what else is hindering plant growth? Even though there are no eruptions of lava currently at the summit, there are other types of volcanic activity? What do you smell near Halema'uma'u and which way does the wind normally blow? About 1,100 tons of sulfur dioxide (SO_2) per day were emitted from Kīlauea from 1979-1997, and carried with the wind toward the southwest (Sutton and others, 2000). When you mix SO_2 with rain, you make acid rain. Plants do not thrive on acid rain; hence the result is a further reduction of vegetation downwind of the caldera.

Take a walk around the area near the visitor center, the Volcano House, and down Crater Rim Trail towards the steam vents to see other vegetation clues. Along the path you should see a surveyor's marker amongst the trees and vegetation changes farther down the path. Why is there a marker amongst the trees? Doesn't the surveyor need to be able to see the marker to make an elevation measurement? Back in the 1800's and early 1900's there were not as many trees in the area around the Volcano House and Visitor's Center as today. Have you looked at your feet recently? People come to see lava but on this trail you are walking on Keanakāko'i Ash resulting from the explosive 1790 eruption at the summit. Close to the steam vents there is not very much vegetation growth because the ground, made out of volcanic ash, is not very nutritious for plants and it is heated locally by a magmatic intrusion. The normal faulting and fractures along the caldera edge provide pathways for steam to rise.

Some other vegetation clues around the summit occur near Thurston Lava Tube. If you stroll down Escape Road and look into the pit craters that line the road, you will see something very interesting that lends clues to Kīlauea's history. What do you notice about the trees inside and outside the pit crater? The trees inside the pit crater reach to the same heights as the trees outside the crater. What does this clue tell you about the age of the trees inside and outside of the pit crater? If the trees in the pit crater are the same age as the trees outside the pit crater, the trees outside should reach much higher. However, the trees all reach the same elevation because the trees inside the pit crater are older. During explosive phreato-magmatic eruptions of Kīlauea, as occurred in 1790, base surges flowed across the landscape, killing and flattening trees. Trees residing in pit craters were shielded from the blast and survived, while trees outside the blast were killed. If you reflect on the 1980 eruption of Mt. St. Helen's, the lateral blast flattened large pine trees like they were matchsticks (Figure 2.24). A base surge with less force would flatten supple hapu'u pulu ferns and 'ōhia-lehua trees. As the vegetation grew back, the trees inside and outside the pit craters continued growing at the same rate so that they reach to the same height in the sky (Figure 2.25).

As you travel throughout the park and explore on foot, you'll notice patches of vegetation (trees, shrubs, grasses) surrounded by lava flows. These patches of vegetation are known as kīpukas (Figure 2.26). As lava flows over the land, it follows a path of least resistance and fills in low areas, leaving the elevated, higher areas untouched. A kīpuka was formally a higher region of land even if it looks on par with the level of the current landscape. It is always an interesting sight to see a forest amongst a sea of black lava. Kīpukas play an important role as a seed source for plants so they can re-inhabit the landscape relatively quickly after lava-flow coverage.

Figure 2.24 – *The present is the key to the past.* A lateral blast along the ground (base surge) from an explosive eruption can flatten trees like matchsticks. This picture shows trees lying flat on their side after the eruption of Mt. St. Helens, Washington, 1980 (Photo courtesy of L. Topinka, USGS, CVO). In Figure 2.25 the present events at Mt. St. Helen's relate to past events that occurred in Hawai'i.

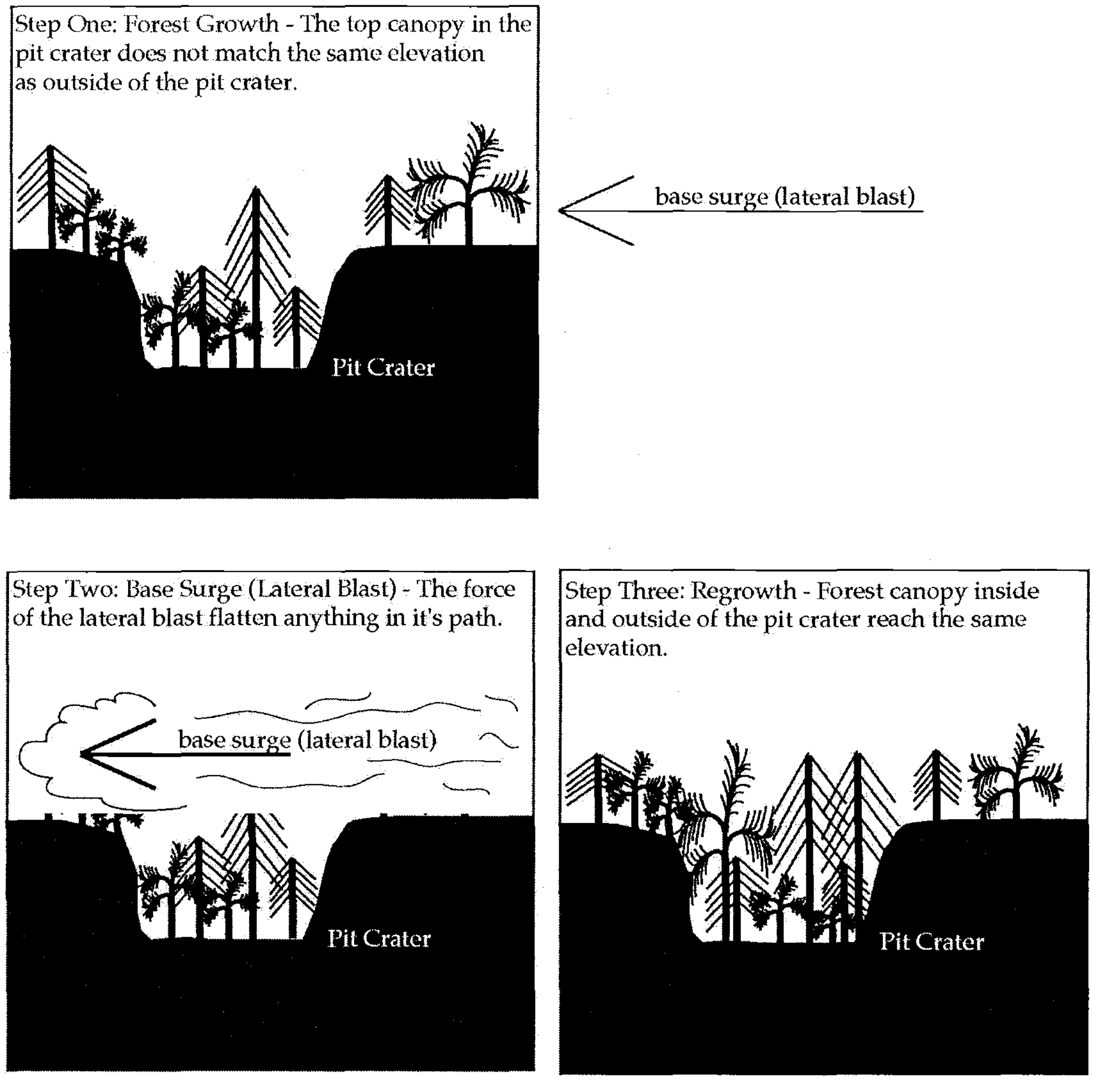


Figure 2.25 – *Ecology Observation.* The process that produces trees of the same elevation inside and outside of the pit crater is a force of nature. A lateral blast will flatten any tree in the way of the force (Figure 2.24). Trees inside a pit crater receive shelter and remain unharmed. After the base surge, new vegetation outside of the pit crater will begin to grow, while growth inside the pit crater continues, creating the match in elevation.

(a)

(b)

Figure 2.26 – *A patch of green in a sea of black.* (a) Kīpukas are islands of vegetation surrounded by black lava that may now display the same elevation as the surrounding landscape (Photo by R.H. Ashton). This kīpuka (a) is located on the southern coast of the Big Island. Kīpukas were originally elevated pieces of land. They remained unaffected by lava as it flowed through the area. Some kīpukas are easy to see because they are still elevated regions of land. For example, Pu'u Huluhulu (b) is a kīpuka on an old cinder cone (Photo courtesy N. Nesvadba, USGS, HVO).

Chapter Three

Lava Flow Features:

A detailed look at surface features

"As we trotted up the almost imperceptible ascent and neared the Volcano, the features of the country changed. We came upon a long dreary desert of black, swollen, twisted, corrugated billows of lava – black and dismal desolation! ... There had been terrible commotion here once, when these dead waves were seething fire; but now all was motionless and silent – it was a petrified sea!"
- Mark Twain's Letters from Hawaii (Day, 1966)

A few questions from curious visitors ...

- *How long does it take the lava to cool?*
- *When is it cool enough to walk on?*
- *When is it cool enough for plant growth?*
- *Which type of lava flow moves faster?*
- *Which is heavier?*
- *Which is more common? Which is located where?*
- *How do lava tubes form?*

Types of Lava Flows

When people think of lava flows, they usually come up with a picture portrayed in a movie. A rushing river of hot stuff eating everything in its path. Yes, it may destroy vegetation, buildings, and roads in its way, but, in reality, people can usually out-walk an advancing lava flow. Lava flows in a channel travel at speeds of about 3-6 feet (1-2 meters) per second (Cashman and others, 1999), although some rare lava flows in Africa have been recorded to travel at velocities as high as ~40 miles per hour (60 kilometers/hour; 60 feet/second; 18 meters/second) (Francis, 1995). If you have the opportunity to view an active lava flow, it will probably move almost painfully slowly. And the surface of the lava commonly cools enough in a day to enable someone to walk across a fresh lava flow. But this is not at all recommended because it may still be hot enough to melt the souls of your shoes! The surface of the flow chills and hardens quickly, but lava is a poor conductor of heat. Therefore, the interior of a flow may stay hot for weeks or even months.

There are two common end-member types of basaltic lava flows. Pāhoehoe and 'a'ā are Hawaiian terms that date back to the time when researchers first became interested in Hawaiian volcanoes during the 1800's. MacDonald (1953) was the first to begin modern, groundbreaking work classifying solid pāhoehoe and 'a'ā and the connection between surface morphology and flow emplacement. Today, these terms are used universally around the world. Oftentimes the terms are used for lava flows as opposed to the solidified product. Hon and others (2003) propose reverting back to the usage of pāhoehoe and 'a'ā as stationary, solid products as opposed to something in motion. It was commonly thought that only pāhoehoe could transition to 'a'ā. However, it has been recently well documented during the Pu'u 'Ō'ō-Kūpaianaha eruption that 'a'ā can transition to pāhoehoe. The difference between the two terms relate to physical changes in the lava flow rather than a chemical difference. It is very easy to pick out a solidified pāhoehoe flow versus an 'a'ā flow in the park (Figure 3.1). Pāhoehoe is smooth and ropey, while 'a'ā is rough, jagged and very difficult to walk across. Your boots and legs will not thank you if you decide to traverse an 'a'ā flow!

Pāhoehoe flows are usually found near the volcanic vent and result from sustained low to moderate effusions of lava for longer periods of time (MacDonald, 1953; Holcomb, 1987; Kauahikaua and others, 1998). Pāhoehoe travels across the landscape by budding toes, lobes, and lava tubes. The scenario where pāhoehoe dominates the landscape involves transportation long distances in lava tube systems (Swanson, 1973; Greeley, 1987; Peterson and others, 1994). The abundant amount of pāhoehoe found on the coastal areas were mostly fed by lava tubes that help retain heat, hindering the transition from pāhoehoe to 'a'ā. Holcomb (1987) reported that 86% of Kīlauea is covered with pāhoehoe. More recently, Clague and others (1999) suggest 81% of Kīlauea's surface is covered by pāhoehoe flows distributed by lava tubes or surface flows. If you peer at a pāhoehoe flow unit, the thickness is usually on the order of a few inches to a few feet.

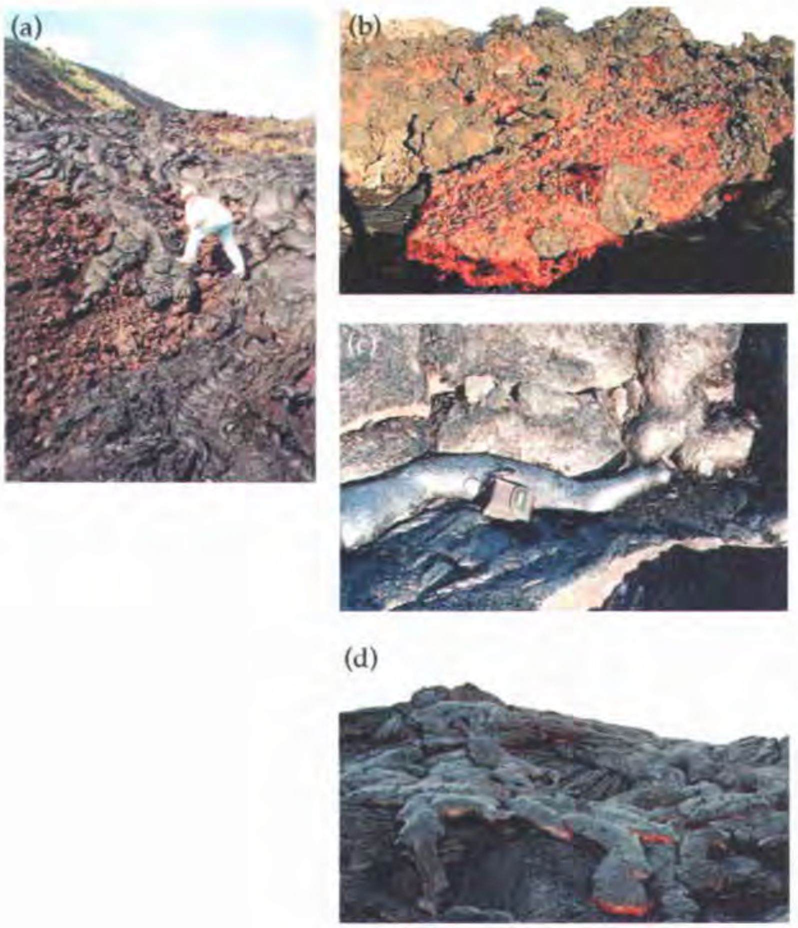


Figure 3.1 – *Difference between pāhoehoe and 'a'ā lava flows.* (a) The surface features of a pāhoehoe flow include *smooth* and *ropey* textures that are *easier to walk across* than the *jagged, crumbly* 'a'ā flows (Photo by R.H. Ashton). (b) Because of the *massive interior* and the *clinkery top,* an 'a'ā flow can look like a *tank tread* heading your way (Photo courtesy USGS, HVO). (c,d) When a pāhoehoe flow moves forward, unlike the 'a'ā tank trend, it moves by *inflation, budding toes,* and *breakouts* (Photos by R.H. Ashton).

As a pāhoehoe flow travels across the landscape at millimeters to 10's of centimeters per second (a fraction of an inch to a few feet per second), it breaks out and forms lobes that are about 8 to 120 inches (20 to 300 centimeters) wide and about 4 to 20 inches (10 to 50 centimeters) thick (Keszthelyi and Denlinger, 1996). Pāhoehoe may even form sheets 100's of feet (10's of meters) wide and 1,000's of feet (100's of meters) long and inflate to 10 to 16 feet (3 to 5 meters) thick, which are called tumuli. Internally, a pāhoehoe flow has lots of holes (i.e., it is vesicular), and the vesicles are usually round (Macdonald, 1953) (Figure 3.2). If the pāhoehoe flow is thick and inflated, the vesicles may be concentrated in upper and lower layers (Hon and others, 1994).

'A'ā often seems to resemble a bull-dozed pāhoehoe flow. 'A'ā flows are produced from short-lived, high volume eruptions of lava (Macdonald, 1953). The majority of 'a'ā flows are found farther down-slope, away from the vent. This relationship may be hard to notice because there is a lot of pāhoehoe near the coast; in this case, either, lava tubes insolate lava and provide a subway system to allow pāhoehoe flows to be distributed at great distances from the vent or as an 'a'ā flow progressed from a steep slope to a gradual slope, it transitioned back to a pāhoehoe flow. 'A'ā flow units tend to be much thicker, on the order of several to 10's of feet (several meters) thick and travel like a tank tread across the ground. Due to the mixing and turbidity of 'a'ā flows, their surface morphology characteristically changes along the flow length showing a wide variety of flow types (Katz and Cashman, 2003). Internally 'a'ā flows are massive, often thermally stratified, commonly contain more developed and a higher density of mineral crystals with fewer vesicles present. The vesicles that are present are irregular in shape and more interconnected (Macdonald, 1953; Polacci, 1999; Cashman and others, 1999) (Figure 3.2).

While exploring the park, take a look at the differences where the Chain of Craters Road cuts the lava flows, exposing the internal structure of a lava flow. Look at the differences in vesicles, internal structure, and thickness of the two different flows. Even though there are several differences between 'a'ā and pāhoehoe, none of them are so great as to change the density of the rock. If you pick up two same-sized chunks of lava, one pāhoehoe and the other ʻaʻā, they will weigh about the same.

Why the looks?

Two important factors in lava flow surface texture are viscosity and strain rate (Figure 3.3). Viscosity refers to the resistance of a fluid to flow. If you increase viscosity it will become less fluid. For example, water is less viscous and hence flows more easily, than cookie dough. Cooling, crystallization, and degassing all increase the viscosity of the lava; it becomes stickier. *Strain rate* can be easily related to stress. Stress refers to how much force per unit area (pressure) is placed on an object, while *strain* is the deformation (compression, stretching, or shearing) caused by the applied stress. Strain rate is simply how fast the deformation occurs. For example, if you have a block of Play-Doh and push down on it with your hand, you are applying stress. The strain is the change in shape the block undergoes as you push down on the Play-Doh. Shear strain refers to the internal distortion of a lava flow caused by the shear stresses. The best way to imagine shear strain involves a deck of playing cards. If you take a stack of cards and press your hand across the top, the deck will begin to slide and slant. The slanting of the deck resembles shear strain. The rate is how fast the deck of cards slides.

The surface of pāhoehoe and ʻaʻā flows may be distinctive to the naked eye, but the chemistry of pāhoehoe and ʻaʻā are the same, the extrinsic and intrinsic physical processes involved in creating what is seen on the surface are complex. Geologists have been studying the cause of the morphologic changes between pāhoehoe and ʻaʻā since the late 1800's, but the work of Macdonald (1953) began a trend to describe the connection between morphologic controls and flow emplacement. More recently, geologists are further trying to constrain the processes involved in the creations we see today. If the processes are well determined, it will help protect and determine future high-risk, hazardous areas. The two main factors controlling surface morphology of pāhoehoe and ʻaʻā link to viscosity and strain rate (Peterson and Tilling, 1980) (Figure 3.3). Viscosity and strain rate are influenced by flow advance and emplacement that varies with eruptive style and distance of transport (Cashman and others, 1999; Hon and others, 1994; Holcomb, 1987; Peterson and Tilling, 1980; Swanson, 1973; Macdonald, 1953). Surface distribution is controlled by slope (Holcomb, 1987; Peterson and Tilling, 1980), duration of eruption (Holcomb, 1987; Peterson and Tilling, 1980), eruption rate (Holcomb, 1987; Peterson and Tilling, 1980), and location of the vent. However, temperature (Swanson, 1973; Peterson and Tilling, 1980; Greeley, 1987; Peterson and others, 1994), crystallization (Swanson, 1973; Peterson and Tilling, 1980), amount of gas (Macdonald, 1953; Polacci and others, 1999), mixing (Macdonald, 1953), shear stress (Macdonald, 1953), and yield strength are all intrinsic conditions affecting the transformation process of a lava flow. For some time, scientists would state that the irreversible transition from pāhoehoe to 'a'ā' occurred due to cooling and degassing of a flow. However, every flow cools and looses gas, so why doesn't every flow transition to 'a'ā? As a pāhoehoe flow cools and crystallizes, it will eventually stop flowing and solidify in place.

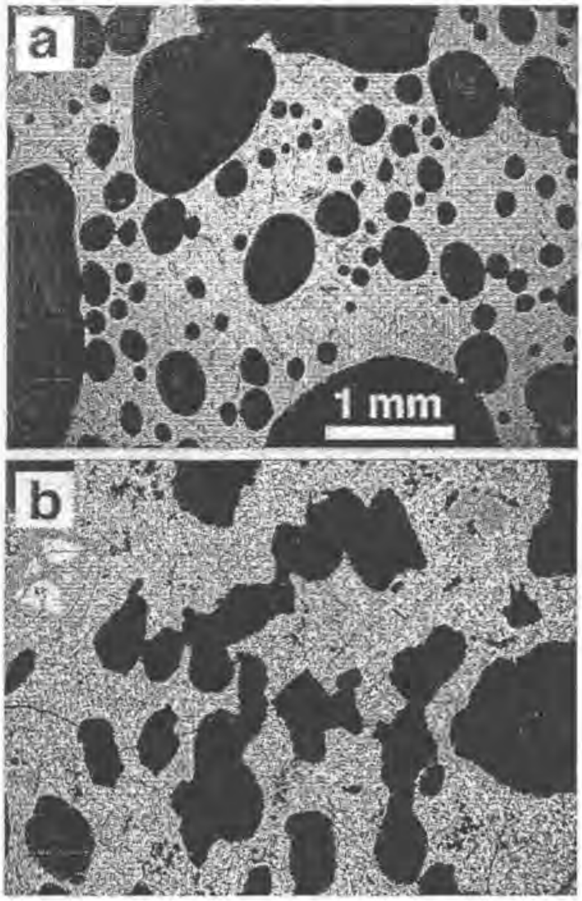


Figure 3.2 – *Internal structure of lava flows* (from Cashman and others, 1999). The interior of pāhoehoe and 'a'ā lava flows display differences just like their surficial differences, even though their chemistry may be identical. (a) The interior of a pāhoehoe flow can be *massive* or *layered* with *highly vesiculated* zones. The vesicles are *rounded* and *uniform*. (b) The interior of an 'a'ā flow is massive with *fewer vesicles*. The vesicles that remain in the interior of the flow are usually *mangled* and *deformed*.

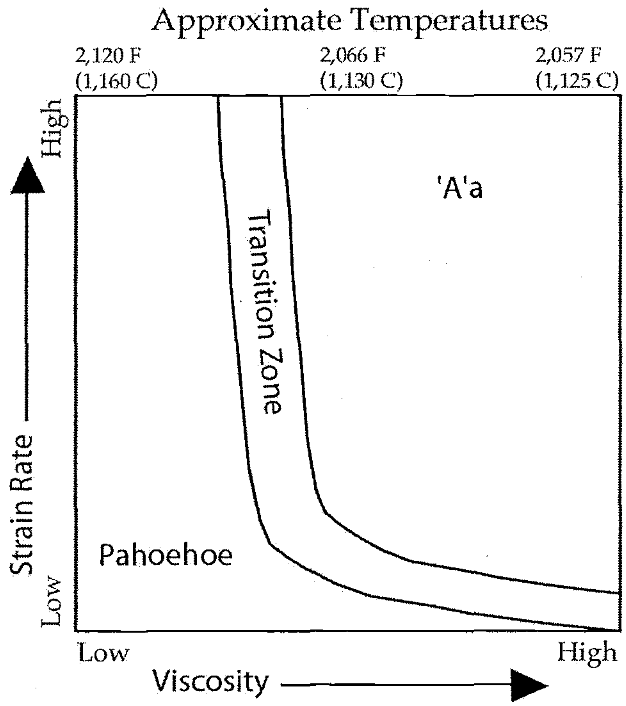


Figure 3.3 – *Viscosity vs. Strain Rate.* The diagram, modified from Peterson and Tilling (1980), has been the foundation explaining the transition of pāhoehoe to ʻaʻā for the past few decades. It shows that as viscosity or strain rate increases, a lava flow may reach a critical point and begin the transition from pāhoehoe to ʻaʻā. A lava flow may also begin as ʻaʻā and transition to pāhoehoe if there is a rapid decrease in strain rate. Current lava flow research greatly supports this idea and strives to constrain what controls viscosity and strain rate. For example, crystallization of a flow increases viscosity, and slope or eruption rate are key factors that determine strain rate. An increase in slope (pali) increases the strain rate.

If a force is pushing the flow forward, the flow front will break into chunks to become an ʻaʻā flow. In most instances, the transition from ʻaʻā to pāhoehoe occurs as a flow moves from a steep slope such as a pali to a more gentle slope. Therefore, the shear strain decreases. Other forces that change the strain rate include a change in eruption rate, or volume of material.

Usually you can describe a cause and effect relationship between many controlling factors that link back to viscosity and strain rate. For example, if you cool a lava flow, it will increase crystallization that, in turn, increases the viscosity. Or, if you increase the mixing (strain rate) within the flow, it will cool and crystallize more rapidly, and that increases the shear stress. If the eruption rate is high, there is more mixing that results in a higher strain rate. If a lava flow travels down a pali, it will increase the shear stress and strain rate. If a flow overcomes the yield strength of the material, it will break apart and turn into an ʻaʻā flow. Of course, not just one condition, but the right combination of conditions affecting the viscosity and strain rate of a flow results in the production of pāhoehoe or ʻaʻā. Geologists are continually trying to constrain those parameters in order to understand the hazards associated with volcanoes.

To relate viscosity and strain rate to a lava flow, think about cooking oil as analogous to hot, very fluid lava just erupted out of the ground. If you apply any velocity or amount of shear strain to plain cooking oil it will flow easily and quickly wherever you want it to go. If you add oatmeal, flour, sugar and sunflower seeds to the mixture (analogous to more crystallization in a lava flow farther down-slope) and apply more shear strain, the effect will be much different. The mixture will not flow as quickly or easily because the solid chunks or crystals will get in the way. If you change other parameters slowly (gentle slope or low to moderate eruption rate/volume), the mixture will remain intact and not break apart (pāhoehoe). But, if you change parameters quickly (steep hill/pali or increased eruption rate/volume), it may just crumble and break apart (ʻaʻā).

For a long time it was commonly accepted that pāhoehoe can change to ʻaʻā; the reverse, however, was not observed (Macdonald, 1953). But, the longevity of the current eruption of Pu'u 'Ō'ō-Kūpaianaha along with advancements in science and technology provide opportunities to study active volcanic processes in great detail. Due to the thermal stratification (hot internal core) of 'a'ā flows, it can lead to 'a'ā transitioning to pāhoehoe. What physically changes in the lava flow to create the two-way transition? After approximately 2,100°F (1,150°C) lava erupts from a vent, it cools, looses gas, and crystallizes. In one study, pāhoehoe transitioned to 'a'ā about 1 mile (1.5 kilometers) from the vent, with an interior temperature of about 2,080°F (1,140°C) and 15% crystal formation, and an exterior temperature of about 2,010°F (1,100°C) and 45% crystal formation (Cashman and others, 1999). Viscosity, in relation to cooling, de-gassing, and crystallization, combined with shear strain (greatly influenced by eruption rate or slope) determine whether pāhoehoe will change into 'a'ā or the vice versa. When the forces acting on a pāhoehoe or 'a'ā flow reach a critical point, the flow will begin to break up and become a chunky, clinker 'a'ā flow or smooth over to become a pāhoehoe flow (Figure 3.1).

Demonstration for Junior Rangers –
Supply list:

- Play Doh
- Deck of Cards
- Glass jar (ie - old spaghetti jar)
- Any type of cooking oil
- Oatmeal
- Flour
- Sunflower seeds
- Sample of pāhoehoe
- Sample of ʻaʻā

The goal of this program is to help kids understand what is going on inside a lava flow (how crystallization changes viscosity) to make it change from something smooth to something chunky. The program may be just as useful for adults if adjusted for them.

Get the kids involved by making someone the jar holder (depending on size of the group, you may need more than one jar) and others the oil, oatmeal, flour, and sunflower seed holders. Relay that plain oil is hot molten lava that has just erupted out of the ground. Fill 1/3 of the jar with oil and demonstrate how it moves freely around the jar (very fluid, little crystallization=low viscosity). As crystals form they may be all different sizes and minerals (i.e. – flour, oatmeal, sunflower seeds may represent olivine, pyroxene, and plagioclase). Use your helpers to begin adding crystals to the mixture and watch the effect to the oil. As the mixture becomes thicker, have the jar holder shake it up. Continue crystallizing the mixture until it becomes chunky (highly viscous). As you go through this process ask questions about what the audience thinks will happen. The more they talk and see the results, the better they will grasp the concepts. As a program wrap-up, take out pieces of pāhoehoe and ʻaʻā to discuss the demonstration. Hopefully, the kids will perceive the two flow types differently and then explain what they see on the trail to their parents!

To understand better the internal differences between a pāhoehoe and ʻaʻā flow, let's look at a study where thin sections were used to determined whether the flow type was pāhoehoe or ʻaʻā. Katz and Cashman (2003) examined lava cores to study how morphology reflects flow emplacement and the distribution of different flow types in the third dimension (depth). Because the flows were not on the ground surface, one could not identify a flow type based on its surface morphology.

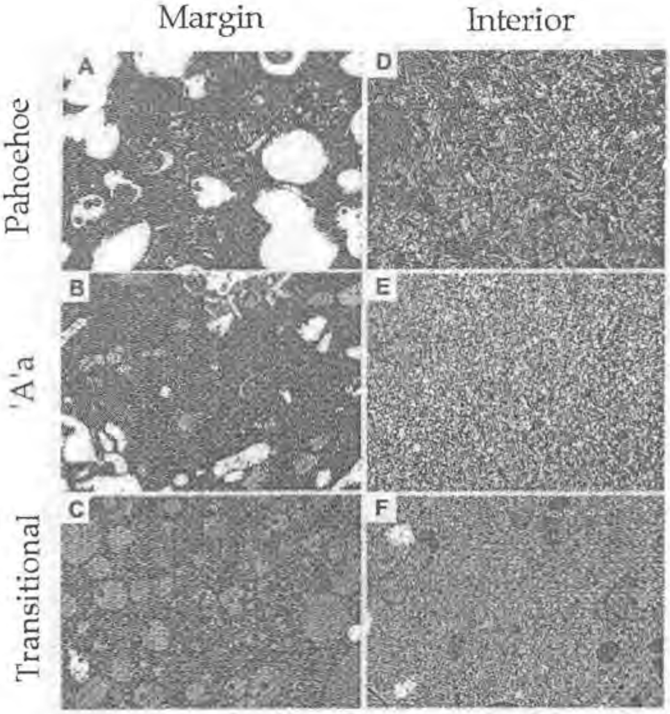


Figure 3.4– *A look at the insides, part II* (modified from Katz and Cashman, 2003). These photomicrographs and BSE images display the difference between the interior and edge of pāhoehoe and 'a'ā flows. Notice the spherical vesicles and glassy matrix in the edge pāhoehoe flow and the increase in grain size towards the interior. Notice the irregular vesicles towards the edge of the 'a'ā flow and the slight increase in grain size towards the interior. Images (a) through (d) are photomicrographs with a width of 4.5mm and images (e) and (f) are BSE with a width of 1.2 mm.

The description of pāhoehoe and 'a'ā in thin section provides a detailed look at the microscopic controls that elude the naked eye and support trends identified in the past. The margins of a pāhoehoe flow displayed a glassy matrix with spherical vesicles and little plagioclase or pyroxene crystal growth. A glassy matrix demonstrates how the exterior of the lava flow quenched and cooled very quickly. The interior of pāhoehoe flows are holocrystalline (completely crystalline) of moderate grain size. In the 'a'ā thin sections, the margins of the flows are very fine grained. Towards the interior of the flows, grain size increased slightly (Figure 3.4). The plagioclase groundmass in pāhoehoe and 'a'ā tell a story about different cooling histories. The flow interior plagioclase grains are larger in the pāhoehoe sample. This results when a flow is emplaced hot and cools slowly by conduction, allowing the growth of larger plagioclase crystals towards the interior of the flow and leaving the margins finer grained than the interiors (Katz and Cashman, 2003). In contrast, 'a'ā experiences a lot of mixing that more quickly and homogenously cools the entire 'a'ā lava flow resulting in similar crystalline margins and interiors.

Perhaps you are now thoroughly confused with geology lingo, so let's map out the transition from pāhoehoe to 'a'ā another way. If you have a stick of taffy, it will stretch as you slowly pull it apart. If you chill the stick of taffy or pull it apart too quickly, it will not stretch, but break instead. The stretching of the taffy can equate to pāhoehoe, while the breaking of taffy is more like 'a'ā.

Lava flows seem like an easy topic to talk about, but as you can see, it gets complicated very quickly. You could easily develop an hour-long guided hike focused on the differences between the two types of lava flows and their variations. Get out the hand lenses to show visitor's how to properly use them and ask if they can see any of the crystal differences between the types of flows. Visitor's come to Hawaii Volcanoes National Park to see flowing lava. That is not always possible, but you can inspire them to look at solid lava and become detectives in identifying the differences and "imagine" lava flowing and the different processes influencing a lava flow. Turn visitors into geologists for an hour, get out hand lenses, traverse an 'a'ā flow, and talk about why it looks like someone bulldozed the lava field. If visitors take a closer look at the scenery as they tour the park, they might notice that there is 'a'ā that looks like cauliflower or a variety that is rubbly. Pāhoehoe varieties include entrail, ropy (corded), shelly, and slabby. Be careful around the shelly variety because it often breaks under your weight, dropping you a few inches to a foot downward!!!

The best way to experience and understand textures so that you, as an interpreter, become more effective requires you to go out and experience the landscape for yourself and interact with the experts at HVO. (Don Swanson, chief scientist in charge, enjoys interpretation and loves to help people understand the landscape. Why not talk to him, someone who has studied volcanoes for many decades? What fascinates him the most and how does he think about a lava flow? Jim Kauahikauna grew up in Kālapana; how does he view lava flows as a Hawaiian and scientist?) It is easy to come across visitors hiking out to the active flows and constantly stopping to gaze at what is beneath their feet. There are so many features to ponder that an hour-long guided hike, where the visitor becomes a detective of lava flow features, could be very useful and frequently attended. The interpretation visitors make of the evidence all about them will help them imagine lava flowing, garner greater appreciation for the land around them, and in turn, inspire them to preserve the natural beauty.

> *"The last lava flow occurred here so long ago that there are none now living who witnessed it. In one place it enclosed and burned down a grove of coconut trees, and the holes in the lava where the trunks stood are still visible; their sides retain the impression of the bark; the trees fell upon the burning river, and becoming partly submerged, left in it the perfect counterfeit of every knot and branch and leaf, and even nut, for curiosity seekers of a long distant day to gaze upon and wonder at."*
>
> *- Mark Twain's Letters from Hawaii (Day, 1966)*

Lava Tube Formation

Lava tubes in Hawai'i Volcanoes National Park provide a playground for exploration. A lava tube is a conduit beneath the ground surface that lava flows (or has flowed) through (Greeley, 1987). Lava channels are also prevalent in the park. A lava channel is an unroofed groove that lava flows (or has flowed) through. The formation of lava tubes and how they contribute to the construction of a volcano are topics that can easily fascinate visitors. Three factors help the creation of intricate systems of lava tubes. First, the eruption should consist of a moderate amount of lava. A trickle or torrents of lava will not result in the formation of lava tubes. Second, the eruption should last more than just a day or two. Third, lava tubes will form more readily if the lava is pāhoehoe and has not degassed greatly (Greeley, 1987).

There are several ways to make a lava tube. The first way requires a lava channel. As the flow moves down the channel, it may overflow, building up levees and cool, forming a bridge over time. Second, flat, solidified crusts can grow across a channel to eventually form a roof for a lava tube. Third, large plates or slabs of lava can float down the channel of lava and become caught up and form a lava tube (Figure 3.5). Finally, at the front of a pāhoehoe flow, there are small breakouts called lava toes. As these lava toes progress forward, they may coalesce and form a tube (Figure. 3.6) (Peterson and others, 1994). If a hole develops in the top of a lava tube, it is called a skylight. Skylights generally form as lava cools and contracts, creating cracks and instabilities in the roof of the lava tube. The roof then collapses, forming the skylight hole (Figure. 3.5 (b)). Geologists use skylights to take lava temperature readings, measure lava flow velocity through the tube, and collect samples of flowing lava. Videography by Jenda Johnson and others (2002) helps.

What makes lava tubes so important? Geologists suggest that 58% (Greeley, 1987) to 67% (Holcomb, 1987) of the lava flows on Kīlauea are at least partially emplaced by lava tubes. These figures are estimates from air photography. I like to think of lava tubes as the arteries of the volcano. If people did not have veins, it would be a lot harder to transport blood around the body, especially to the far extremities. So lava tubes can transport lava long distances, like all the way to Hilo!

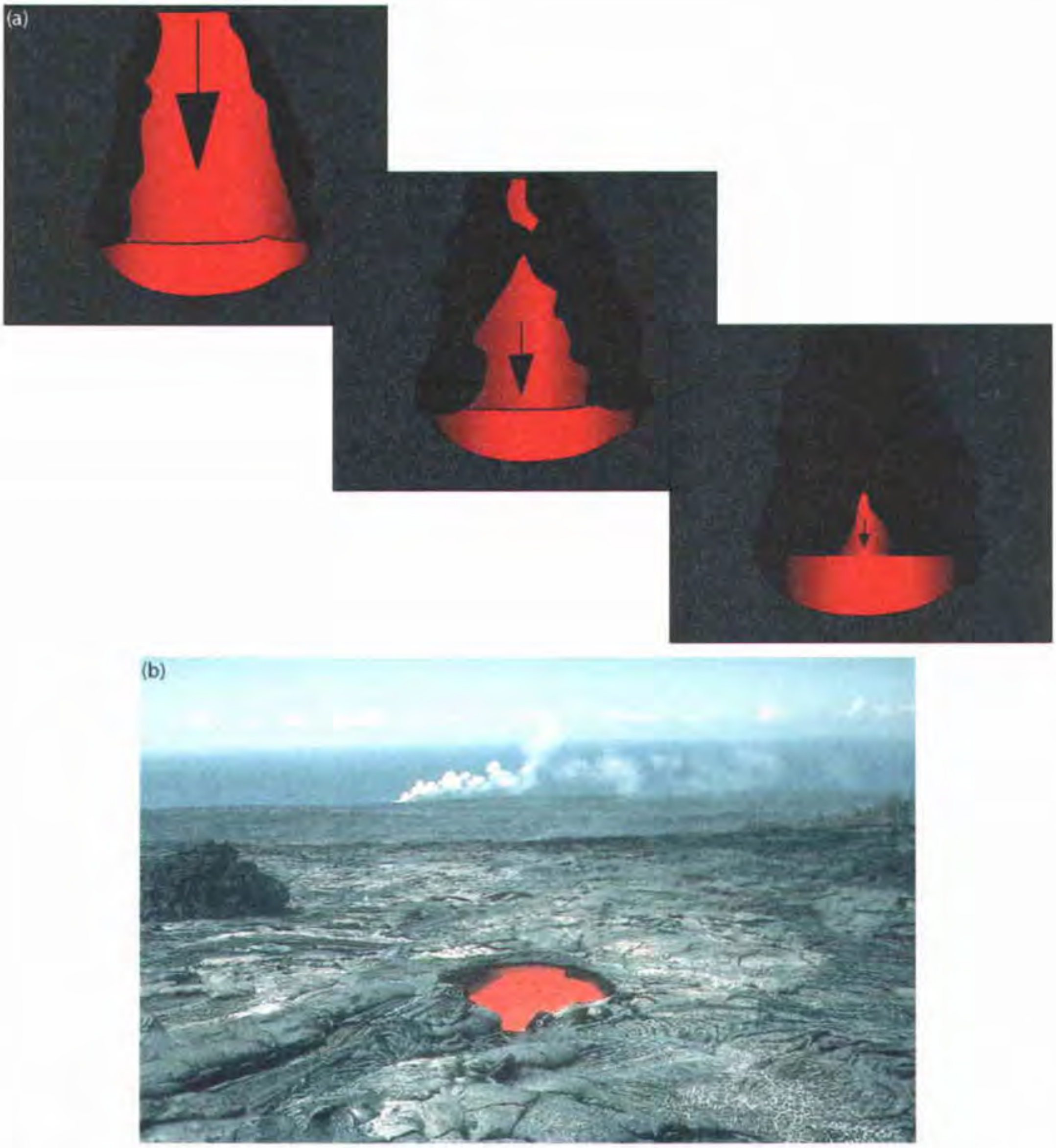


Figure 3.5 – *How does it do that?* There are several ways to create a lava tube. (a) The sides of a lava channel cool and crust over until they meet, forming a complete roof. (b) If a hole develops in the top of the tube as it cools and contracts, the hole is called a skylight (Photo courtesy USGS, HVO).

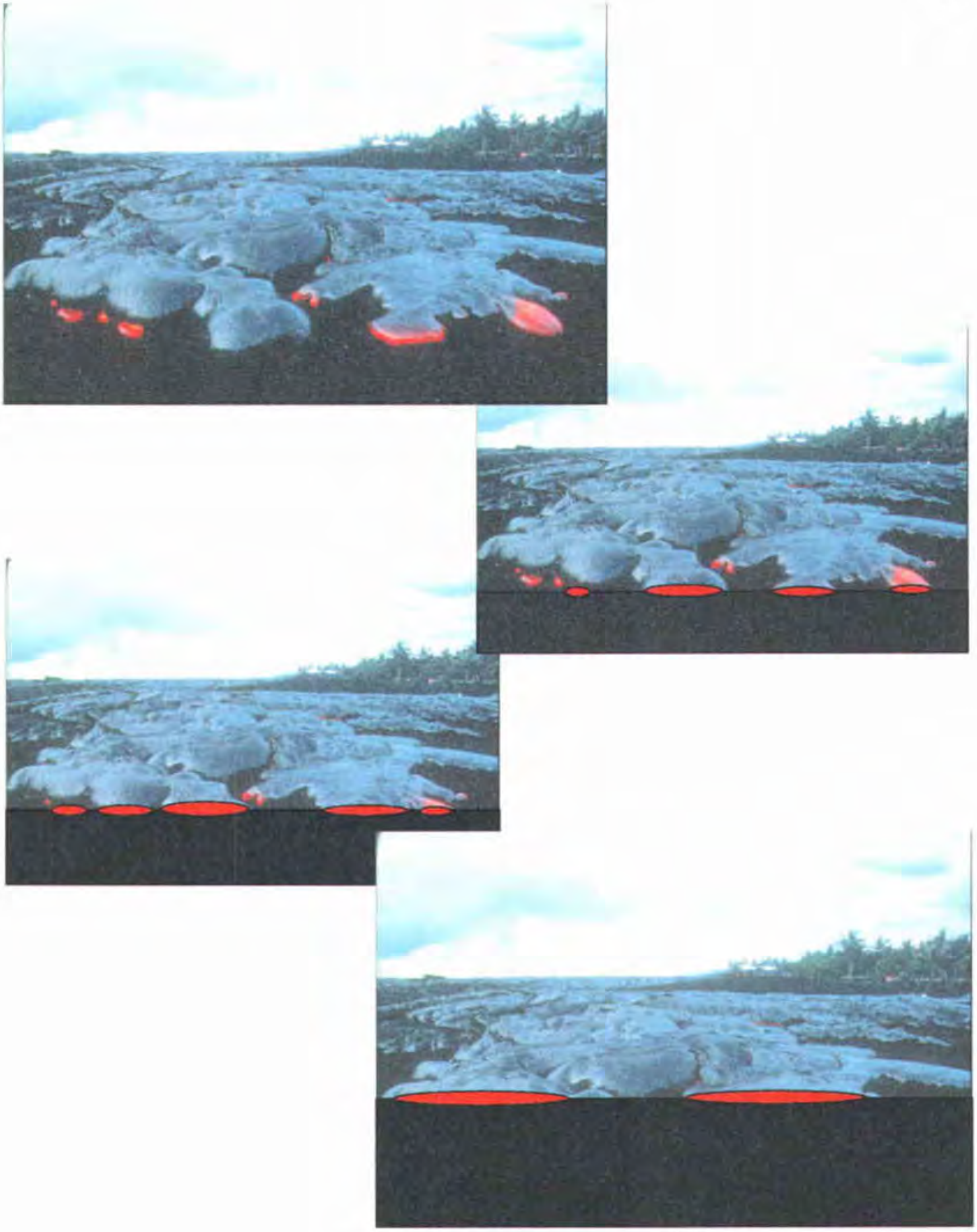


Figure 3.6 – *It can form in other ways?* Another way to form a lava tube consists of a more complicated process. As pāhoehoe flows progresses forward through *breakouts* and *budding of toes,* the toes may *coalesce* and form a tube if the interior remains hot enough (Photo courtesy NPS).

When lava enters a tube, the tube insolates the lava, hindering crystallization, allowing it to stay hot and retain gas thus enabling it to travel faster and farther downhill. This is why large amounts of pāhoehoe can form near the coast, far down-slope from the original volcanic vent. During the Mauna Ulu eruption heat loss was about 2.9 to 5.8°F per mile (1 to 2°C per kilometer) (Swanson, 1973) in lava tubes. With a flow velocity of about 3 to 7 feet per second (1 to 2 meters per second) (Kauahikaua and others, 1998) equating to cooling rates of less than 6.5 to 13.0°F per hour (3.6 to 7.2°C per hour). In contrast, lava cools faster in an open channel. Lipman and Banks (1987) observed 'a'ā flows from the 1984 Mauna Loa eruption cooling about 1.4°F per mile (0.5°C per kilometer) with a flow velocity of about 16 feet per second (5 meters per second). This produces a cooling rate of 26.0 °F per hour (14.4°C per hour). It does not seem like a large contrast, but the cooling rate is two to four times greater in an open channel as opposed to a lava tube.

Lava tubes not only help emplace flows far away from the vent by retaining heat, they can also provide linkage between a vent and a holding, or lava pond. T.A. Jaggar often noticed during active summit periods that lava ponds seemed to be linked because it appeared that one pond would drain its lava as another lake level rose (Bevens, 1988). The two ponds may have transported lava via a lava tube. Once a lava tube forms, it may or may not be a conduit for later eruptions. Lava tubes can become blocked or filled in through time by the occupation of other lava flows.

Thurston Lava Tube is the best known and most visited lava tube in the park (Figure 3.7). Sadly, most of the natural internal features of Thurston Lava Tube have been removed by people. As lava travels down-slope, it retains heat and can thermally and mechanically erode into previous lava flows, making the tube rounded. Kauahikaua and others (2003) recounted field measurements where lava flows down-cut within the tube at a rate of about 4 inches (10 centimeters) per day over the course of several months. But not all lava tubes are symmetrical and rounded like Thurston Lava Tube. On flatter areas, there is not as much downward gravitational force, so the lava tubes tend to be more oblate (Figure. 3.8).

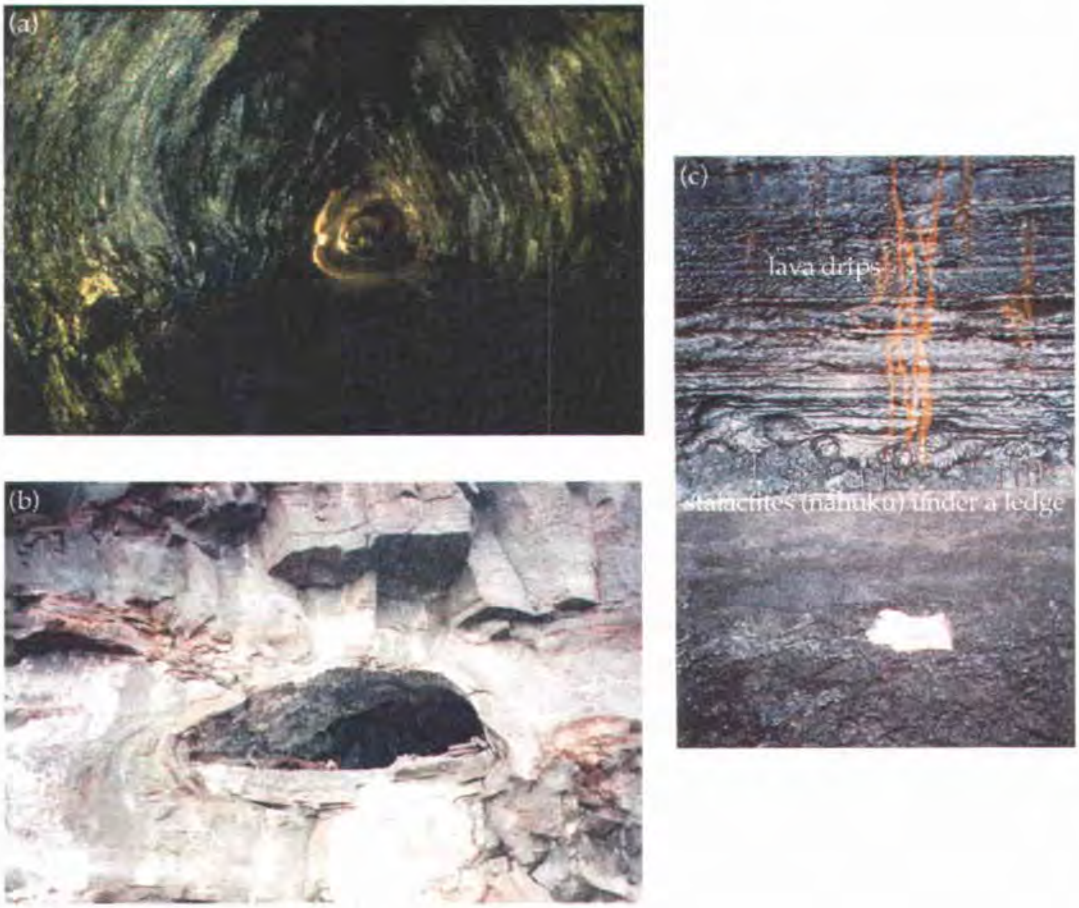


Figure 3.7 – *Fame brings sacrifice.* (a) The most famous lava tube in Hawai'i Volcanoes National Park, Thurston Lava Tube, has been *stripped by people* of much of its intricate detail (photo courtesy NPS). (b) Undisturbed lava tube on the coast (Photo by R.H. Ashton). (c) A pristine, untouched tube does not look like the inside of a plumbing pipe, rather it has many features, including *lava drips, stalactites,* and *ledges.* These features and others can also be seen on a guided hike through in the Pua Po'o lava tube (Photo by R.H. Ashton).

Figure 3.8 – *Lava tubes can come in all sorts of rounded and oblate shapes* (Photos by R.H. Ashton). Reading the landscape and the "roundness" of the tube tells you a lot about its history. An *oblate,* flat bottomed tube (a, b, d) may indicate that the *topography was fairly flat* and that there has been *no thermal erosion* that would tend to cut downwards and make the tube floor more rounded (c). An oblate tube may also indicate a *short lived tube* that did not have enough time to mature, thermally erode, and achieve a rounded shape. Photos (a, b, d) were taken at sea-level in HAVO and photo (c) was taken in a tube on the west side of the Big Island at an elevation of several thousand feet.

And lava tubes occupied for short periods of time do not erode to become more rounded, so that "young" lava tubes tend to be oblate as well. These ideas are similar to rivers. In the flatlands of the Midwest, rivers are often wide and do not cut down into the ground as much. Anyone who has been through the Rockies, however, has seen how rivers cut downward and are often flanked by steep canyon walls.

A wondrous world like no other resides hidden away from light amongst the small inner details of a lava tube. Most of the time when people explore a lava tube, they concentrate on their feet to make sure they do not stumble and fall. Some of the things at your feet offer numerous clues about lava that flowed through the tube. Here are just a few examples. As other flows occupy a tube, they can crust over and create bench marks on the side. A bench mark is a ledge that sticks out midway up the side of the lava tube. There can even be entire tubes within tubes. Another fun feature is flow ripples and younger flows "frozen" in the lava tube, creating a lining (Figure 3.9).

If you are brave enough to take your eyes off the floor or stop to take a look around, an amazing world of discovery awaits your attention. Some of the smaller features found in lava tubes consist of nāhuku (lava stalactites), lava stalagmites, lighter brown drip lines running down the sides of the walls, and the famous Pua Po'o, a feature that resembles a cockscomb (Figure 3.10). Nāhuku diameters range from 0.4 to 1.0 centimeter. Lengths range from perceptible up to ~3 feet (~1 meter) (Allred and Allred, 1998). After the features cool and harden, they will not grow any larger. Once these features are broken off by humans, they are gone forever. Unlike limestone caves that continue to grow and develop large stalactites, stalagmites, and pillars over long periods of time, lava tubes do not continue to develop once the lava stops flowing. Pua Po'o, the name of the cave that holds the cockscomb feature, was discovered when installing a pig control fence. The Pua Po'o feature is not found in every lava tube, but similar features could be present. There are several Pua Po'o-looking structures along the cave tour conducted by the National Park Service. These features display naturally-formed, intricate detail.

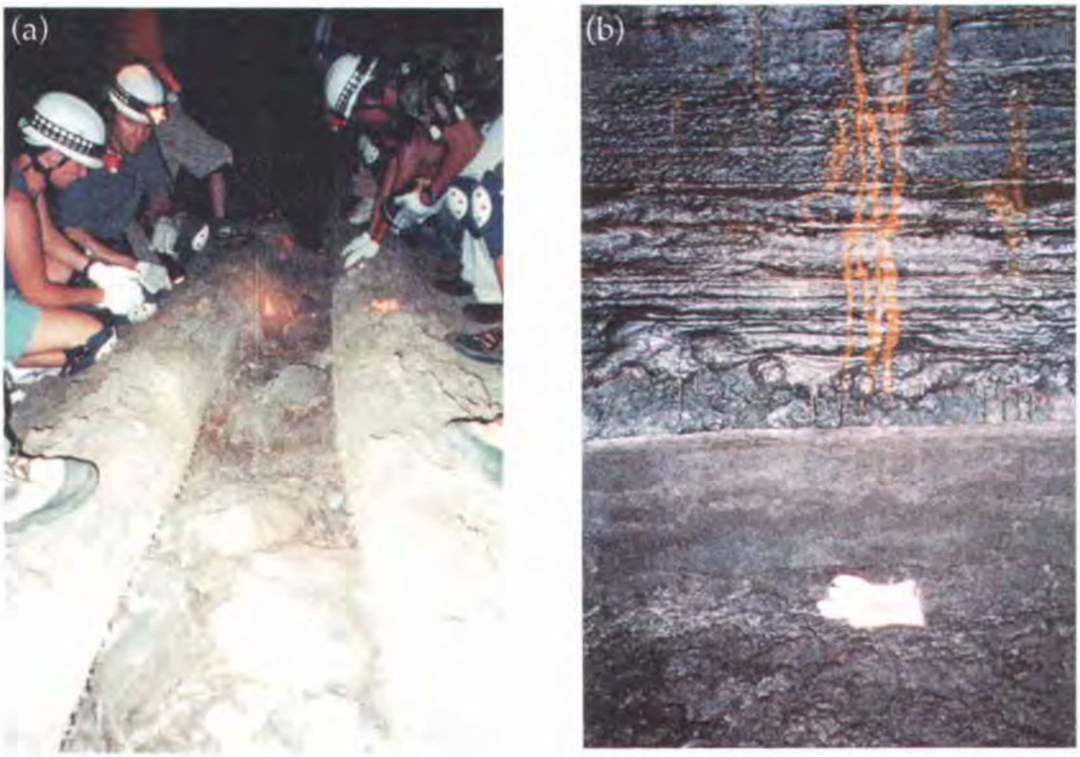


Figure 3.9 – *Geologist are like detectives.* They are given some clues and have to piece together a story. But it does not take an experienced geologist to identify clues and features inside a lava tube. There are various indications that a lava tube has been occupied more than once, such as channels (a), benchmarks on the side of the tube (b), lava ripples frozen in time, lava tubes within lava tubes, lava linings (b), and drip lines. (Photos by R.H. Ashton).

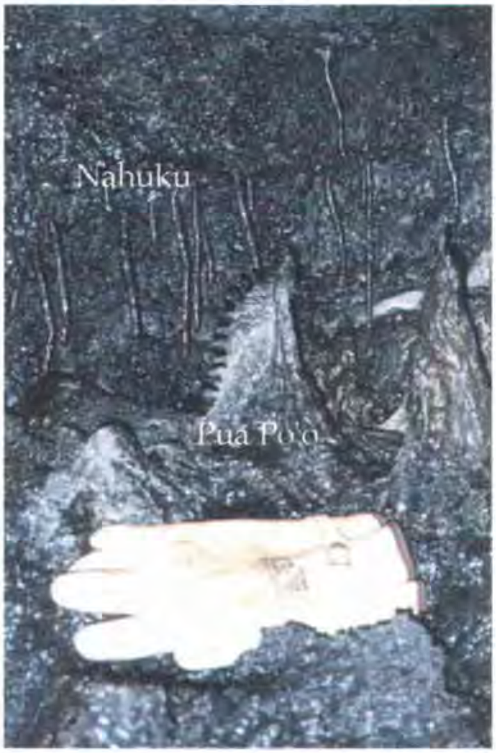


Figure 3.10 – *Pieces of the story.* Other features inside a lava tube include nāhuku (stalactites) and the Pua Po'o (cockscomb) (Photo by R.H. Ashton). The environment of a lava tube when it is occupied by molten magma is nearly impossible to imagine. Think about 2,000°F (1,100°C) lava flowing swiftly downslope. The resulting drafts and currents of air make the inside of a lava tube so extreme that it cannot be monitored very well or recreated in a laboratory.

A proposed hypothesis on the formation involves the action of hot gases flowing turbulently throughout the lava tube (Robinson, J., 2001, personal communication). We can theorize about how formations come about, but lava tubes are just simply too hot and too hard to recreate in order to actually see formation of some of the awesome features. To think about possible explanations for these features, let's take a moment to re-address the conditions inside a lava tube during occupation. The lava is about 2,000°F (1,100°C) with hot gases roaring throughout. As the lava cools and crystallizes, it can segregate at ~1,070°C to ~1,000°C (1,960°F to 1,830°F) forming drips from the ceiling that make features similar to icicles in the winter, called lava stalactites (Allred and Allred, 1998) or nāhuku in Hawaiian. The brown dripple lines could have formed by segregation during cooling, but the reddish-brown color indicates that the iron oxidized to the mineral hematite (Allred and Allred, 1998). Geologists call the segregation retrograde or resurgent boiling. When lava begins to crystallize, the remaining fluid phase with excess water separates, possibly creating the stalactites and brown dribble lines.

Interpretation in Hawaii Volcanoes National Park

> *Here and there were gleaming holes twenty feet in diameter, broken in the dark crust, and in them the melted lava – the color a dazzling white just tinged with yellow – was boiling and surging furiously; and from these holes branched numberless bright torrents in many directions, like the "spokes" of a lady's fan, and kept a tolerably straight course for a while and then swept round in huge rainbow curves, or made a long succession of sharp wormfence angles, which looked precisely like the fiercest jagged lightening.*
>
> *- Mark Twain's Letters from Hawaii (Day, 1966)*

This chapter, up until now, has taken a detailed and magnified look at why and how lava reacts in certain ways. I have discussed a few ideas that are hot on the research platter. But, the general public may not receive much of this information. Let's venture back to interpretation in Hawai'i Volcanoes National Park.

Well travelled paths

Let's talk about the most important localities for an interpretive ranger at Hawai'i Volcanoes National Park. The majority of people circle the 11 mile (~18 kilometer) loop , Crater Rim Drive. A few people venture to the coast and, unfortunately, even fewer attend a program. Most of your programs will be in the summit area or related to the East Rift Zone. Study up on the specifics of Kīlauea Iki, Kīlauea Caldera, Mauna Ulu, and the current eruption. Hazlett (2002) is a superb resource for all of the nitty gritty details. I left the current eruption of Pu'u 'Ō'ō mostly out of this manual simply because it is ongoing and there is a plethora of information. Much of what I might say today will be out of date tomorrow. A book about Pu'u 'Ō'ō could be three times longer than this manual all on its own. A good starting reference for the current eruption of Pu'u 'Ō'ō-Kūpaianaha is the U.S. Geological Survey Professional Paper 1676 edited by Heliker and others (2003). Below is a table of some specifics about the destruction of the Pu'u 'Ō'ō eruption to get you started.

Table 3.1 – *Current Kīlauea Eruption - Crunching the numbers*

Total area covered, March 1983 - December 2002:	42.6 square miles (110.4 km^3)
Net total of new land created, November 1986 – December 2002:	544 acres (220 ha)
Volume of lava erupted, March 1983-December 2002:	0.6 cubic miles (2.3 km^3)
Height of Pu`u `O`o cone (September 2002): Max height (1987):	613 feet (187 m) 835 feet (255 m)
Dimensions of Pu`u `O`o Crater:	820 ft x 1,312 ft (~250 m x 400 m)
Thickness of lava at the coast:	33-115 feet (10-35 m)
Length of highway covered by lava flows:	8 mi (13 km)
Residences destroyed, 1983-1991: Total number of structures destroyed since 1983:	181 189
Total losses:	$61 million

(Brantley and Heliker, 2002 and USGS, HVO, 2002)

Use the resources of the USGS, HVO website (http://hvo.wr.usgs.gov/) as a launching pad. A lot of material is all right there for you to read and curb your curiosity. I encourage you to explore as much of the park as possible. Expand on your knowledge. And remember that not all of your knowledge is meant to reach the visitor, it is part of an accumulation process that will ultimately enhance your interactions with visitors.

Safety

- Hardened lava rock is extremely sharp. If you fall, you will gash yourself on whatever body part hits the ground. It is important to always wear long pants.
- If you plan to venture during the later part of the day carry plenty of flashlights with extra batteries. There were numerous families that I helped because Mom or Dad was holding the only source of light while the kids stumbled along trying to find their footing.
- Out on the coast, it is very hot, dry, and windy with no shade in sight. Often times the flowing lava is a long hike. A long sleeve t-shirt, hat, sunscreen, food, and a couple of liters of water are necessary.
- People worry about falling into the lava. Falling into the lava is almost impossible because the heat of the lava limits oneself. Visitors will know when they are close to the lava because they will be able to feel and see the heat waves.
- When lava hits water, it creates large explosions of hot rock and a large steam plume. The steam plume contains fragments of glass and harmful vapors like sulfur dioxide. INHALING THIS IS EXTREMELY HAZARDOUS TO YOUR LUNGS AND EYES.
- Another danger of the ocean entry is stepping on ground that looks deceptively solid. As lava enters the ocean it fractures and breaks apart creating rubble. Solid lava then covers the rubble, appearing stable. Geologists call this stable-looking feature a *bench* because it is significantly lower than the older, stable part of the land. At any moment the bench can break off and slide into the ocean. Visitors have died because they were on the bench, trying to get the perfect picture when the bench collapsed.

Remember, visitors are on vacation when they explore HAVO and do not follow their daily routine. Many people are pretty sedentary during their daily lives and may not be physically conditioned for an all-day adventure out on the coast in the hot sun. Because they are out of their element and not following their daily routine, they may not be eating or hydrating themselves properly. Weekend warriors will likely get hurt if they go on an all-day traverse across lava flows unprepared or uninformed. Some visitors may not think they need the proper information before they leave for a hike, so it is your job to talk to as many visitors as possible. Someone may *not* look like they are heading out to the lava flows even though that is their exact plan. As an interpretive ranger, your job not only entails inspiring the visitor about the beauty of Hawai'i Volcanoes National Park, but also acting as a safety officer to make sure no one injures themselves.

Questions for you to investigate?

There will be many questions that will come up in your stay in Hawai'i. These are just a few asked by visitors which I did not answer in the manual.

- *Why is it mostly steam at the steam vents area, but right across the road at the sulfur banks there is sulfur and steam?*
- *What is vog made of?*
- *What is the difference between a tree mold and a lava tree?*
- *Do volcanoes on the same island ever erupt at the same time?*
- *When will Mauna Loa erupt again?*
- *Why does the East Rift Zone erupt more frequently than the Southwest Rift Zone?*
- *When will the summit erupt again?*
- *When will we see lava fountains that every tourist brochure shows?*

Parting Thoughts

It has been an interesting journey to this point in time. I entered graduate school to study volcanoes. I love the field aspect of geology and the fascination of volcanic processes spark me to enter this exciting field of study. With the opportunity to combine education with geology, I took the challange to go to Hawai'i for six months. Within two weeks of arriving, I found that a few permanent interpretive rangers had already left Hawai'i to travel for part of the summer (hence, the need for me to fill in) and some permanent interps were as new as myself. Because a bulk of the experts were on vacation, my beginning preparation for becoming an interpretive ranger was largely supplimented by my 6 roommates who were volunteers for the last 1-3 months in the park. I realize now that I should spend four years reading and researching to find all of the articles, test ideas, and explore new ones. Because here I am, two years later, wrapping up this thesis and I find a reference for the Hawai'i bibliographic database begun in 1997. Bad job at searching for references ... Maybe. By now, I can project that there are well over 10,000 references in the database all about Hawaiian geology. There has been an explosion of publication since 1960 when technology allowed people to gather more data, more quickly, leaving a plethora of information for analysis and publication. The daunting task of a graduate student learning, organizing, and writing about Hawaiian geology is immense and I even have a 4 year background in geology as a headstart. Imagine not knowing anything about geology and arriving at Hawai'i Volcanoes National Park to be an "expert" on the geological acitivities of everything. Imagine relating it to someone who walks into the park for the day (or a few hours) and explaining something that will be meaningful to them in 10 minutes or less. There is a slim chance that someone can absorb the over 10,000 articles in the Hawai'i bibliographic database, understand it all, and then turn it around and make it stimulating and accurate for the public. An interpreter can do his or her best to make geology as accurate as possible, without pretending to be an expert. But, it is important for an interpreter to know, use, and explain geology terminology where appropriate. Do not overload visitors with too much lingo.

An interpreter balances on a fine line and often times they are not given the same resources or time to learn, absorb, and teach the material. A geologist may be an expert, but the interpretation aspect takes time to understand and develop. After working as an interpretive ranger, I feel there are a few important ideas to grasp. When an interpreter develops a program, the topic should be specific. Develop a concise theme statement and write a program that provides some background and quickly progresses to what visitors see and experience first hand. Include relations to everyday occurances to connect with the audience and gauge how well they are responding to the program. If there is a lack of response or enthusiasm, change the direction of the program. Remember, the program will not be perfect the first time. Revise often.

No matter what path is taken to interprete geology within a national park, there have been several people from both disciplines, geology and interpretation, that have greatly influenced my journey. First and foremost, Bob Lillie, began as a geologist and found a passion in the park service. He found a way to excite people about something more than just rocks. Bob helps break the stigmatism that geology in national parks is too complicated or boring for interpreters and the general public. Another geologist that successfully made the transistion to interpreter is Don Swanson (although not officially). His knowledge and excitement is infectous. He always takes time with the HVO volunteers and new interps to talk about hidden things right before their eyes and some of the off-the-beaten path geology in HAVO. He not only loves geology, but he enjoys collaborating with the park service. Ed Bonsey, a volunteer at HAVO, has so many years of experience. He is a meticulous gentleman who religiously reads and processes geology articles to better understand how Hawaiian volcanoes work and why the landscape looks the way it does. He is a wealth of knowledge in geology, biology, and history of the park. James Gale, HAVO Chief of Interpretation, is a legend in the discipline of interpretation. Relatively new to HAVO, but no stranger to interpretation and geology. He is a good teacher and knows how to make a good interpreter. Everything he says is valuable, just don't try to follow one of his diagrams after his lecture is over☺. You have to be there to experience it. Last but not least, Jay Robinson, another interpretation legend has dedicated his life to developing and training interpreters and actively continues as a field interpreter. His passion and understanding of interpretation and the national parks is a treat if you participate in one of his programs or training sessions. He is one of the most effective interpreters I have ever met along with Kevin Bacher. After a program by Jay, you feel how much he enjoys his job. It is hard to single out just a few people who have guided my path, but these are the ones who went above and beyond the call of duty. Interpretation is a process and for me it got off to a slow start, but the richness of knowledge and experience at HAVO is invaluable. Thank you for helping me continue to learn and fuel my love of nature. Cheers.

Glossary

% silica – Relative amount, by weight, of silica (silicon and oxygen; SiO_2) contained in an igneous rock. A volcanic rock with a low percentage of silica (~ 50% SiO_2) is basalt, the type of rock found in Hawai'i.

'a'ā – Lava flow that looks chunky and broken up on the surface. People often ask, "Who bulldozed the lava?"

andesite - A salt and pepper colored, fine grained, moderate silica (~60% SiO_2), extrusive igneous rock composed mostly of the minerals plagioclase, feldspars, and some iron-rich minerals. Has more silica than basalt, but less than rhyolite.

angle of repose – The maximum angle at which a pile of loose material can remain stable.

aseismic ridge – An ocean ridge that does not display seismic (earthquake) activity. For example, the Hawaiian-Emperor seamount chain, away from the Big Island, is an aseismic ridge.

asthenosphere - The relatively soft, solid layer of mantle that plates of lithosphere move around on.

basalt - A dark, fine grained, extrusive igneous rock composed of low (~50%) silica minerals rich in iron. Virtually every rock in Hawaii is basalt.

base surge – A ring-shaped blast of air and material that travels close to the ground after an explosive volcanic eruption.

caldera – A flat-bottomed, steep-walled, bowl-shaped, volcanic collapse feature with a diameter larger than about 1 mile (1.6 kilometers).

cinder cone – A cone-shaped hill, usually with a slope of about 30°, built up from ejected volcanic material ("cinders").

cinders – Small (0.2 – 1 inch (0.5 - 2.5 cm)), broken pieces of low-silica material ejected out of a volcano.

composite volcano (stratovolcano) – A cone-shaped mountain made up of generally high-silica lava flows with inter-layered mudflows, ash, and other volcanic materials.

convergent plate boundary - Where two plates slowly push together and one plate commonly slides (subducts) beneath the other causing volcanoes to form on the over-riding plate.

core - The center portion of the Earth which is composed of heavy iron and nickel.

crust - The Earth's outermost layer which is composed mainly of relatively light compounds of oxygen and silicon (silicates).

decompression melting – Formation of a liquid from a mass of hot rock by a release of pressure. Occurs because many materials have lower melting temperatures at lower pressure. Especially common at hotspots and divergent plate boundaries, where hot mantle rock rises to a shallow level, where pressure is much less.

diapir – An arch or anticline of rock with a soft core that has injected into brittle upper regions of rock.

dike – A slab of intrusive igneous rock (commonly nearly vertical) formed where magma cuts across existing rock layers.

diorite – A salt and pepper colored, coarse grained, moderate silica (~60%), intrusive igneous rock composed mostly of feldspars and iron-rich minerals. Diorite is the intrusive equivalent of andesite.

divergent plate boundary - Where two plates rip apart, and move in opposite directions, usually accompanied by volcanoes and small, shallow earthquakes. Divergent plate boundaries form continental rifts and mid-ocean ridges.

East Rift Zone – A line of weakness where eruptions extend from Kīlauea Caldera to ~ 50 miles (80 kilometers) offshore of Cape Kumukahi.

element - The most basic form of matter, with distinct physical and chemical properties.

fractionation – Process where minerals formed early during cooling and solidification of magma, sink, settle, and are thereby removed from their original magma source.

fissure – A long crack in the land.

fissure eruption – An eruption of lava that occurs along a long crack in the ground, creating a curtain of lava.

flow unit – The nearly-horizontal surface boundary that separates one lava flow from another.

fountain eruption – An eruption of fluid lava, propelled by expanding gases, that shoot up in the air like a fire hydrant.

flux melting – The addition of water lowers the melting temperature of minerals, leading to the formation of liquid.

gabbro - A dark, coarse-grained, intrusive igneous rock composed of low (~50%) silica minerals rich in iron. Gabbro is the intrusive equivalent of basalt.

geology – The study of the Earth and the processes above and below its surface that results in its landforms, rocks, and other features.

graben – A collapse feature similar to a caldera, but elongate rather than circular.

grain size – The size of the particles (mineral crystals or rock fragments) that make up a rock.

granite - A light, coarse grained, high (~70%) silica, intrusive igneous rock composed mostly of the minerals orthoclase, quartz, feldspars, and some iron-rich minerals. Granite is the intrusive equivalent of rhyolite.

Great Crack – A continuous crack along the Southwest Rift Zone that extends for about 14 miles (23 kilometers) long and up to about 49 feet (15 meters) wide.

hotspot – The expression on the Earth's surface of hot, buoyant rock rising through the mantle beneath the plates of lithosphere.

igneous rock - Cooled and hardened Earth material that was once partly or completely molten.

inner core - The center-most portion of the Earth, composed of iron and nickel that is solid because of the great pressure.

interpretation – To bring out the meaning or to demonstrate one's conception of observations.

intrusion (intrusive rock) – An igneous rock that cooled and hardened slowly beneath Earth's surface (plutonic rock).

kīpuka – An island of vegetation, consisting of older soil surrounded by younger lava flow rock.

laccolith – The cooled, hardened remnants of intrusive, horizontal layer of magma that creates so much pressure that the layers above are pushed upward into an arch.

lava – Molten Earth material (magma) that flows out onto the surface of the Earth.

lava channel – An open (unroofed) groove through which lava flows (or has flowed) like a river.

lava dome – Magma piled near a volcanic vent, like a bulb of lava.

lava toes – Small break-out of magma at the front of a lava flow that look like toes or fingers.

lava tube – Hollow groove though which lava flows (or has flowed) that is entirely enclosed like a pipe or tunnel.

lithosphere - The Earth's solid outer layer made up of both the crust and the uppermost part of the mantle; it is divided into the tectonic plates.

lower mantle – The hard part of the Earth's mantle between the relatively soft asthenosphere above, and the liquid outer core beneath.

magma – Molten Earth material consisting of liquid and often some solid and gaseous components.

mantle - The layer between the core and the crust of the Earth made up of compounds of oxygen and silicon (silicates) rich in iron and magnesium.

metamorphic rock – A sedimentary, igneous, or other metamorphic rock that has recrystallized, in a solid state, due to heat and/or pressure.

mid-ocean ridge – Broad, uplifted, and fractured area in the ocean basins where new crust is formed through volcanic activity at a divergent plate boundary.

mineral – A naturally occurring, inorganic solid with definite chemical composition and crystalline structure.

nāhuku – A lava sickle hanging from the ceiling of a lava tube, resembling ice sickles or stalactites.

olivine – A dark green, iron and magnesium-rich silicate mineral that is one of the first to crystallizes as magma cools. The Earth's mantle is rich in olivine.

outer core - The outer portion of the innermost Earth, consisting of iron and nickel in a liquid state because of the high temperature.

oxidation – The process of combining with oxygen ions. Iron-rich minerals undergo oxidation and turn a reddish, rust color.

pāhoehoe – Basalt lava flow with a smooth and ropey surface.

pali – Hawaiian word meaning "cliff" or "steep slope" normally associated with normal faults near the coast in Hawai'i Volcanoes National Park.

Pele's hair – Basalt that has been stretched into delicate, thin, flexible strands that are light brown in color.

pele's tears – Small pieces of rock formed as molten lava assumed spherical or tear shapes as the magma flew through the air.

peridotite – A coarse grained, dark colored, very low (~40%) silica rock comprised of the minerals olivine and pyroxene. It is the rock found in Earth's mantle.

phreatic – Steam explosions caused by heat, not driven by magma.

pit crater – A volcanic collapse feature with a diameter less than about 1 mile (1.6 kilometers).

plagioclase – A light colored, feldspar mineral made up of silicon, oxygen, aluminum, sodium, and calcium.

plate – A slab-like part of the Earth's outer shell (lithosphere), that rides on softer mantle (asthenosphere) beneath.

plate tectonics - The theory that Earth's outer shell (lithosphere) is broken into plates that move and interact along their boundaries or above hotspots, forming major features (mountains, continents, ocean basins) and resulting in major processes (earthquakes, volcanic eruptions).

Pua Po'o – A rock formation in a lava tube that resembles a cockscomb.

pyroclastic – Fragmented rock material formed as volcanic material is thrown into the air during a volcanic eruption.

pyroxene – A dark green, brown, or black, iron-rich silicate mineral, common in igneous rocks.

resurgent boiling – The process that occurs as lava cools and crystallizes separating the remaining, excess fluid (water) phase.

retrograde boiling – See resurgent boiling.

rhyolite – A light, fine-grained, high (~70%) silica, extrusive igneous rock composed mostly of the minerals orthoclase, quartz, feldspars, and some iron-rich minerals. Rhyolite is the volcanic equivalent of granite.

rift zone – An area of faults on the flanks of a volcano resulting from the land sliding down-slope due to gravity and to the intrusion and extrusion of magma.

rock – An aggregate of minerals.

scoria – A dark, heavy igneous rock containing a lot of holes (vesicles) resulting from volcanic (pyroclastic) material thrown out of a volcano. Scoria is the low-silica equivalent of pumice.

scrubbing – A process in a volcano where water combines with, and removes, sulphur dioxide gas from magmatic gases.

Sedimentary rock - A rock composed of fragments of pre-existing rock, remains of deceased organisms, and/or chemical precipitates (such as salt or calcium carbonate) that have been compacted, cemented, and hardened.

shear strain – Change of shape in response to stress.

shield volcano – A broad, dome-like shape built up from mostly free-flowing basaltic lava flows. The slope of shield volcanoes are rarely greater than about 8°.

silicate – A tetrahedral compound of the elements oxygen and silicon.

sill – A tabular (commonly horizontal) layer of igneous rock that forms as magma pools between layers of rock.

sinkhole – A depression in the ground surface caused by collapse of the roof over a cavern.

skylight – A hole or window in the top of a lava tube.

Southwest Rift Zone - An area of faults resulting from extension due to gravity and the intrusion and extrusion of magma on the southwest flank of Kīlauea volcano.

spatter cone – A cone-shaped mound built up by the accumulation of basaltic lava splashed around a volcanic vent.

spatter rampart – An elongated feature built up by the accumulation of basaltic lava splashed around a fissure.

stratovolcano (composite volcano) – A steep-sided volcano built up of successive layers of lava flows, ash, mudflows, and other volcanic materials.

subduction zone – A convergent plate boundary, where one plate is shoved (subducts) beneath the other.

tephra – Ash, dust, bombs and other pyroclastic material erupted from a volcano.

transform plate boundary - Where two plates slide past one another, often accompanied by earthquakes, but not volcanoes.

tumulus – A large mound of basalt formed from the inflation of a pāhoehoe flow by magma from beneath.

viscosity – The resistance to flow. An increase in viscosity indicates a decrease in fluidity, or the ability to flow.

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