
HAWAII
Planetary Geology
Field Studies
PTYS 590
2023
March 1st-11th
University of Arizona
Lunar and Planetary
Laboratory

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Table of contents

COVID Policy – LPL Hawaii Field Trip, Spring 2023

Due to the travel we must take to get to Hawaii and the size of our group (30), the risk of a Covid outbreak is non-trivial. While the consequences of Covid are mild for many people it is important to recognize that they can be life-changing for others.

Covid safety is not something that can be effectively enforced from the top down, but rather requires the cooperation, good faith, and honesty of everyone on the trip. In the run up to the trip we ask people to be careful, e.g. use masks, especially on the journey itself to Kona. While in Hawaii please make a good faith effort to keep the group safe by avoiding crowded locations, monitoring yourself for any symptoms, and wearing masks when appropriate. Please be honest about your symptoms and test results and cooperate with the trip leaders concerning tests and quarantine if needed. We encourage people to test themselves before leaving for Hawaii. A few days of quarantine is easier at home than in a hotel room.

Here, we lay out our policies to 1. Limit Covid outbreaks and 2. Deal with Covid cases that may occur.

1. Limiting COVID Outbreaks

- We will provide a supply of masks and tests throughout the trip.
- UA policy is that masks cannot be required. However, we encourage the use of masks in all indoor situations (including vehicles, stores, and restaurants).
- All group members will test themselves upon arrival at Kona (March 1st), after three days (March 4th), and after another three days (March 7th). Any positive results need to be reported to the trip leaders.
- Anyone experiencing symptoms on other days that could be consistent with Covid will test themselves and report any positive results. If you're unsure if your symptoms qualify then test yourself anyway.

2. Responses to Covid Outbreaks

- A positive result (even faintly positive) from any individual will trigger a test for everyone in the group (unless it was already done that day i.e. on March 1st, 4th, or 7th).
- Anyone testing positive must be separated from the group and quarantine in an alternate location. This will likely be a hotel in Hilo where medical facilities are close by in case symptoms worsen. If possible, the covid-positive person/people will take a vehicle and drive themselves to the hotel. The trip leaders will retrieve the vehicle and deliver food. If people are so sick that they're unable to drive then a trip leader may need to call an ambulance.
- UA does not pay for employees' Covid expenses (e.g. quarantine lodging or air ticket changes fees), but LPL has agreed to refund people up to $750 for these. This may not fully insulate someone from all costs so it is important everyone make a good faith effort to keep the group healthy.
- If the number of available instructors falls to one due to quarantines then all field trip activities will be paused (except for returning to the airport if at the end of the trip).
- People may rejoin the group after two negative tests separated by one day.

LPL Field Trip Safety Protocol – Spring 2023

Overall responsibility for trip safety lies with the instructor of record: **Shane Byrne**.

Talk to other trip leaders, **Christopher Hamilton and Brett Carr,** in any situation when the instructor of record is not immediately available. General safety guidelines are in the Code-of-Conduct (please consult for additional details), some overall principles to highlight include:

- **Safety is always the priority** – communicate any concerns ASAP to the field trip leaders.
- **Report all personal injuries, illnesses, and accidents** (even if perceived to be minor).
- **Report all vehicle accidents or mechanical problems** (even if perceived to be minor).
- **Never go anywhere alone.**
- **Drive defensively and within the speed limit** at all times.

If confronted by an emergency situation then follow the 3 C's: **Check, Call, Care.**

1. **Check for hazards and make yourself safe.** Before calling anyone or helping another person, make sure that you yourself will not be injured. If you've been injured then stop whatever you are doing.
2. **Call for help.** If people are at risk and time is critical then call 911 first (see notes on calling 911 below). As soon as possible call or alert one of the trip leaders.
3. **Care for anyone who is injured.** Don't attempt procedures that you have no training in. Don't make physical contact with anyone until they consent. If the victim appears unresponsive then still announce what you're about to do aloud e.g. *"I'm going to check your pulse now".* If a back or neck injury is suspected then don't attempt to move the injured party.

Calling 911:

1. As with most high-pressure situations, **stop and take a breath**. You need to be ready to recite details, answer questions, follow instructions etc… If you're in a group then assess who has the best phone signal/battery for a lengthy call.
2. Be ready to **report your cell number and location** – have an idea of where you are at all times. If in the wilderness, then dropping a pin in Google Maps can get you your exact lat/lon (make sure you have this app or something equivalent). If you have the only phone then, write these numbers on a piece of paper before placing the call.
3. Be ready to **describe the victims (rough age and gender) and accident** or how you discovered the people that are in trouble.
4. Be ready to **describe the status of the people in trouble** e.g. breathing/not beathing?, responsive?, ongoing blood loss?, etc… If possible have one person make the call while another assesses the injured party. Report the most serious injuries first.
5. **Report additional relevant things** like other risks at the scene, weather deteriorating etc..
6. **Never hang up** on a 911 operator until they end the call.
7. **Don't change locations** unless safety requires it.

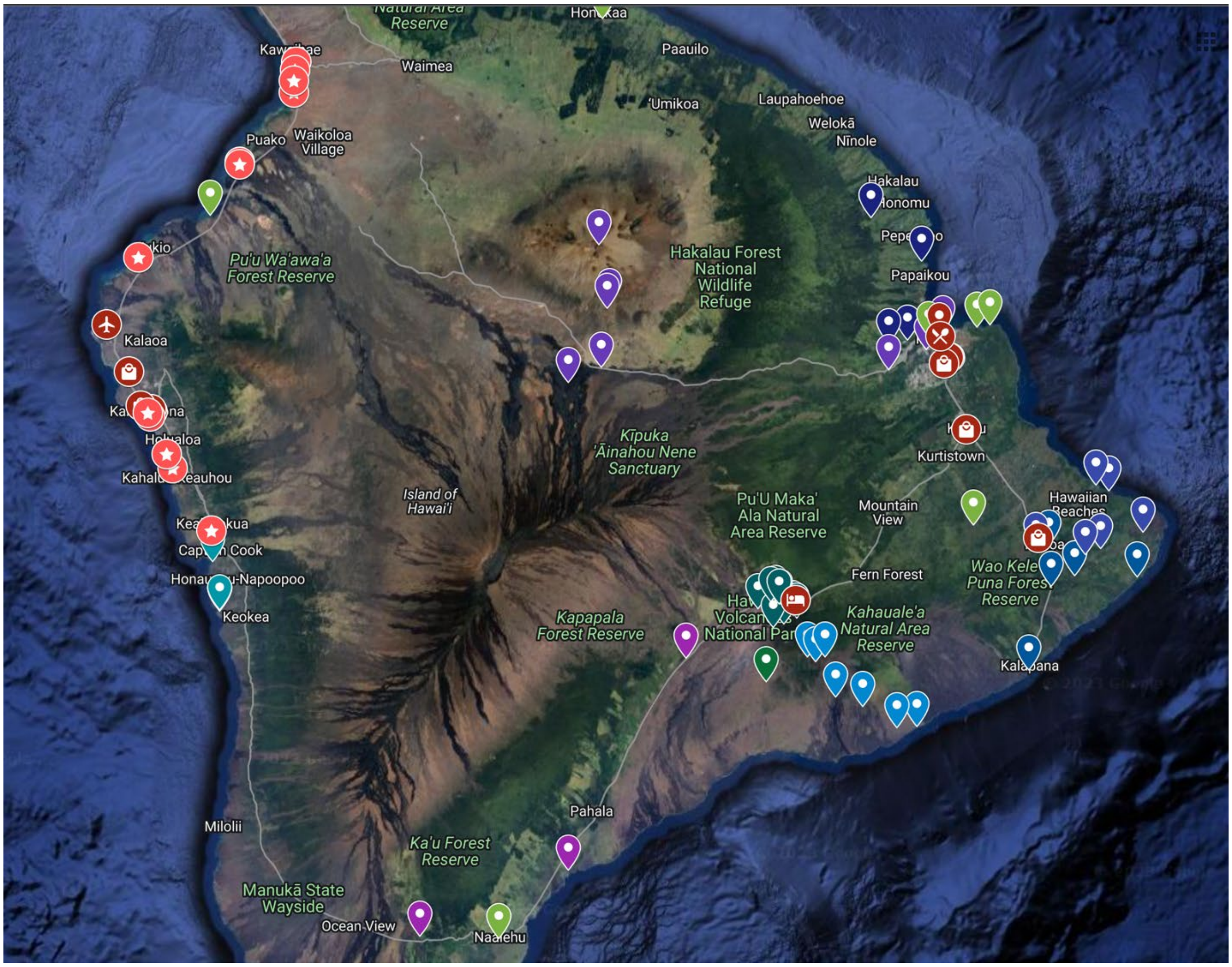
Many 911 guides/scripts exist online that are worthwhile to read before an emergency arises e.g. https://www.alpinesavvy.com/blog/how-to-make-a-backcountry-911-call.

911 calls usually trigger an emergency services response or a wilderness rescue. They are both necessary and not to be used lightly. Contact trip leaders for non-emergency situations.

Contact Info for Spring 2023

Shane Byrne	Email: shane@lpl.arizona.edu	Phone: 520-269-1022
Brett Carr	Email: bbcarr@arizona.edu	Phone: 405-473-5512
Christopher Hamilton	Email: chamilton@arizona.edu	Phone: 301-305-3818
LPL Academic Office	Email: maryg1@arizona.edu	Phone: 520-621-2828
Keaau Urgent Care	16-590 Old Volcano Road, Keaau	Phone: 808-966-7942

(a 25-minute drive from Volcano Village, but other facilities may be closer to field locations)


Waimea
Paauilo
Laupahoehoe
Waikoloa Village
Puako
Pu'u Wa'awa'a Forest Reserve
Hakalau Forest National Wildlife Refuge
Papaikou
Kalaoa
Kurtistown
Kīpuka 'Āinahou Nene Sanctuary
Island of Hawai'i
Pu'U Maka' Ala Natural Area Reserve
Mountain View
Hawaiian Beaches
Fern Forest
Wao Kele Puna Forest Reserve
Keokea
Kahauale'a Natural Area Reserve
Kapapala Forest Reserve
Pahala
Milolii
Ka'u Forest Reserve
Manukā State Wayside
Ocean View

LPL Hawaii Field Trip Itinerary

Google Map with all locations marked:
https://www.google.com/maps/d/u/0/edit?mid=111O2iec4BB5C0T9iWQXNWarsgvEPSAA&usp=sharing

Wednesday, March 1st

Arrival Day!

Everyone already on island should meet at the Kona Airport National Car Rental at 2:30
73 109 Aulepe St, Kailua-Kona, HI 96740

Flight arrival times in Kona:

- 2:10 pm (3 people): Nathan, Zoe, Robert (SW 0253)
- 3:27 pm (8 people): Fuda, David, Roberto, Beau, Maizey, Rishi, Allison, Reed (AA 603)
- 5:34 pm (1 person): Rocío (AA 59)
- 9:30 pm (4 people): Kana, Claire, Dingshan, Kiana (DL 311)
- 10:23 pm (2 people): Christopher, Harry (UA 1723)
- 10:44 pm (1 person): Mackenzie (Alaska 807)

Stay:
AirBnB in Kona Town
75-184 Ala Onaona St. Kailua-Kona, HI 96740 (19 people)
75-5729 Lamaokeola St. Kailua-Kona, HI 96740 (8 people)
75-196 Ala Onaona Street Flying Honu, Kailua, HI 96740 (3 people)
Check in after 3 pm

Thursday, March 2nd

Welcome to the Big Island! Drive to Volcano

Restrooms:	Available at every stop
Lunch:	12:30 or later, opportunities to purchase
Hiking:	No, some walking
Lava Walking:	No
Other Considerations:	Have food groups organized for shopping, have jacket available in case of a stop along the saddle road, have National Parks pass available if you have one
Presentations:	3 (Lori, Robert, Reed)

9:30 am **Everyone packed and ready to go**
Presentation: The Six Main Volcanoes on the Big Island (**Lori Huseby**)
Depart: 10:00

10:45 am **Stop 1: Kealakekua Bay Boat Ramp**
Presentation: Mass Wasting (**Reed Spurling**)
Presentation: Colonialism in Hawaii (**Robert Melikyan**)
Discussion (Brett):
1877 Mauna Loa flank eruption
Captain Cook History
Depart: 11:30

11:45 am **Stop 2: Pu'uhonua O Honaunau National Historical Park** (Place of Refuge)
Access requires a National Parks Pass. Make sure every vehicle has one
~45+ minutes to wander grounds

12:30 pm **Fun & Lunch Break**
It is a 40 minute drive to the 3pm meeting location. Please account for that time in your plans.

3:00 pm **Stop 3: Meet at the Kona Safeway parking lot for Shopping**
Shopping Options:

1. Costco (for those with memberships)
2. Safeway/KTA/Target/Walmart in Kona
3. Safeway/KTA/Target/Walmart in Hilo

For those not going to Costco and purchasing items that need to be kept cold, driving to Hilo and going shopping there (35 minutes from Volcano) may be a better option.

It is a 2 hour drive from Kona to Volcano (route goes through Hilo)

6:00 pm **Groups can begin to arrive at Holoholo Inn for check-in**

Stay:
Holoholo Inn, Volcano Village (and every night for the rest of the trip)
19-4036 Kalani Honua Rd, Volcano, HI 96785
Park at the Old Japanese Schoolhouse nextdoor

<u>Friday, March 3rd</u>

Kilauea Summit

Restrooms:	Available at every stop, hikes will be 2+ hours w/o facilities
Lunch:	1:30 pm, must pack your own
Hiking:	Yes, ~7-9 miles with some elevation gain
Lava Walking:	Yes

Other Considerations: The summit area is at 4,000 feet elevation and it can be quite chilly and windy. Also wet. The sun can also be scorching.
Presentations: 6 (Kana, Harry, Roberto, Rishi, Zoe, Searra)

8:00 am **Depart:** Everyone packed, fed, and ready to go

8:30 am **Stop 1: Kīlauea Overlook**
Discussion (Brett):
- Introduction to the summit
- 2018 eruption & summit collapse

Presentation: Magma Plumes (and Hawaiian Islands) (**Kana Ishimaru**)
Presentation: Monitoring Systems (**Harry Tang**)
Depart: 9:30

9:45 am **Stop 2: Kīlauea Iki Hike**
~4 miles, 600 vertical feet (including **Nāhuku lava tube**)
Presentation: Lava Tubes (**Roberto Aguilar**)
Presentation: Kilauea Iki: Lava Lakes (**Rishi Chandra**)
Depart: 1:15

1:30 pm **Stop 3: Puʻupuaʻi**
Lunch

2:00 pm Hike the devastation trail (< 1 mi.)
Presentation: Kilauea Iki: Fire Fountains and Tephra Fall; and lunar fire fountaining (**Zoe Wilbur**)

2:45 pm **Stop 4:** Continue to **Keanakākoʻi crater and lava lake overlook** (2 miles RT)
Additional Discussion (Brett):
- Kīlauea: Recent and current eruptions & lava lakes
- Keanakākoʻi explosive phases of Kīlauea

Watch the lava
Depart 5:00

5:15 pm **Stop 5: Visitor Center (Optional/If Time)**
Hike Sulfur Banks trail (1 mile RT)
If time: Continue to Steam Vents and loop back (+1 mile)
Presentation: Astrobiology on Hawaii (**Searra Foote**)
Depart 5:55

6:00 pm **Return to Holoholo Inn**

Saturday, March 4th

Maunaulu & Chain of Craters Road

Restroom: Available at Maunaulu & Hōlei, hikes will be 2+ hours w/o facilities
Lunch: 12 pm, must pack your own
Hiking: Yes, ~4-7 miles with some elevation gain
Lava Walking: Yes
Other Considerations: Bring layers, elevation today will range from 4000 feet to sea level
Presentations: 6 (Beau, Iunn Jenn, Xiaohang, Namya, Kiana, Fuda)

8:00 am **Depart:** Everyone packed, fed, and ready to go

8:30 am **Stop 1: Pauahi Crater**
Presentation: Chain of Craters (**Beau Prince**)

9:00 am **Stop 2: Maunaulu**
Hike Puʻu Huluhulu Cinder Cone (2.5 miles round trip, 300 vertical feet)
Explore perched lava pond on Maunaulu north flank
Also hike fissure nature trail
Presentation: Magma Plumes (and chemical zoning) (**Ong Iunn Jenn**)
Presentation: Magmatic Eruptions (**Xiaohang Chen**)

12:00 pm **Lunch on return to parking lot**
Depart 12:35

12:45 pm **Stop 3: Maunaulu Lookout**
Explore Maunaulu flow field for ~90 minutes
Depart 2:15

2:20 pm **Stop 4: Kealakomo**
Presentation: Seismicity and the Hawaiian Volcanoes (**Namya Baijal**)
Depart 2:45

3:00 pm **Stop 5: Hōlei Sea Arch**
Walk to sea arch viewpoint, then explore Puʻuʻōʻō flow field (2+ miles RT)
Presentation: Lava cooling and thermorheology (**Kiana McFadden**)
Depart 5:15 pm

X:XX pm **Stop 6: Puʻu Loa Petroglyphs (Optional/If Time)**
~1.5 miles RT

It is 45 minutes back to the Holoholo Inn

6:00 pm **Return to Holoholo Inn**

<u>Sunday, March 5th</u>

Lower East Rift Zone 1: Vent & Ocean Entry

Restrooms:	Not readily available, can find in Pāhoa and at Isaac Hale Beach
Lunch:	1:30 pm, possible to purchase in Pāhoa and maybe Kalapana
Hiking:	Yes, 2-3 miles, but over lava
Lava Walking:	Yes
Other Considerations:	Be aware of gasses emitted from vents, be respectful of locals when visiting areas destroyed by 2018 eruption
Presentations	1 (Allison)

8:00 am **Depart:** Everyone packed, fed, and ready to go

9:00 am **Stop 1: Ahuʻailāʻau (Fissure 8) Tour**
Explore the main vent from the 2018 eruption

12:00 pm **Stop 2: Pahoa Lava Zone Museum**
Depart 1:00 pm

1:10 pm **Stop 3: HW 130 Ground Cracks**
Brett will present

1:30 pm **Stop 4: Kalapana (Optional/If Time)**
LUNCH
Walk over Puʻuʻōʻō lava to coast (~1 mile round trip)
Discussion (Christopher & Brett):
- Puʻuʻōʻō & Kalapana
- 2018 Fissure 20 & 22 lava flows

Depart: 3:00

3:30 pm **Stop 5: Isaac Hale Park**
Explore the newest black sand beach in Hawaiʻi
See hot springs heated by lava
Presentation: Meteorites, Mantles, and MORBs- oh my! (**Allison McGraw**)
Depart: 4:30

It is 90 minutes back to the Holoholo Inn.

6:00 pm **Return to Holoholo Inn**

Monday, March 6th

LERZ 2: Rootless Cones & Lava Channels

Restrooms:	Not available at all, closest are Lava Tree State Park
Lunch:	12:00 pm, must bring own lunch
Hiking:	Yes, <3 miles, but over lava & through jungle Lava Walking: Yes
Other Considerations:	Be very careful when crossing over rough lava surfaces, be respectful of locals when visiting areas destroyed by 2018 eruption
Presentations:	1 (Mackenzie)

8:00 am **Depart:** Everyone packed, fed, and ready to go

9:00 am **Stop 1: Sand Hill Rootless Cone**
Christopher leads
Depart 11:30 am

11:40 am **Lunch at Kahakai Park in Hawaiian Beaches**
Depart 12:15

12:30 pm **Stop 2: "Old 4 Corners"**
Explore lava morphologies and the 2018 flow channel
Explore 1960 Kopoho flows
Presentation: Lava Flow Morphology (**Mackenzie Mills**)
Discussion (Brett):
Sections of the 2018 Fissure 8 flow & HW 132 roadcuts
Depart 3:00 pm

3:15 pm **Stop 3: "Shipping Container Point" (Optional/If Time)**
More opportunity to see the flow channel
Depart 3:50 pm

4:00 pm **Stop 4: Lava Tree State Park (Optional/If Time)**
See lava trees from 1840 LERZ eruption & ground fissures
Depart 4:30

4:45 pm **Stop 5: Pāhoa Transfer Station (Optional/If Time)**
2014 Puʻuʻōʻō lava flows
Depart 5:15 pm

It is 45 minutes back to the Holoholo Inn.

6:00 pm **Return to Holoholo Inn**

Tuesday, March 7th

Hamakua Coast & Time Off

Restrooms: Available at all stops
Lunch: 1:00 pm or later, can purchase at various locations
Hiking: Yes, <2 miles
Lava Walking: No
Other Considerations: Even if its dry in Volcano, it can be very wet in Hamakua, bring bags for grocery shopping
Presentations: 2 (Fuda, Maizey)

8:00 am **Depart:** Everyone packed, fed, and ready to go

9:00 am **Stop 1: King Kamehameha Statue, Hilo Bayfront Park**
Discussion (Brett):
Hilo town & tsunamis
Presentation: Hawaiian Ethnography through time (**Fuda Nguyen**)
Depart 9:45 am

10:00 am **Stop 2: Rainbow Falls**
Depart 10:20 am

10:30 am **Stop 3: Boiling Pots**
Presentation: Flora & Fauna of the Hawaiian Islands (**Maizey Benner**)
Brett will preview the next part of the drive
Depart 11:20 am

12:00 pm **Stop 4: Akaka Falls State Park**
Drive VIA the Onomea Bay Scenic Drive (no place to park 5 vans, so no stops)
0.5 mile paved loop hike

1:00 pm **Afternoon Off**

Wednesday, March 8

South Point

Restrooms: None available once we are in South Point area
Lunch: 12:00ish, depending on hiking time, must pack own lunch
Hiking: Yes, 5-7 miles

Lava Walking:	No
Other Considerations:	It can be VERY windy in this area- have sunglasses to block blowing sand. I've seen people need to use ear plugs because the wind across their face was so loud. We may be returning to Volcano later compared to other days
Presentations:	3 (Weigang, Rocio, Nathan)

8:00 am **Depart:** Everyone packed, fed, and ready to go

9:30 am **Stop 1: South Point**
Presentation: Hawaiian-Emperor Seamount Chain (**Rocio)**
Depart 10:00 am

10:15 am **Stop 2: Hike to Papakōlea Green Sand Beach**
5 mile RT hike, will include lunch at Papakōlea
Presentation: Phreatic and Phreatomagmatic Eruptions (**Nathan Hadland**)
Depart 2:30

3:15 pm **Stop 3: Punaluʻu Black Sand Beach**
Presentation: Weathering Environments (**Weigang Liang**)
Depart 4:00

4:30 pm **Stop 4: Footprints Trail, Kaʻu Desert (Optional/If Time)**
2 miles round trip hike
If lots of time somehow, can add 2 miles RT out to Mauna Iki
Depart 6:15

6:30 pm **Return to Holoholo Inn**

Thursday, March 9

Mauna Kea & Hilo

Restrooms:	Available in Hilo and at Mauna Kea VC. Also available along at rest stops along Saddle Road
Lunch:	Before meeting in Hilo at noon. Bring snacks or second lunch because we will be returning to Volcano LATE
Hiking:	Yes, 1-3 miles, some elevation gain
Lava Walking:	Yes
Other Considerations:	Bring headlamps! It will be VERY cold on the saddle and at the Mauna Kea Visitor Center (40s F). Be prepared to stand in the dark in these conditions for an extended period of time. Also be alert for symptoms of altitude sickness, the VC is at 9000 feet.
Presentations:	8 (David, Chengyan, Claire, Arin, Dingshan, Naman,)

Morning Off

12:00 pm **Stop 1: Meet at Coconut Island having already had lunch**
Presentation: Seeing and telescope site selection (**Chengyan Xie**)
Discussion (Brett):
Mauna Kea, Mauna Loa, and the life cycle of a shield volcano
1881 Mauna Loa eruption
Depart 12:45

12:50 pm **Stop 2: 1881 Lava flow exposure on Mohouli St**
Just a drive by (Do Not Stop)

1:00 pm **Stop 3: Kaumana Caves**
Explore the lava tubes
Depart 2:00

2:30 pm **Stop 4: Puʻu Huluhulu Cinder Cone (and/or nearby)**
~1 mile and some elevation gain
Presentation: Mauna Loa: 2022 Eruption (**David Cantillo**)
Presentation: Mauna Kea: Glacial History (**Claire Cook**)
Presentation: Astronomy, Telescopes, and Related Cultural Issues (**Arin Avsar**)
Depart 4:45

5:00 pm **Stop 5: Mauna Kea Visitors Center**
Presentation: CO2, atmospheric studies, trade winds, climate (**Dingshan Deng**)
Presentation: Kuiper and Astronomy at Mauna Kea (**Naman Bajaj**)
Hike Puʻu Kalepeamoa (1 mile, some elevation)
Watch sunset (6:30 pm)
Presentation from West Hawaii Astronomy Club when itʻs dark
Depart 8:00-8:30?

It is 90 minutes back to the Holoholo Inn

9:30 pm **Return to Holoholo Inn**

<u>Friday, March 10th</u>

December 1974 flow, Southwest Rift Zone

Restrooms: Trailheads only, hikes will be 3+ hours w/o facilities
Lunch: 12:00ish, must pack your own
Hiking: Yes, 6-10 miles, minimal elevation change
Lava Walking: Yes

Other Considerations: Long day away from the vans, be prepared for changing weather conditions
Presentations: None

8:00 am **Depart:** Everyone packed, fed, and ready to go

9:00 am **Stop 1: December 1974 Hike**
Depart from Kulanaokuaiki Campground Trailhead
Christopher Leads, see lava flow, faulting, pit craters, etc.

2:30 pm **Stop 2: Footprints Trail, Ka'u Desert (If not done on South Point Day)**
Finish '74 flow hike by 2pm if also doing Footprints Trail
It is 35 minutes to drive between these trailheads
2 miles round trip hike
Depart 3:30

4:00 pm **Return to Holoholo Inn early for packing, cleaning, etc.**

Saturday, March 11th

Departure Day

Zoe & Maizey need to leave Volcano at 4:00 am to catch an 8:00 am flight. We need 3 additional volunteers to join them (including a driver)

Everyone else:
8:00 am **3 hours for breakfast, packing, cleaning, etc.**

11:00 am **Depart for Kona side**
It is a 2 hour drive to Kona

Departure times from Kona:
8:00 am (2 people): Zoe, Maizey (SW 4128)
11:25 am (1 person): Nathan (SW 3692)
3:20 pm (1 person): Mackenzie (Alaska 822)
5:01 pm (1 person): Rishi (AA 58)
8:50 pm (1 person): Christopher (UA 1731)
9:10 pm (4 people): Kana, Claire, Dingshan, Kiana (DL 485)
10:55 pm (3 people): Shane, Namya, Robert (DL 370)
11:20 pm (13 people): Lori, Searra, Xiaohang, Weigang, Naman, Reed, Iunn Jenn, Fuda, David, Roberto, Beau, Rocio, Arin (AA 664)
11:38 pm (1 person): Harry (UA 1724)

Lori Huseby

The Five Main Volcanoes of the Big Island

Introduction

The Hawaiian Islands are volcanic in origin and are made up primarily of at least one volcano, and the Big Island is one of those composite volcano islands. The Big Island is constructed of five main volcanoes: Kilauea, Mauna Loa, Mauna Kea, Hualalai, and Kohala.

The Big Island is also home to the largest number of active volcanoes of the islands:

- Kilauea (Currently Erupting)
- Mauna Loa (November 2022)
- Hualalai (Erupted in 1801)
- Mauna Kea (4,500 years ago)
    - considered to be active, but unlikely to erupt.
- Kohala, which is the oldest volcano on the island, has concluded its active history.

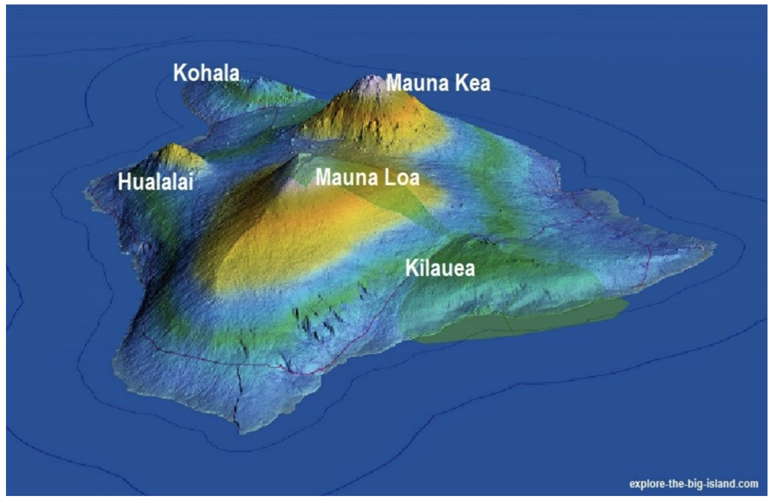


Figure 1: The five Hawaiian volcanoes on the Big Island. https://www.explore-the-big-island.com/hawaii-volcanoes.html

Brief Formation

The eight Hawaiian Islands we know today are the most recent formations in a chain of over 80 volcanoes that extend for thousands of kilometers to the northwest, that can be seen both above sea level and below. The further southwest that you travel, the younger the volcanoes. All of these volcanoes in this chain, including the Big Island, were formed by the Hawaiian Hot Spot, a stationary plume of super-heated material that has been rising and melting rock into magma, and when it makes it to the surface, causes a volcanic eruption. The exact size of this hot spot is unknown, but it is estimated to be over 300 km with other narrower vertical passageways that feed magma to the individual volcanoes.

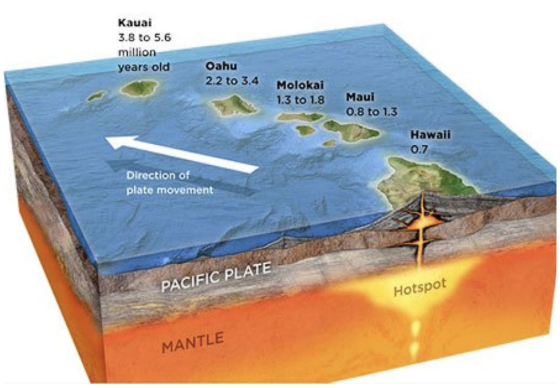
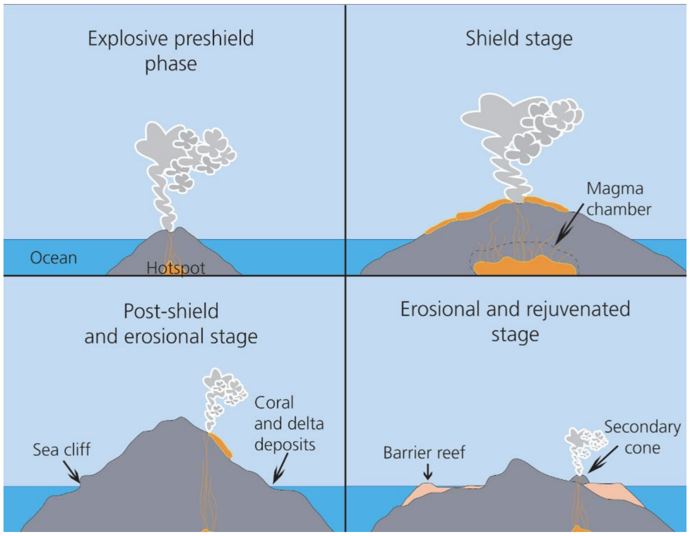


Figure 2: Volcano assembly line creating the Hawaiian chain of islands. https://www.smithsonianmag.com/travel/what-were-still-learning-about-hawaii-74730/

In addition to the hot spot, the Pacific Tectonic Plate migrates slowly to the northwest. It moves approximately 2-4 inches per year, taking the land created by any of the volcanic erupted matter with it. This result can be considered an "assembly line." The stationary hot spot builds up material into volcanoes, and the pacific plate slowly takes them away. Eventually, the Big Island will also be taken away by the tectonic plate, and more volcanoes will follow.



In this figure, there are 4 main phases of the volcanoes that will be used to describe each of the five volcanoes making up the Big Island. In chronological order, the explosive preshield phase is first, followed by the shield stage, then the post-shield and erosional stage, and then finally the erosional and rejuvenated stage (National Park Service).

The Main Volcanoes (From North to South)

Kohala

Kohala is the oldest volcano on the island. It is located just northwest of the Mauna Kea volcano and is considered extinct. The volcano itself consisted of shield lavas, like the surrounding volcanoes on the island. This volcano is home to the oldest lava found at approximately 460,000 years old, and post-shield lavas as early as 60,000 years old. At the present rate of subsidence, approximately ⅛ inch per year, Kohala will become a separate island 350,000 years from now. Kohala makes up the northern part of the Big Island and is now known for its rolling hills and steep, deep cliffs. This volcano used to be much larger, but chunks have been falling off into the ocean for the last 100,000 years, and large landslides have caused tsunamis up to 150 m tall. The volcano's northwest rift zone extends into a depression, which used to be a basin that was moved to the northwest. Waipi'o and Pololu valleys have formed along these faults created by landslides. The towns of Hawi and Kapa'au are built on the northern part of this volcano, and Waimea sits to the southeast. There is thick ash cover on the volcano, mostly due to Mauna Kea eruptions, although some of it is of local origin.

Figure 3: Waipi'o Valley sea cliffs. https://www.lovebigisland.com/hawaii-blog/hawaii-volcano-history/

Mauna Kea

Mauna Kea ("White Mountain") is the tallest volcano in the world and is a dormant volcano that was active approximately 4,500 years ago. There are still earthquakes that originate inside of the volcano, but has been mostly concluded to be structural readjustments rather than any eruptive volcanic activity. The volcano is in its post-shield phase, as large lava flows and cinder cones have covered the summit's caldera. Even though a few lava flows have been able to reach the coast of the Big Island, the most recent eruptions created thick and pasty lava. Many previous eruptions were explosive, leaving massive deposits of ash triggered by lava/glacier interactions. There were three distinct periods in which there was glacial coverage on the summit of this volcano. The height of the volcano reaches 9,750 m total (taller than Mt. Everest), with 4205 m above sea level, including the high elevation lake Waiau. Due to the thin and clear air, it is home to 12 separate non-profit observatories from 11 countries. Mauna Kea could erupt again, but it is unlikely due to it being in its post-shield phase.

Figure 4: Observatory & snow-capped cinder cones on Mauna Kea https://www.hawaii.com/things-to-do-island-of-hawaii/mauna-kea/

Mauna Loa

Mauna Loa ("Long Mountain") is known as the largest and most active volcanoes in the world, covering over 800 km^2 (60 miles long, 30 miles wide) and has erupted a total of 36 times since 1843. It is nearing the end of its shield stage, as it has only erupted three times since 1950. The most recent of this being November 27 - December 10, 2022. In addition to two prominent rift zones, repeated fissures have opened on the northern and northwest flank of the volcano. The southeast and west flank of the volcano slips towards the ocean and has caused large earthquakes and landslides on the mountain. Mauna Loa will likely erupt again in our lifetimes.

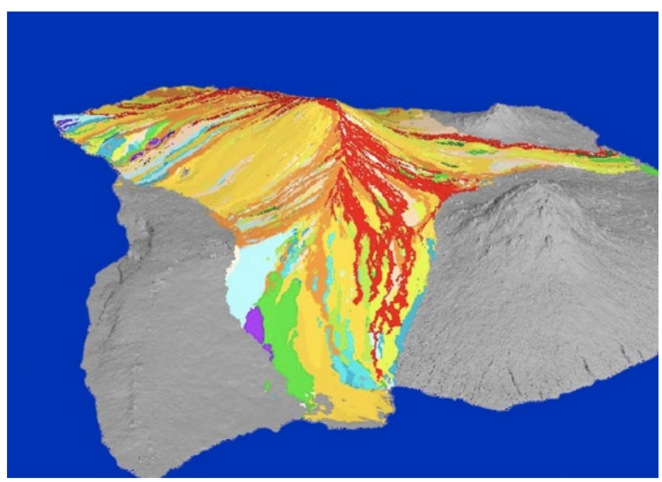


Figure 5: Overlain lava flows on Mauna Loa since 1832. Hilo can be found in the bottom center, with Kilauea at the left, and Kona on the north coast. https://www.soest.hawaii.edu/GG/HCV/maunaloa.html

Hualalai

Hualalai volcano is an active volcano in its post-shield stage with its last eruption in 1801. There was also a flurry of earthquakes that occurred in 1929, likely due to a shallow magma intrusion. It has been known to erupt every few hundred years and is considered the third most active volcano on the island. On top of this, due to its steep slopes, the flows advance quickly and can be extremely dangerous, as it is only 15 km away from Kailua-Kona. The volcano has a well-developed northwest rift zone (1801 eruption) and southeast rift zone, and a poorly developed north rift zone. Hualalai is also known on the island to be a good source of mantle xenoliths and perfect ash soil for coffee. It is home to many of the resorts on Hawaii, and the Kona International Airport is sitting on the Hu'ehu'e flow. This volcano is expected to erupt in the next 100 years.

Figure 6: Overhead picture of a pumice cone on the northern flank https://www.soest.hawaii.edu/GG/HCV/maunaloa.html

Kilauea

Kilauea ("Spewing") is one of the most active volcanoes in the world and is also home to Pele, the volcano goddess in Hawaiian culture. The volcano is in its explosive substage of the shield phase. Eruptions can occur anywhere along the summit or on the east and southwest rift zones. Kilauea is the youngest of all volcanoes on Hawaii and has been in eruption often (and is erupting currently!). Other than at the summit, the east rift zone is the most active, erupting from 1983 to 2018. Over 90% of the surface of the volcano is less than 1,000 years old, with 30 separate eruptions since 1952, ultimately creating its own separate "plumbing system" extending over 60 km deep. However, unlike most other active eruptive volcanoes, this is considered a "drive-up" volcano, because of its ease of access to the summit. The south flank of the volcano does slip a few inches per year on a flat-laying fault 6 miles deep, and large earthquakes, namely in 1975 and 1989, have caused large-scale movement around this fault. This volcano is likely to continue erupting for years to come.

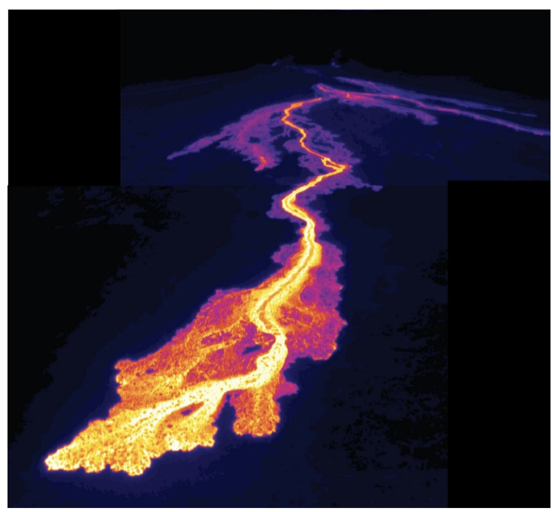


Figure 7: Thermal image of surface flows on day 1 of the June 2014 breakout (USGS HVO Image Library)

Planetary Connection

Large advancements in extraterrestrial bodies come from in-situ methods done on Earth, as well as In-Situ Resource Utilization (ISRU) experiments on top of the large breadth of geology and geographic processes. Namely there is:

- HI-SEAS: The Hawaii Space Exploration Analog and Simulation, which is located on a Mars-like site on the Mauna Loa volcano that has hosted long duration NASA Mars and Moon simulations.
- PISCES: Pacific International Space Center for Exploration Systems, which has found that Hawaiian lava rock composition is nearly identical to Martian rock, specifically sintered Hawaiian basalt.

Hawaiian localities are also used as terrestrial analogs when it comes to lava flows and other volcanic features and activities. Also, weather permitting, there are opportunities for aerial footage so that impact craters, the large shield volcanoes, and various channels can be mapped and compared to aerial footage by orbiting telescopes and other instruments. I highly recommend looking at this book by Ronald Greeley of University of Santa Clara and NASA Ames research center. titled *Geologic Guide to the Island of Hawaii: A Field Guide for Comparative Planetary Geology*. Not only does it have plenty of planetary analogs, but also road guides to the various formations as we go by them.

Guide Link: https://rgcps.asu.edu/nasa-pdfs/GeologicGuideToTheIslandOfHawaii.pdf

References:

[1] U.S. Department of the Interior. (n.d.). National Parks Service. Retrieved February 20, 2023, from https://www.nps.gov/havo/index.htm [2] Hawaiian Volcano Observatory. (n.d.). *Active volcanoes of hawaii*. U.S. Geological Survey. Retrieved February 20, 2023, from https://www.usgs.gov/observatories/hvo/active-volcanoes-hawaii [3] Rubin, K. (2018). SOEST. Retrieved February 20, 2023, from http://www.soest.hawaii.edu/GG/HCV/kilauea.html [4] Love Big Island. (2022). Retrieved February 20, 2023, from https://www.lovebigisland.com/hawaii-blog/hawaii-volcano-history/ [5] *Hawaii volcanoes of the Big Island*. Explore The Big Island. (2011). Retrieved February 20, 2023, from https://www.explore-the-big-island.com/hawaii-volcanoes.html [6] *Maunakea observatories*. IfA Facilities. (2022). Retrieved February 20, 2023, from https://about.ifa.hawaii.edu/facility/mauna-kea-observatories/ [7] Britannica, T. Editors of Encyclopaedia (2022). Retrieved February 20, 2023 from *Hawaii*. *Encyclopedia Britannica*. https://www.britannica.com/place/Hawaii-island-Hawaii [8] *HI-SEAS* (n.d.). Retrieved February 20, 2023, from https://www.hi-seas.org/ [9] Pisces. (2021) PISCES. Retrieved February 20, 2023, from https://pacificspacecenter.com/2018/12/05/why-is-hawaii-a-great-analog-for-mars/ [10] Greeley, R. (1974, August). *Rgcps.asu.edu*. Geologic Guide to the Island of Hawaii: A Field Guide for Comparative Planetary Geology. Retrieved February 20, 2023, from https://rgcps.asu.edu/nasa-pdfs/GeologicGuideToTheIslandOfHawaii.pdf

Reed 1

Reed 2

Reed 3

Reed 4

Robert 1

Robert 2

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Robert 4

Kana Ishimaru

Magma Plumes and the Hawaiian Islands

The Hawaiian Islands Formation

Before the 1960's, a rigid, immobile Earth model was a widely accepted concept. A formation mechanism of the Hawaiian Islands that fits this concept was by extrusion of lava through a large fault that formed the chain of islands at once.

This theory was being challenged as studies revealed more:

- Age differences determined by fossils are significant among islands. Completely eroded islands in the northwest could be 50 million years old.
- The Hawaiian ridge does not resemble any fault-like structure.
- No earthquakes caused by a fault. Almost all earthquakes on Hawaii are from eruptions.

An alternative mechanism was proposed based on a possible mantle convection. In 1963, Wilson suggested that island chains such as Hawaii were formed as plates moved over a fixed region of mantle where large amount of magma was being produced [1].

In 1971, Morgan proposed that certain volcanic island chains including Hawaii were the result of plumes of hot rock rising from the core mantle boundary (CMB) [2]. Those spots in the mantle that are anomalously hotter than the surrounding are called hotspots.

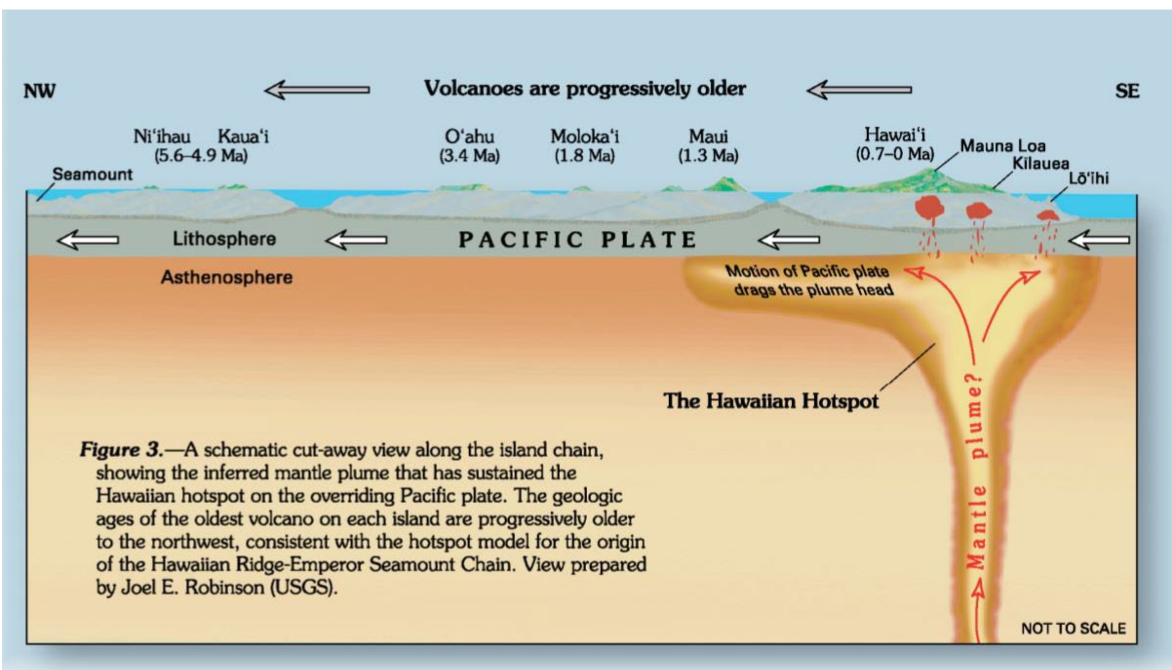


Figure 1. A schematic showing the Hawaiian island chain and the hotspot beneath the lithosphere. Mauna Loa, Kīlauea, and growing submarine Lōi'hi are recently active and likely to be above the hotspot [3].

Mantle plumes

Mantle plumes are localized upwellings of hot buoyant material [4].

- A plume consists of a large head with a diameter of 800 – 1200 km and a conduit with a diameter up to 500 km. when it reaches the lithosphere, the head flattens to form a disk with a diameter or around 2500 km [4, 5]
- Mineralogical study shows that the temperature of plume head can be potentially up to 1700 °C, which is 400 °C higher than the ambient temperature [6].
- They are likely sourced near the CMB (2900 km depth).
- It takes tens of millions of years for a plume to reach the base of lithosphere from the CMB.
- How many mantle plumes exist, their longevity, and dynamic behavior are not understood well.
- Some seismic tomography studies have proposed that "large low shear velocity provinces" (LLSVPs), which show lower seismic velocities than surrounding regions, could be primary plume nurseries.
- Some LLSVP-rooted plumes contain unusually large ultra-low velocity zones (ULVZs), where seismic velocities are even lower than in LLSVP. ULVZs indicate that the material there is compositionally different and likely denser, possibly due to the presence of partial melt or iron enrichment.

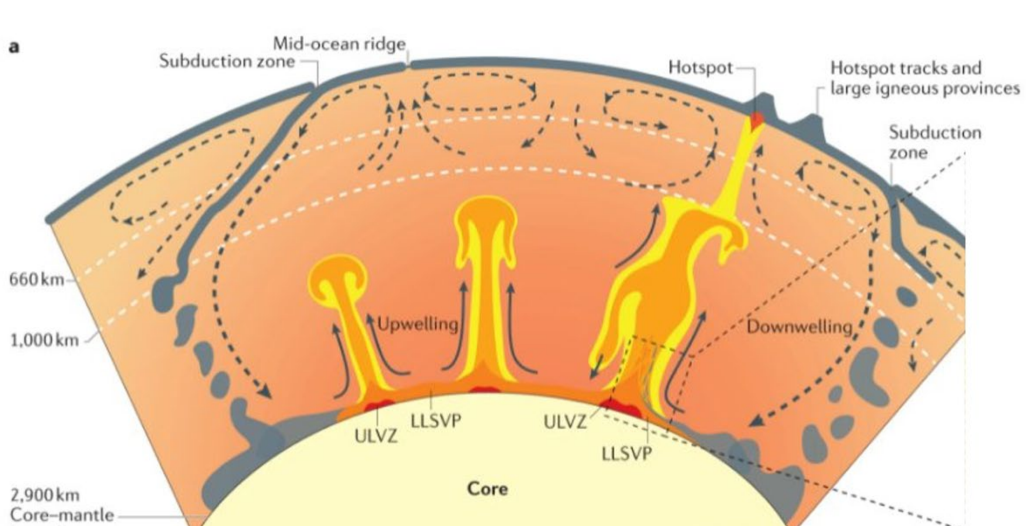


Figure 2. Schematic cross-section through Earth's interior [4]. Plumes generate near LLSVP, ascend, and reach the base of the lithosphere. Plumes deflect at 1000 km depth (40 GPa) due to the increase in viscosity of MgO – FeO system, which also causes subducting slab to stagnate [7].

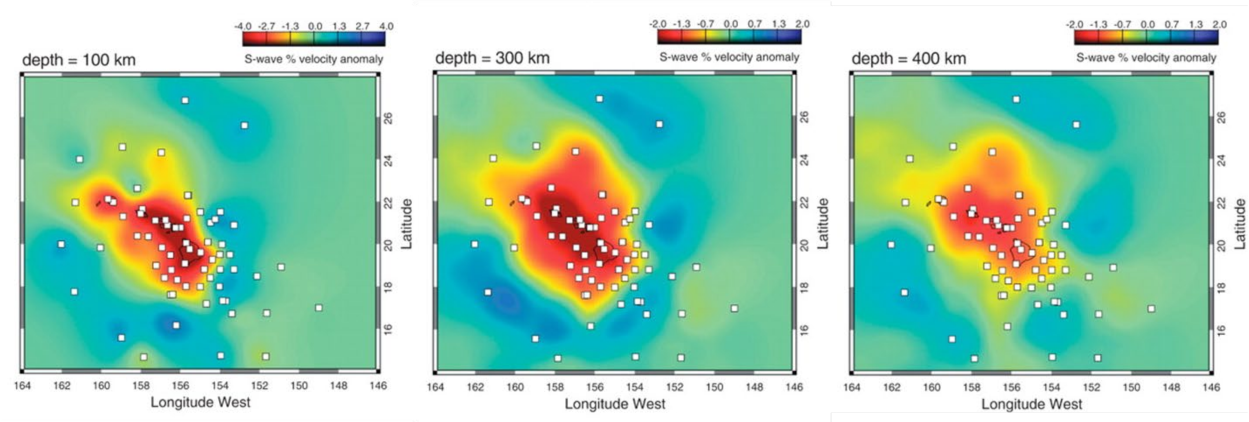


Figure 3. Seismic velocity heterogeneity in the upper mantle at depth of 100 km, 300 km, and 400 km beneath the Hawaiian Islands. Temperature is estimated to be 250 – 300 °C higher than the ambient temperature. Squares indicate locations of seismometers [8].

Planetary Analogs

Venus

- Volcanoes in Atla Regio and Beta Regio might have been produced by mantle plumes [9, 10].
- They are both more than 2000 km across, elevated topography with shield volcanoes, and show rift zones and extensional faulting.
- Models of mantle plumes are consistent with topography and gravity data obtained by NASA's Magellan mission.
- Models suggest that the plumes originate at the base of the mantle at 2800 km depth, and 300 °C hotter than the ambient temperature (similar to Hawaii).

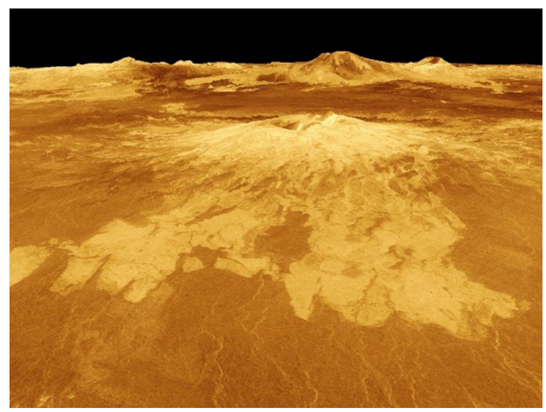


Figure 4. Volcanoes in Atla Regio [11].

Mars

A mantle plume might exist beneath Elysium Planitia [11].

- This region has been experiencing volcanism recently (< 350 Ma), and some are recorded by InSight.
- Recently experienced extensional tectonics, surface uplift, and the elevated topography and gravity.
- This plume is proposed to have a plume head diameter larger than 3500 km, temperature anomalies of 95 – 285 K, and aspect ratios of 5 – 10%.
- Based on gravity and topography data, the plume head center is located at the center of the Cerberus Fossae.
- However, most models predict more sluggish mantle convection without large plumes.

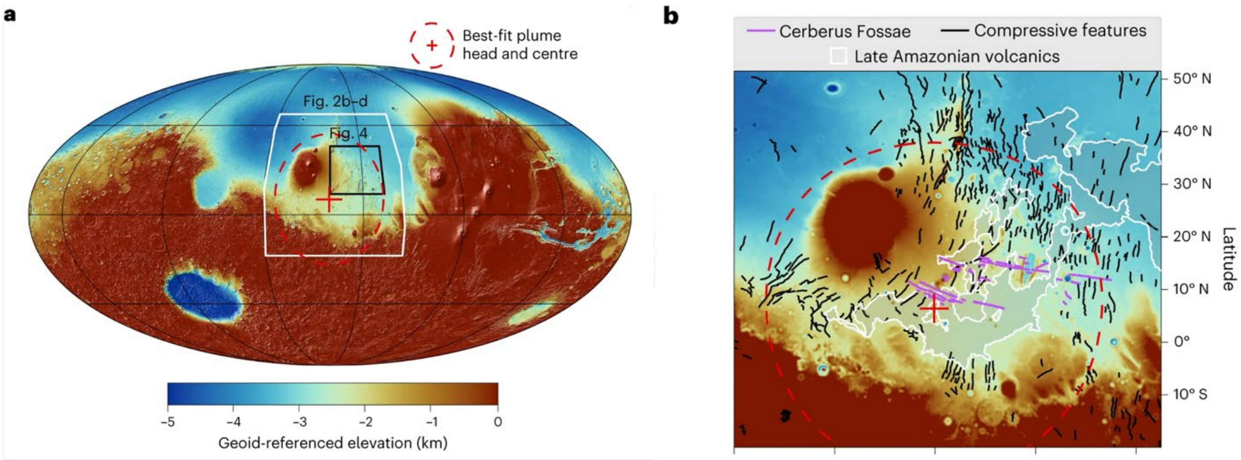


*Figure 5. **a**, Elevation map of Mars centered on 160 E. **b**, Elevation map of Elysium Planitia overlain by tectonic features and Late Amazonian volcanics. Best fit plume head center is located at Cerberus Fossae [11].*

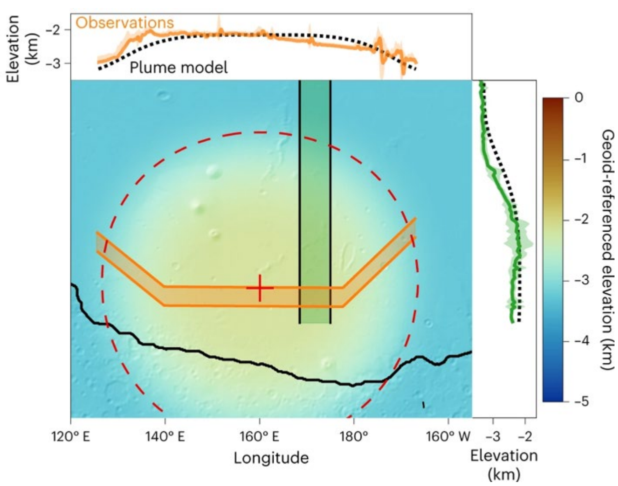


Figure 6. Predicted relative plume-induced uplift is compared with the observations [11].

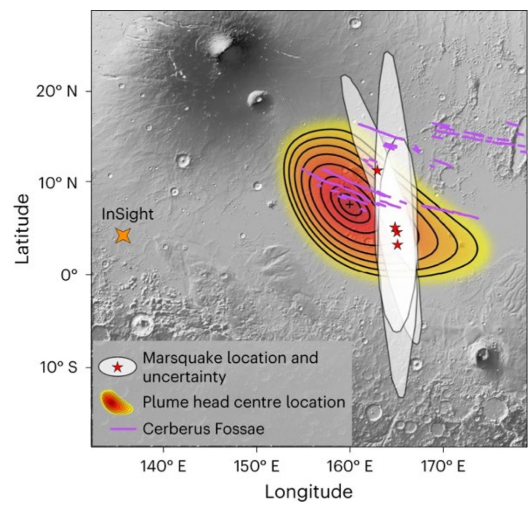


Figure 7. Plume head center location is shown in a misfit contour, where red colors indicate a better fit. Marsquake epicenter locations are estimated by InSight data [11].

References:

[1] Wilson. (1963) *CJP, Vol. 41.6*, 863-870. [2] Morgan. (1971) *Nat, Vol. 230*, 42-43. [3] Simkin et al. (2006) *USGS.*[4] Koppers et al. (2021) *NREE, Vol. 2.6*, 382-401. [5] Hill. (1993) *Lithos, Vol. 30.3-4*, 193-206. [6] Thompson et al. (2000) *Nat, Vol. 407*, 502-506. [7] Deng et al. (2017) *Nat Comm, Vol. 8.1*, 1997. [8] Wolfe et al. (2009) *Sci, Vol. 326.5958*, 1388-1390. [9] Smrekar (1994) *Icarus, Vol. 112.1*, 2-26. [10] https://www.lpi.usra.edu/science/kiefer/Research/venus.shtml, Accessed Feb 20, 2023. [11] Broquet et al. (2023) *Nat Astr, Vol. 7*, 160-169.

Harry Tang

Monitoring Systems

History

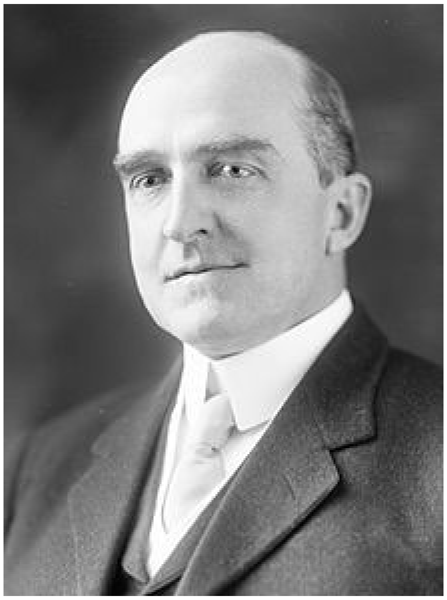


Fig 2. Dr. Thomas Jaggar

The Hawaiian Volcano Observatory monitors earthquakes and active volcanoes in Hawaii in order to assess their hazards, and issue warnings as necessary. While oral traditions have recorded eruptions going to ancient history, the first scientific observatory was established in 1912, directed by Professor Thomas Jaggar, on the rim of the Kilauea Volcano's summit caldera inside the current day Hawaii Volcanoes National Park. This set of structures remained until the partial summit collapse in 2018, forcing the relocation of HVO to Hilo.

In present day, the monitoring network consists of more than 200 sensors, including seismometers, GPS, tiltmeters, infrasound, gas detectors, and thermal/visual cameras. These sensors transmit data to HVO 24 hours a day in order to track activity and support research.

Sensors

Seismic - Volcanic activities are often accompanied by seismic activities, with Kilauea experiencing hundreds of small quakes. However, near the onset of an eruption, these increase significantly in both numbers and magnitude, being associated with the movement of magma (though usually 4 or less). The 2018 lower Puna eruption was accompanied by significant earthquakes in the areas where vents erupted. Other earthquakes may occur from weaknesses in the volcanic structures.

Fig 3. Installing seismic sensors.

The seismic monitoring network in the Hawaii includes sensors at about 100 sites operated by a variety of different partners, which together form a statewide virtual network known as the Hawaii Integrated Seismic Network (HISN). These also provide tsunami warnings for the island, including those feared from the 2011 Tōhoku earthquake. In addition, automated detection algorithms help detect swarms of detection, and tremors, which could indicate magma movement that could indicate ongoing or impending eruptions.

HVO uses four main types of seismic instruments as part of its monitoring network.

- Short period, frequency of ~1 Hz, especially useful for P-wave arrival
- Broadband, seismic signals ranging from about 0.01 – 120 seconds or higher
    - More broad range of periods, more in-depth study of seismic sources
- Strong motion, to compensate for large quakes that can cause more sensitive equipment to go off-scale
- Infrasound, a special type of microphone that measures sound waves in the air, with great promise to aid in rapid eruption detection

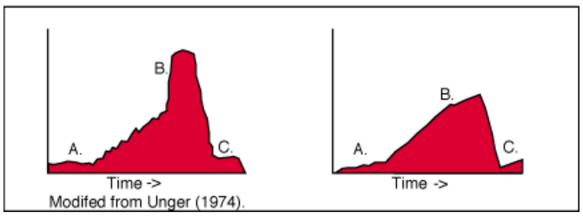


Fig 3. Figures showing correlation between number of earthquakes and the amount of tilt changed over the course of an eruption.

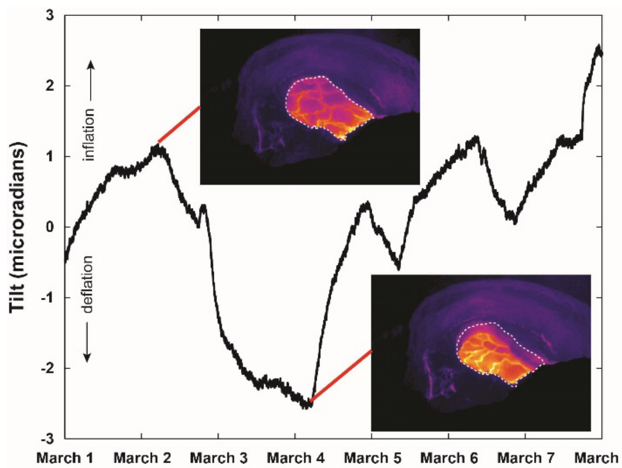


Fig 4. Tilt measured at the summit of Kīlauea during March 1-7, 2012, shows a series of U- and V-shaped DI events, with deflation indicated by downward tilt and inflation by upward tilt. Images from a thermal camera that overlooks the summit eruptive vent demonstrate how the lava level (noted by white dashed line), depicted by warmer colors, charges across tilt cycles.

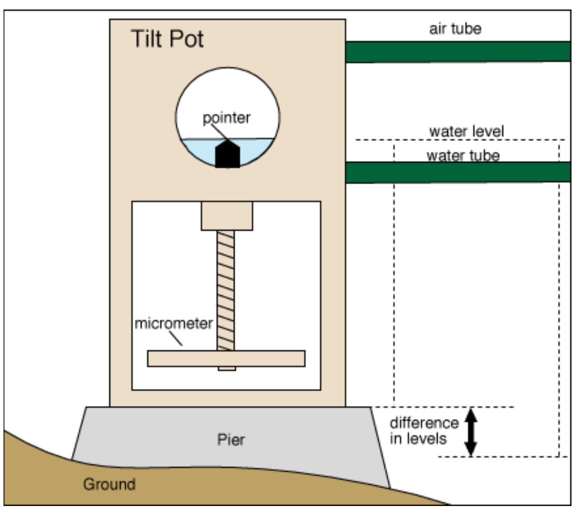
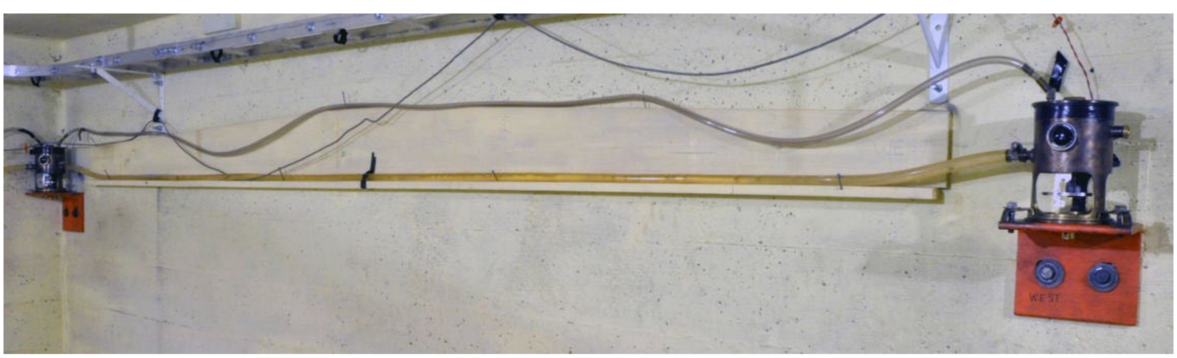


Fig 5. The schematics of such a tiltmeter.

Fig 6 (below). Water-tube tiltmeter installed in 1956 in an underground vault near Kilauea Volcano's summit. Two pots are connected by a tube filled with water that flows between pots as wall tilts.



Tiltmeters – Set up along the flanks of a volcano, tiltmeters have monitor how the slopes of volcanos change since 1956. As magma accumulates in or leaves the reservoir under Kilauea, the change in pressure causes the summit to either inflate or deflate, causing changes on the slopes of the flanks of the volcanoes. Precise measurements at specific locations over a period of time allows detection of movements caused by magma. These changes are very small, for example the 1979 eruption instigated tilt changes of roughly 5 microradians in about 12 hours.

GPS – Similarly, GPS allows careful 3-dimensional monitoring of movement on the flanks of volcanos for similar changes. This allows continuous monitoring of magma activities, as well as discrete episodes of accelerated seaward motion of the south flank of Kilauea.

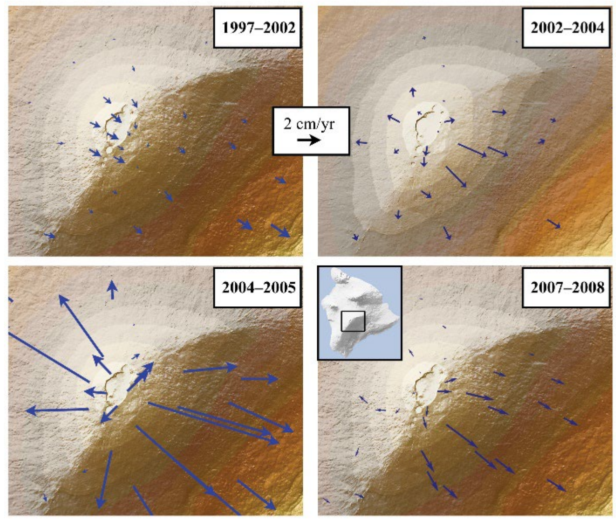
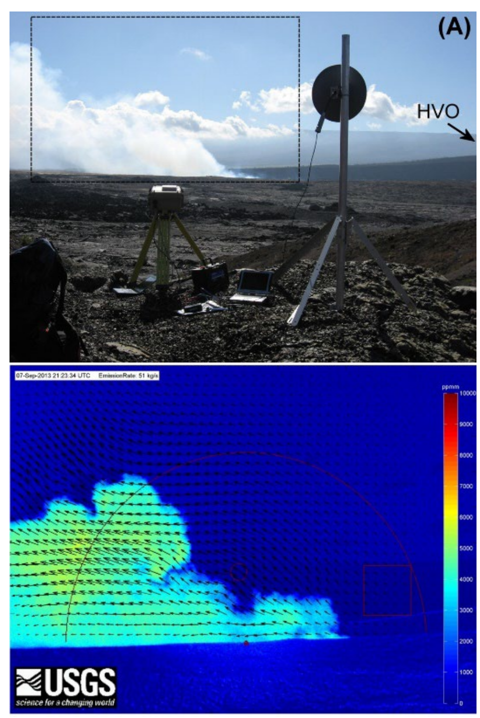


Fig 7. GPS measurements provide models of the direction and rate (length of arrow) of deformation at the summit of Mauna Loa. Arrows pointing in multiple directions away from the summit indicate inflation.

Interferometric Aperture Radar (InSAR) – Radar images are also used to detect ground deformation, which provide broader context than GPS, and can track ground movement associated with sudden volcanic events.



Volcanic gas monitoring – HVO monitors changes in emission rates of certain volcanic gases, chiefly sulfur dioxide (SO_2) and carbon dioxide (CO_2). SO2 absorb UV light, and thus can be monitored with UV cameras (shown on right). FTIR spectrometers are also used to monitor H_2O, SO_2, CO_2, CO, HCl and HF, and can provide insights into how different gases may be related to different types of volcanic activity.

<u>Field work</u>

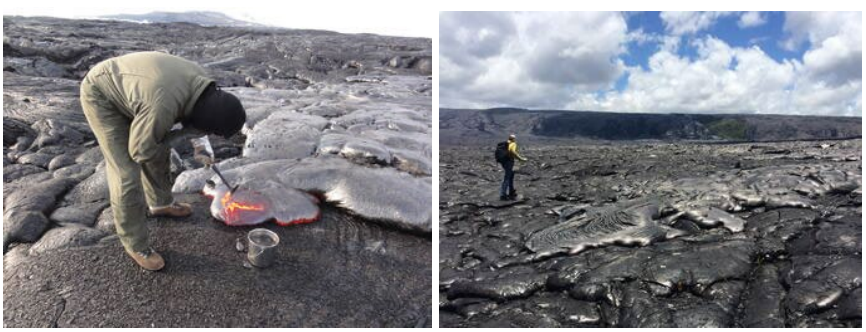
While sensors provide highly valuable and time sensitive information, field observations are still crucial for tracking eruptions and assessing hazards. Geological monitoring involves frequent visits to active vents and

Fig 9. HVO geologist conducts a VLF (very-low-frequency) electromagnetic survey across an active lava tube to determine the cross-sectional area of the lava stream coursing through the tube, Kilauea, Hawai‘i.

lava flows, in order to observe and document newly created volcanic features, and to sample lava or tephra for chemical and mineral analyses. This could be in forms of "boots on the ground", "eyes in the sky", or remote cameras and webcams.

The most accurate method of mapping a lava flow is still to walk along its edges with a handheld GPS, but is highly time consuming. Arial imagery can provide much wider coverage faster, allowing better analysis of past, current and future flow behaviors.

Effusion rate, the volume of lava erupted per unit time, can be monitored using electromagnetic surveys to estimate the vigor of an eruption. This is possible since molten lava is conductive, so the shape of the electromagnetic field induced around an active lava tube can be measured. Similarly, samples of lava are often collected to provide chemical fingerprints to track the progress of magma from various reservoirs. Finally, webcams and time elapse videos provide continuous visual monitoring, allowing better assessments and analysis of eruptions as they take place.



Left: Examples of fieldwork done for active lava flows, such as sample collecting and flow mapping

References:

[1] https://www.usgs.gov/observatories/hvo
[2] https://hilo.hawaii.edu/~kenhon/GEOL205/monitor/monitors.html
[3] https://en.wikipedia.org/wiki/2018_lower_Puna_eruption

Roberto Aguilar

Lava tubes

- Lava tubes are long sinuous cave systems that once carried lava from the erupting vent to downslope locations.
- Formation of lava tubes results in the most efficient method of transporting lava (solidified lava is a great thermal insulator)
- Lava tubes occur near vents, on steep slopes, and on the flat ground near the ocean [1].

Figure 4. Nāhuku Lava Tube (NPS Photo/D. Boyle) [2]

How are lava tubes form?

There are 2 ways of forming lava tubes: crusting over lava channels and within inflated sheet flows.

<u>Crusting over lava channels</u>

- Lava channels in both pahoehoe and aa flows can crust over to form lava tubes. A thin, plastic film of cooler lava forms on the surface of the stream where it is in contact with air.
- Crust begins forming immediately on the sides of active lava channels as it chills against cooler rock. At the edges of the channel, the lava is moving more slowly due to friction along the channel wall. This allows the plastic surface lava to roll up and adhere to the channel wall. The rolls form parallel to the channel edge and are generally less than an inch wide and several feet long.
- These small rolls are continuously added to the edge causing the crust to grow inward over the active lava stream [1].

Figure 5. The lower photo is a closeup of a channel entering a tube (away from the camera). The sides are forming cooled rolls that are building inward. [1]

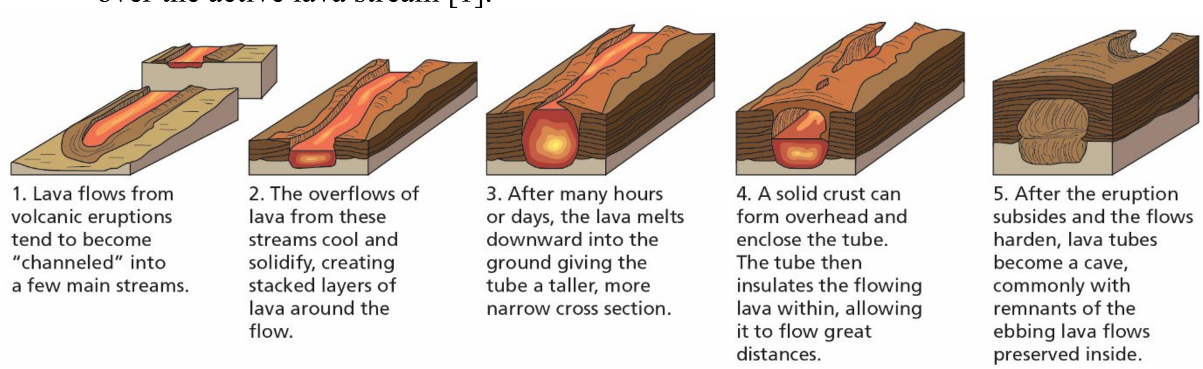


Figure 6. Lava tube formation from crusting over channels. Image from NPS

Inflated sheet flows

- Movement of lava within an inflated pahoehoe sheet flow is initially distributed evenly throughout its liquid core. Within hours after emplacement edge effects contribute to more rapid cooling of the flow margin.
- As the active flow front propagates downslope, the older, upslope flow lobes continue to cool from the sides as well as the top and bottom. These edge effects serve to concentrate transport toward the center of the flow.
- With continued migration of the flow front downslope, the upslope parts of the sheet flow cease to inflate.
- These sections of flow can no longer compensate for increasing crustal thickness; the resulting decrease in distance between the upper and lower crust causes a corresponding increase in factional resistance to flow, which again serves to focus the movement of lava.
- Preferred pathways of transport quickly develop within the liquid core flow. Decrease in cross-sectional area is compensated by increased flow velocity; the additional flux of hot lava also apparently serves to retard crustal growth.
- Eventually, well-developed lava tubes form along these pathways [3].

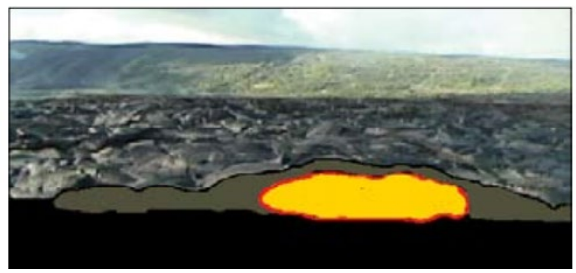


Figure 7. Interpretation: Sheet flow to lava tube [1]

Erosion, deepening, and lava tube formations

- The flowing lava can pluck away and erode the mushy rock at its base, causing the lava tube to deepen. As the tube deepens, it’s shape changes from the original wide and shallow cross–section of the stream to more circular or elliptical in shape.
- Changes in the level of the lava stream within an active lava tube create coatings on the inside of the tubes.
  - If the tube develops a blockage downstream or experiences a surge in lava supply, the lava level rises and applies a new coating of lava to the tube interior.
  - When the lava rises all the way to the roof then recedes, it leaves drips that form triangular stalactites called shark’s teeth (Fig 5).
  - If the lava only rises part way up the tube, it leaves a high lava mark or “bathtub ring”.
  - If the lava gets backed up filling the tube, it either pours through open skylights or bursts open the roof of the tube. These breakouts can form new lava flows and create stacked tube systems [1].

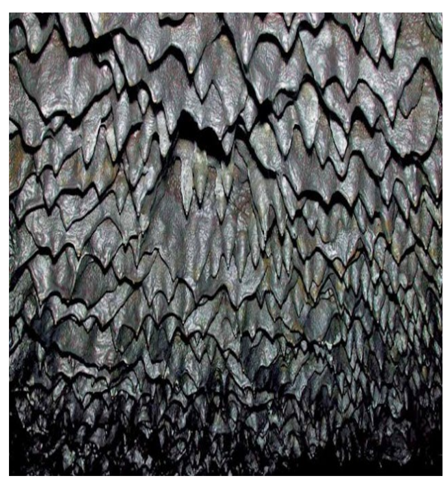


Figure 8. Triangular stalactites (shark’s teeth)

Lava tubes in the Island of Hawai'i

- There are thousands of lava tubes on the Big Island.
- The Kazumura lava tube system, within the 500 year-old ʻAilāʻau lava flow of Kīlauea, is more than 65 km (40 miles) long and is thought to be the longest and deepest lava tube cave, with descends of 1.101.5 meters (3,614 feet).
- Nāhuku Lava Cave is the most visited tube in the world.
- Once lava subsides, ecosystems of distinct species of crickets and spiders develop alongside special microbial colonies found nowhere else.

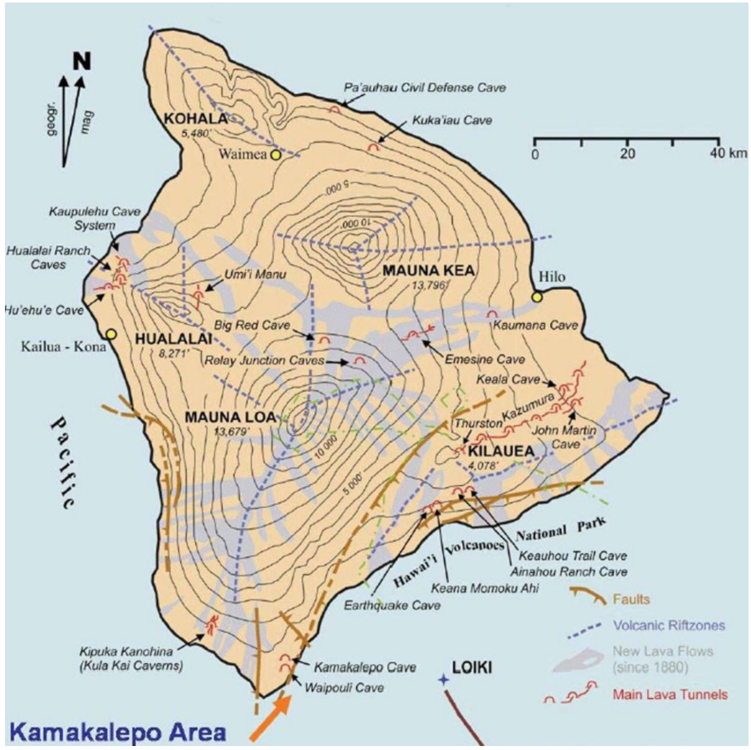


Figure 9. Map showing locations of some of the major lava caves on Hawaii. [4].

Cultural significance of lava tubes in the Island of Hawai'i

- They could be used as shelter from both the elements and human enemies. Food stored in the cooler; more thermally stable lava tubes would last longer. Middens within lava tubes have contained ʻopihi shells, stone tools, and other evidence of daily life.
- Because most of the island of Hawaiʻi has no standing lakes, ponds, or flowing streams, drinking water could be hard to find. Lava tubes were one valuable source. Dripping water from the ceilings, filtered down through porous lava rock, was often gathered in gourd bowls called ipu.
- Lava tubes were also central in some ceremonies and burials. The carefully prepared and wrapped bones of important individuals would sometimes be placed in the caves. The national park protects these sacred burial caves, and no tours or entry is permitted [2].

Lava tubes on the Moon and Mars

Sinuous collapse chains and skylights in lunar and Martian volcanic regions have often been interpreted as collapsed lava tubes. It possible to investigate their surface expression through the analysis of collapses and skylight morphology, morphometry, and their arrangement, and compare these findings with <u>terrestrial analogues</u> [5].

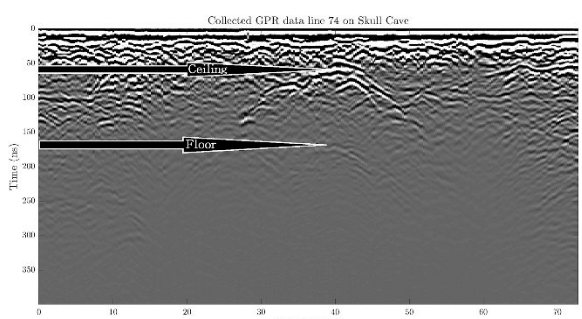


Figure 10. Ground Penetrating Radar data on Skull cave, Lava Beds National Monument in California [6].

- On the Moon subsurface cavities have been inferred from several skylights in Maria smooth plains and corroborated using gravimetry and radar sounder.
- On Mars several deep skylights have been identified on lava flows.

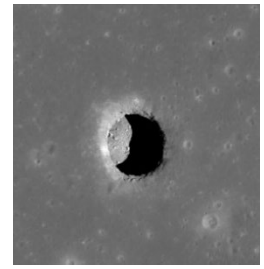


Figure 11. Lunar skylight image from LRO-CTX

This increasing trend of lava tube size from Earth to Mars and the Moon can be correlated to the different gravity parameters of each planetary body:

- Lower gravity bodies present higher effusion rates and longer and thicker lava flows, favoring the emplacement of flood basalts where pressure flow prevails over gravity flow.
- Lower gravity allows the emplacement of wider conduits within the stability threshold.

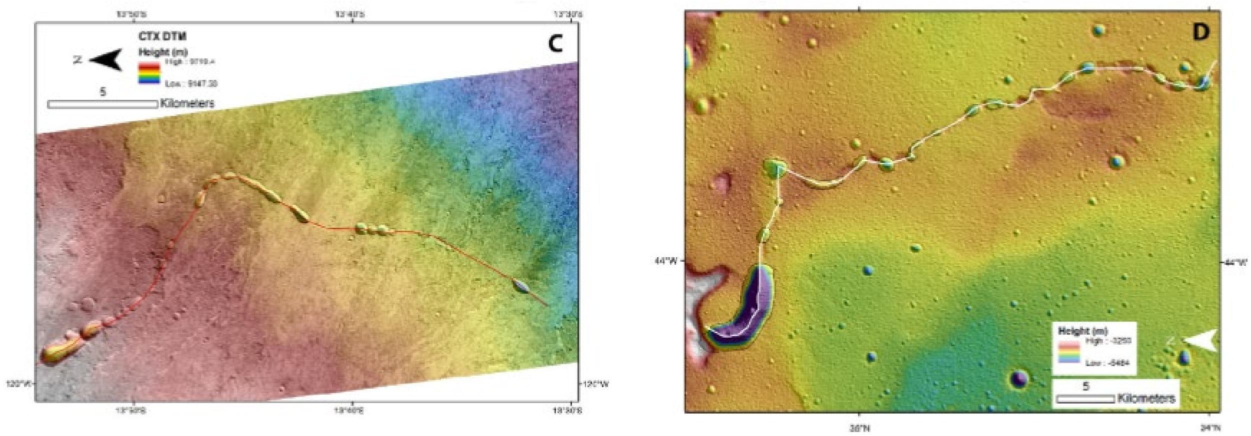


Figure 9. Lava tube collapse chains on Mars (left) and on the Moon (right) are characterized by non-coalescent depressions and sinuous development [5].

References:

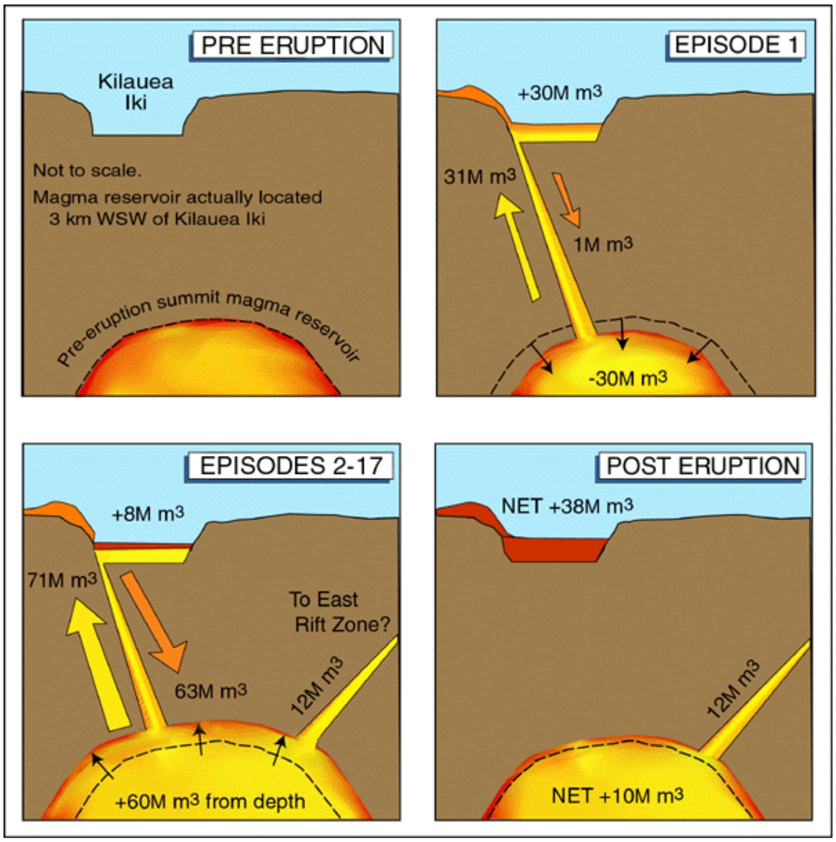
[1] Field interpretations of active volcanoes, A handbook for viewing lava. URL: https://hilo.hawaii.edu/~kenhon/GEOL205/Hawaiian%20Geology.pdf. Accessed: 02/22/2022. [2] Lava tubes, National Park Service. URL: https://www.nps.gov/havo/learn/nature/lava-tubes.htm Accessed: 02/16/2022. [3] Hon, Ken, Jim Kauahikaua, Roger Denlinger, and Kevin Mackay. "Emplacement and Inflation of Pahoehoe Sheet Flows: Observations and Measurements of Active Lava Flows on Kilauea Volcano, Hawaii." *Geological Society of America Bulletin* 106, no. 3 (March 1994): 351–70. https://doi.org/10.1130/0016-7606(1994)106<0351:EAIOPS>2.3.CO;2. [4] Kempe, Stephan & Henschel, Horst-Volker. (2008). Thurston Lava Cave, the most visited tube in the world. What do we know about it? Hawai'i Speleological Survey Newsletter. 24. 16 - 24. [5] Sauro, Francesco, Riccardo Pozzobon, Matteo Massironi, Pierluigi De Berardinis, Tommaso Santagata, and Jo De Waele. "Lava Tubes on Earth, Moon and Mars: A Review on Their Size and Morphology Revealed by Comparative Planetology." Earth-Science Reviews 209 (October 1, 2020): 103288. [6] Esmaeili, S., S. Kruse, S. Jazayeri, P. Whelley, E. Bell, J. Richardson, W. B. Garry, and K. Young. "Resolution of Lava Tubes with Ground Penetrating Radar: The TubeX Project." *Journal of Geophysical Research: Planets* 125, no. 5 (2020): e2019JE006138. https://doi.org/10.1029/2019JE006138.

Rishi Chandra

Lava Lakes: Kilauea Iki

Persistent lava lakes are, contrary to popular depictions, a relatively rare phenomenon.

- Lava lakes are surface expressions of complex magmatic systems
- Lake level controlled by pressure in reservoir
    - Pressure in reservoir controlled by numerous factors:
    - Outflow of melt from magma chamber can cause lava lake to fall
    - Inflow of melt from depth can cause lava lake to overflow



Molten lava lakes show patterns of circulation, convection, and overturn that can be used to infer properties of the magma system at depth, because lava lakes are connected to their sources in a number of ways, chiefly

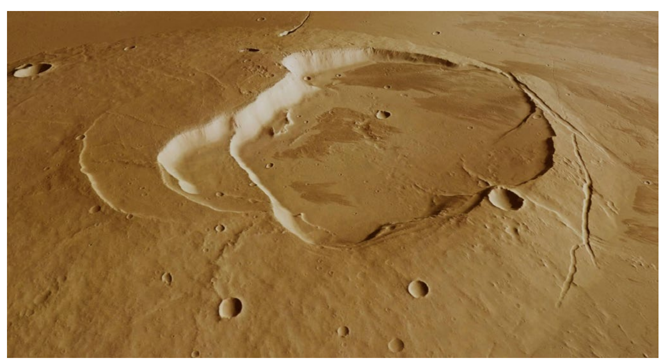
- Thermal balance
- Gas balance

This balance can't last long without a long lived non-explosive source, making most lava lakes an ephemeral feature typically associated with effusive basaltic melts. This isn't to say, however, that the formation of lava lakes can't be as spectacular as an explosive eruption.

In Hawaiian, *Kilauea* means "spewing", which it did a lot of in 1959. Between November 14th and December 20th, 1959, Kilauea Iki erupted in dramatic fashion, fountaining lava as high as 580m in the air in one of the most spectacular recorded eruptions of the 20th century [1]. While during the first eruptive episode, a line of lava fountains simultaneously erupted, outer fountains were blocked leading to all of the lava fountaining at higher pressures from just one vent [2]. This was not unlike plugging a garden hose with your thumb to cause the water to spray much further than it otherwise would. The rapid arrival of an unusually large volume of melt from depth caused the overpressure, and blobs of lava as wide as a meter across were launched high into the sky on seventeen eruptive episodes before the eruption stopped.

The fountain of lava built a cinder cone, Pu'u Pua'i (Hawaiian for "gushing hill"), and it filled the volcanic crater Kilauea Iki with lava, creating a lava lake. Parts of the cinder cone sloughed off while the lava lake was filled, and floated off creating some of the relief you see on the surface of the lake.

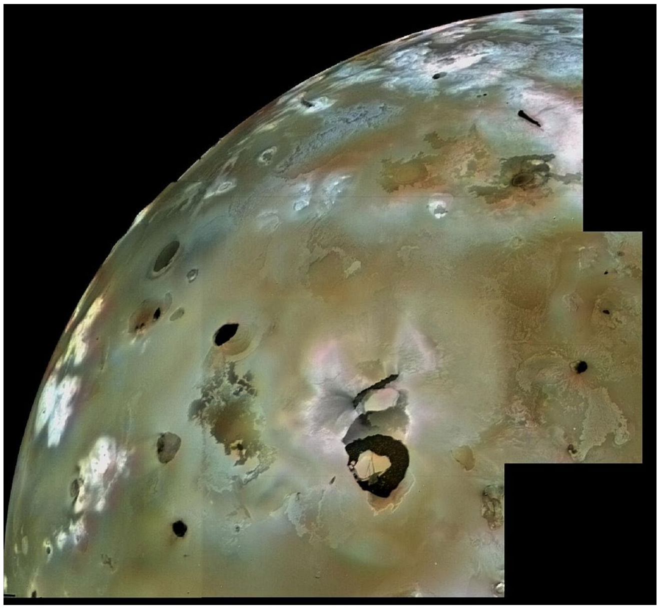
The level of the lava lake was controlled the pressure of the melt at the vent while it was active, and by the elevation of the vent after the lava stopped coming up from depth. As the lava lake deepened, it proceeded to cover the vent from which lava was erupting, and submerged it under a meter of melt. After the eruption stopped, the lava *drained back* into the vent until the lava lake was left at a level even with the vent opening. Like a draining bathtub, the lava sometimes formed a counter-clockwise whirlpool pulling cooled slabs of lake crust down into the vent. We can see the remnants of this filling of the lake with lava in the form of black "bathtub" ring on the walls of the crater, indicating the level to which the lake was filled.



Planetary analogs to Kilauea Iki:

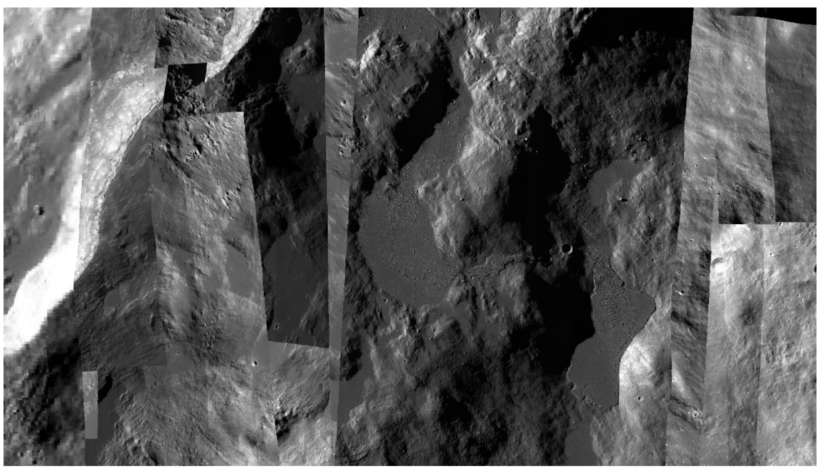
Lava lakes occur on any planetary body that experiences volcanism. Most analogous to Hawaii, Martian volcanism in Tharsis displays some analogous features: Jovis Tholus appears to contain a caldera formed from a large collapsed magma chamber, and its current flat surface appears to have been filled in by a lava lake. This lake also contains some relief that may have formed in similar ways to the relief we see at Kilauea Iki. Additionally, the largest and oldest segment of the caldera of Olympus Mons is believed to have been one massive lava lake [4].

On Io, Loki Patera is the site of an active persistent lava lake [5]. The lake has been observed through ground-based satellites, and the Io Volcano Observer is a mission that has been proposed to take a closer look at this unique site of magmatic processes in the outer solar system.



The lake periodically brightens and darkens, and this has been interpreted as overturn of the lake as rock cools at the surface, allowing hotter lava to periodically return to the surface. This process has direct analogues that can be observed in terrestrial lava lakes, which typically have a thin, cool crust overlying a volume of liquid magma, which can be overturned as the lake convects and advects.

A more tenuous analogy, but lava lakes can also be compared to impact melt ponds that form at the bottom of impact craters, or in uneven ponds on crater rims. Sufficiently large meteorite impacts will generate impact melt that can occupy the bottom of the impact basin, and debris can fall in while the melt pond is still molten or after it cools and solidifies. We can use these observations to understand post-impact modification processes on shorter timescales than otherwise possible Additionally, self-secondary impacts can land on impact melt before it cools, leaving a distinctive crater morphology (sometimes called *ghost* craters) indicating the flow of melt over a small crater inside of a larger crater, giving a rare chance to find ground truth on the frequency of secondary craters which otherwise confound crater counts.



References:
[1] USGS, https://www.nps.gov/havo/learn/nature/kilauea-iki.htm, accessed Feb 22, 2023 [2] https://www.usgs.gov/volcanoes/kilauea/1959-kilauea-iki-eruption, accessed Feb 22, 2023 [3] https://www.dlr.de/content/en/articles/news/2022/01/20220126_island-in-a-lake-of-lava-martian-volcano-jovis-tholus.html. Accessed Feb 22, 2023 [4] Mouginis-Mark, P.J. et al.. (2007). Terrestrial Analogs to the Calderas of the Tharsis Volcanoes on Mars in The Geology of Mars: Evidence from Earth-Based Analogs [5] Howell, 1997.

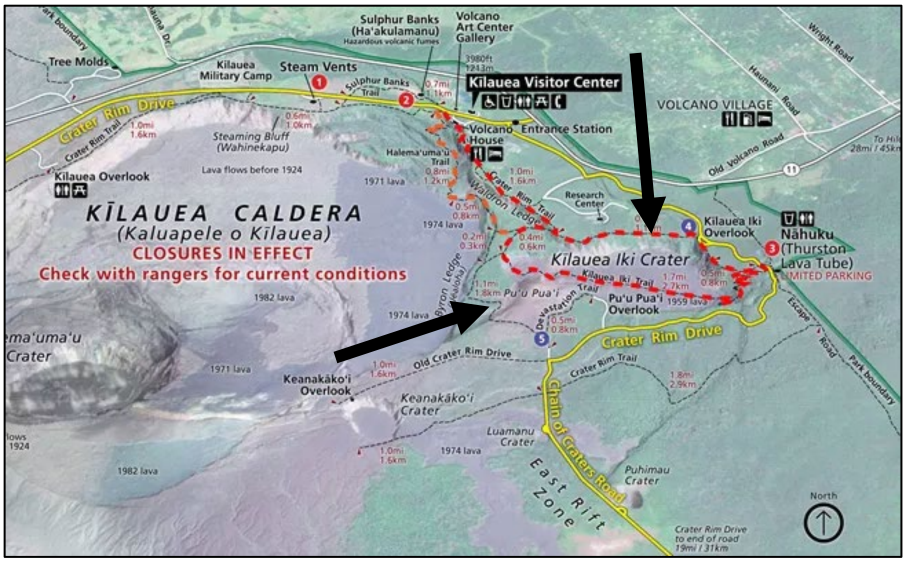
Image credit: 1. USGS, 2. USGS, 3. ESA/DLR/FU Berlin, 4. NASA JPL, 5. NASA, 6. LROC QuickMap, ASU

Zoë Wilbur

KĪLAUEA IKI: FIRE FOUNTAINS, TEPHRA FALL, AND THE MOON

From November 14 to December 20, 1959, amazing fire fountains of lava erupted from Kīlauea Iki. What are fire fountain eruptions, and how do they form? How can these eruptions help us understand samples returned from the Moon and orbital data?

First, some <u>context</u>. **Kīlauea Iki** is a Crater to the East of the main Kīlauea Caldera (**Fig. 1**).



Fire fountaining is an eruption type characteristic of Hawaiian volcanism (**Fig. 2,3**), and the 1959 Kīlauea Iki eruption produced the highest lava fountains (up to 1900 feet/580 meters tall) ever observed in Hawaii in the 20th century [**1**].

<u>**Figure 1**</u>**:** The Kīlauea Iki Pit Crater and trail (outlined in red dashed lines) relative to the main Kīlauea Caldera. Figure courtesy of [**1**].

1959 ERUPTION HIGHLIGHTS [2]:

- Lava fountains erupted through a fissure (fracture) and broke through the wall of the Crater. Within 1.5 hours, the fissure grew to 900 meters long (10 football fields) and the fountains reached up to 100 feet high. Lava flowed down the slopes, pooled, and formed a <u>lava pond</u> (**Fig. 3**).
- Roughly three days later, pyroclastic material (also called tephra), such as pumice (a silicic and highly vesicular volcanic rock) fell onto the downwind side of the vent. This tephra formed a <u>new tephra cone</u> (named Pu'u Pua'i; **Fig. 1**) and also contributed to the lava lake within the Crater.
- The first explosive episode produced 30.5 x 10^6 m^3 of lava in the lake, which eventually started to drain back into the vent until the lava lake reached the vent level.

<u>**Figure 2**</u> **(right):** The Kīlauea Iki lava fountain viewed from Crater Rim Drive, photographed Nov. 29th, 1959. Figure courtesy of [**1**].

- The subsequent 16 explosive episodes (**Fig. 2**) produced smaller volumes of lava and were shorter in duration. Similar to episode #1, tephra was added to the newly formed Pu‘u Pua‘i tephra cone and added to the Crater lava lake.
- Episode #15 produced 589-meter-high fountains.
- Episode #3 produced the greatest volume of tephra, which were carried up to 15 kilometers downwind of the Crater.

FIRE FOUNTAIN PRODUCTION:

- The structure of a fire fountain and the clast size distribution (CSD) within the fountain are determined by the magma’s gas contents and the volume flux of magma [**3**].
- The fountain’s temperature and accumulation rate determine if the eruption will form stationary pyroclastic features or dynamic lava flows.
- Fountain height can be used as an important indicator of magma gas contents during an eruptive episode and trends in volatile contents in an eruption sequence [**3**].
- The paths and destinations of pyroclastic material from the fountain are determined by both a velocity profile and the fountain’s maximum spread angle (**Fig. 3**).

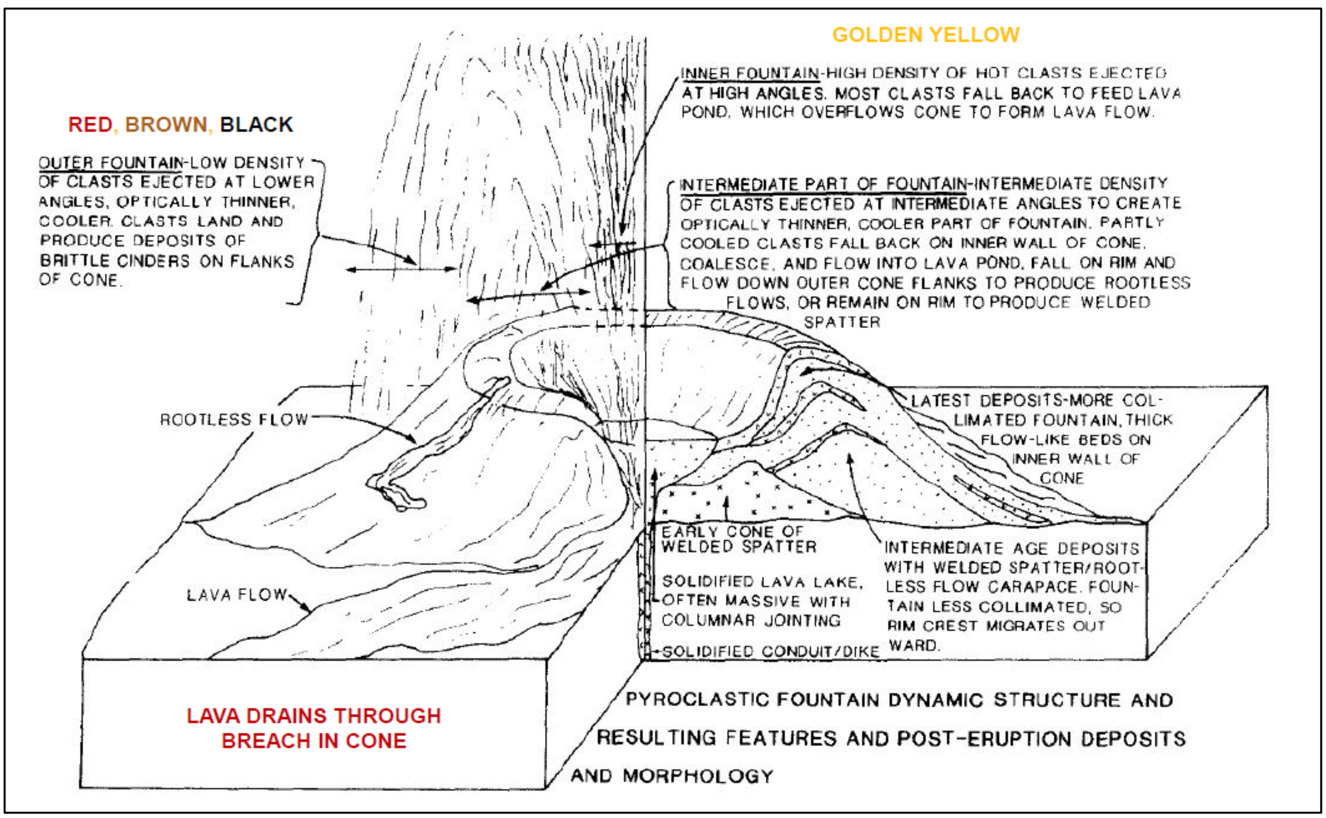


Figure 3: Relationship of a fire fountain structure to its post-eruption deposit types. Note that for typical terrestrial, basaltic pyroclastic eruptions, most of the pyroclastic material stays inside the optically thick central fountain location, and therefore experiences little cooling and falls to the surface to coalescence and add to a lava pond or lava flow (if there is a breach in the cone). Figure modified from [**3**].

CLAST TYPES [4]:

- Scoria: a foamy rock consisting of up to 85% vesicles. These vesicles are round and variable in size. This clast type preserves textures closer to the conditions upon which the lava experienced fragmentation.
- Reticulite: a foamy rock consisting of >95% vesicles. This clast type is formed from the continued vesiculation and clast expansion in the thermally insulated central zone (**Fig. 3**) of the fire fountain.
- A foam can transition from scoria to reticulite as a consequence of larger bubbles growing at the expense of smaller bubbles (also called Ostwald ripening).
- Pumice: similar to scoria but contains bimodal vesicle sizes and smaller vesicles than scoria. Clasts most likely experienced expansion after the fragmentation event (**Fig. 4**).
- Fluidal: clasts have high proportions of smaller vesicles that quenched quickly after the fragmentation event. Fluidal clasts did not experience extended bubble growth or coalescence of bubbles (**Fig. 4**).
- Transitional: In between pumice and fluidal clasts (**Fig. 4**).

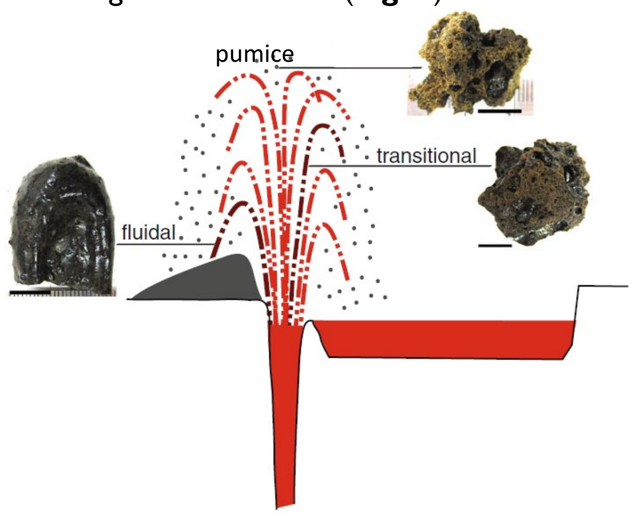


Figure 4 (right): Kīlauea Iki clast types relative to where the clasts originate in the fire fountain. Horizontal lines denote where the clasts are likely to quench (rapidly cool). Scale bar = 1 cm. Figure from [**4**].

THE VOLATILE (that's a pun) STORY:

- Volatile- and Mg-rich (picritic) melt intrudes the summit magma reservoir (**Fig. 5**), which contains cooler, less Mg-rich magmas that could have already lost their gases/volatiles.
- Turbulent mixing occurs because the intruding magma has a high Reynolds #.
- The picritic melt crystallizes with the cooler magma and with cooler, drained-back lava from prior eruptions.
    - This causes rapid vesiculation and rapid olivine growth, which traps melt inclusions.
- Mixed magma erupts as a fire fountain.
- The cooler, degassed magma drains back and mixes further in the reservoir.
- The mixed magma is volatile-rich.

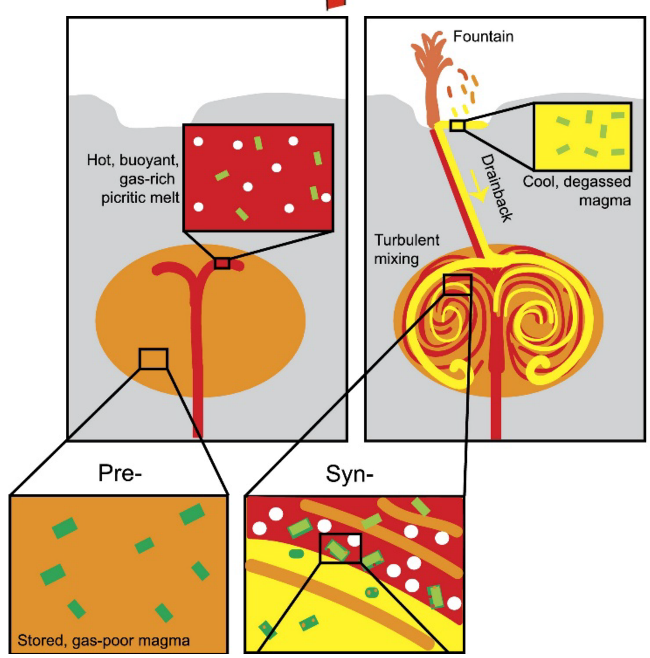
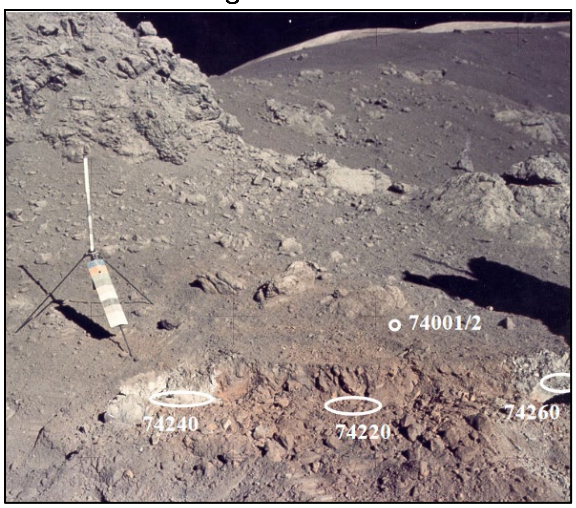


Figure 5 (above): Kīlauea Iki magma mixing and vesiculation. Green = olivine. Figure modified from [**5**].

PLANETARY GEOLOGY APPLICATION: THE MOON

- The Apollo 15 and 17 missions returned samples containing glass beads [**6,7**], which provide evidence of ancient fire fountaining on the lunar surface (**Fig. 6a and 6b**).
- Pyroclastic deposits on the lunar surface are low-albedo features (**Fig. 7).**
- Laboratory-based analyses of returned picritic glasses show that the magmas were derived from great depths in the lunar interior and likely represent the most primitive material from the Moon in our sample collection.
  - Measurements of lunar glass beads with improved analytical techniques detected water and other volatile species [**7**], which revolutionized our views of the Moon's formation (i.e., not "bone dry").
  - Glass beads are critical for understanding the origin and evolution of basaltic magmatism on the Moon.



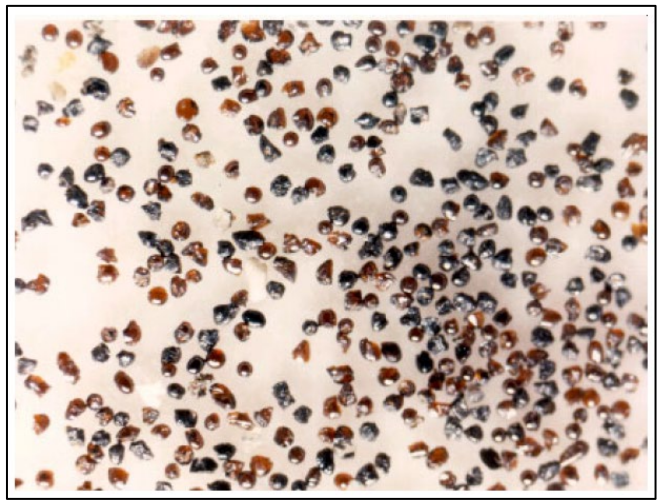


Figure 6: a) Apollo 17 orange glass bead deposits at the rim of Shorty Crater. **b)** Microscope image of orange and black glass beads (~100 μm) sampled from the rim of Shorty Crater. These samples originate from ancient pyroclastic lunar eruptions. Figure courtesy of NASA and [**6**].

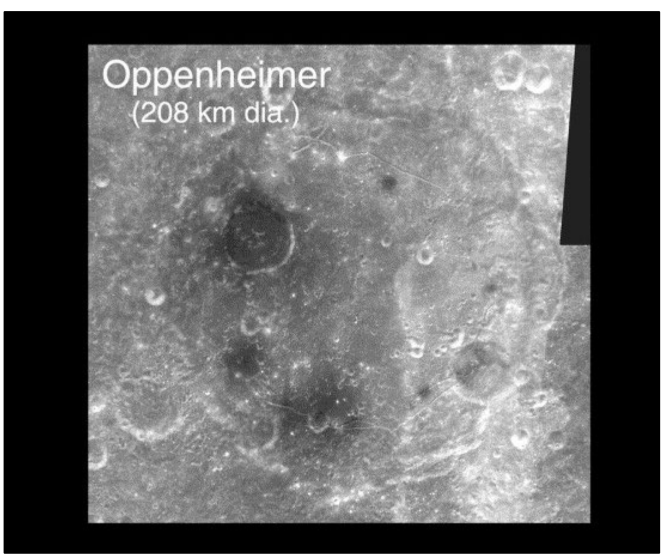


Figure 7 (left): Clementine image of lunar pyroclastic deposits (dark material) in the floor of Oppenheimer Crater. Figure courtesy [**8**].

REFERENCES: [**1**] The National Park Service. https://www.nps.gov/havo/planyourvisit/kilauea-iki-trail-from-kilauea-iki-overlook.htm. [**2**] D. H. Richter, et al. (1970) USGS Num. Series **73** p. E7-E36. https://pubs.usgs.gov/pp/0537e/report.pdf [**3**] J. W. Head and L. Wilson (1989) *Volcanol. Geotherm. Res.* **37** p. 261-271. [**4**] W. K. Stovall et al. (2011) *Bull Volcanol* **73** 511-529. [**5**] I. Sides et al. (2014) *EPSL* **400** 102-112. [**6**] C. Meyer (2005) *Lunar Sample Compendium*. https://curator.jsc.nasa.gov/lunar/lsc/74220.pdf [**7**] A. E. Saal et al. (2008) *Nature* **454** p. 192-195. [**8**] L. R. Gaddis et al. (2003) *Icarus* **2** 262-280.

Astrobiology on Hawaii

Searra Foote

Subfields of Astrobiology

Astrobiology is the study of Earth and planetary bodies to understand more about the history, evolution, distribution of life in the universe. On the big island of Hawaii, there are several points of interest to study this subject and many methods of doing so.

1. To find out more about other destinations inside the solar system, Hawaii provides the necessary habitats to use as an analog for Mars.
2. The assessment and study of biosignatures - and how to recognize false ones - can allow scientists to understand how to detect life in the universe.
3. The presence of prominent telescopes on the island allows for the study of astronomical objects of potential astrobiological importance.

These studies are pivotal to understanding more about our universe and potential life outside of Earth. Several key locations will be highlighted to emphasize how beautiful locations on planet Earth can allow us to learn more about life as we search our own backyard of the universe.

Planetary Analog: Mars

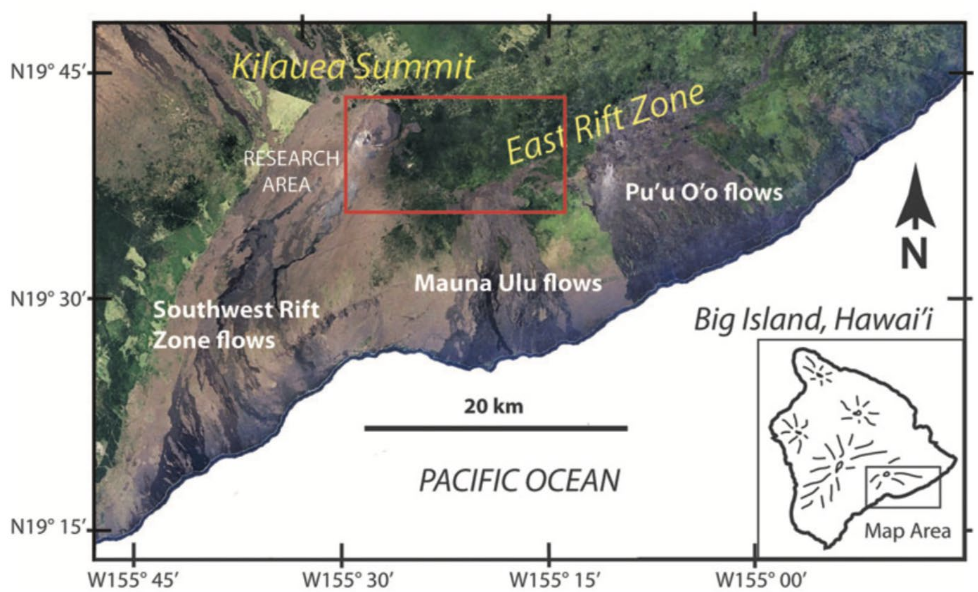


Figure 1: *A Google Earth image of Hawaii in which the red box denotes the Kilauea volcano as an area of interest to be used as an analog for Mars. (Hughes et al 2019)*

The NASA Biological Analog Science Associated with Lava Terrain (BASALT) research team uses the region of the Kilauea Volcano to examine the possibility of habitability on Mars. As is usually the case for astrobiology, the connection between two fields are required to complete this assessment. By studying the interaction between the geology of this region and the biology present, questions can be answered about informing future space exploration on the surface of Mars.

This site is used as an analog because of the basaltic terrain. One assumption of this study is that geologic substrate will affect the diversity and biomass of life, which will vary with different combinations of rock composition, texture, and alteration conditions. This can give scientists the opportunity to identify potential extinct or even life currently present on the surface of Mars. The main findings the BASALT team has gathered from this study are as follows:

- volcanic features on Earth must be associated with specific regions on Mars
- regional alteration of volcanic terrains is likely to have occurred early in geologic history
- long-term alteration since then would be related to cold, dry conditions or the interaction of lavas with ice
- basaltic terrains on Earth host a diverse microbiota
- lava is capable of hosting a diverse microbial assemblage that includes the capacity to oxidize sulfur and iron as sources of energy
- processes related to rock alteration include:
    - oxidizing effects of high-temperature, syn-eruptive volcanic gasses
    - secondary fumarolic or other hydrothermal reactions
    - low-temperature weathering by meteoric fluids
    - physical weathering and reworking

Biosignatures and False Positives from Volcanoes

Biosignatures:

- any piece of evidence that supports the presence of life
- studied on Earth to learn how we can detect evidence from a biological source
- relevant to astrobiologists to know how to find life in the universe
- not exactly a smoking gun to know that life is present due to false positives
- can be observed on Earth, an example is atmospheric O2

False Positives:

- an instance of detecting a possible signature of life that's actually from a non-biological source
- can lead to an incorrect assumption that life is present
- need to understand how to spot a false positive to better constrain and inform the search for life

Here are some examples of biosignatures on the island of Hawaii:

1. Sulfur Banks

- Heated groundwater released as steam contain volcanic gasses
- Carbon dioxide, sulfur dioxide, hydrogen sulfide
- Sulfur dissolved in magma
- Can deposit crystals
- Deep faults extend to the magma layer
- Sulfuric gasses can deposit crystals
- Sulfuric acid breaks lava down to clay
- Notice the smell of rotten eggs or lighting a match

Figure 2: *Sulfur Banks in Hawaii (Calvin J. Hamilton 2008)*

2. Mauna Loa

- Methane and carbon dioxide
  - Increase over time due to anthropogenic emissions

3. Kilauea

- Sulfur dioxide
  - Shallow subsurface magma

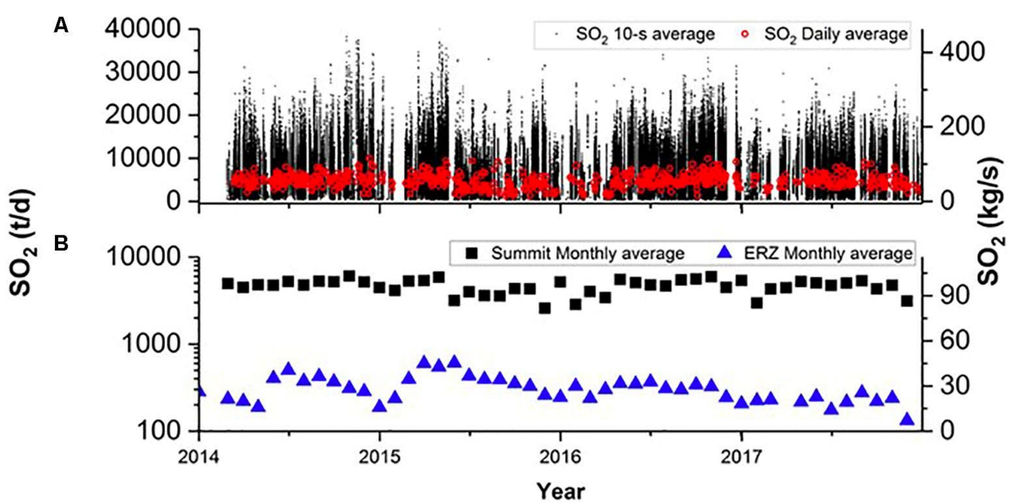


Figure 3: *Measure of SO2 emissions from Kilauea. (Schwieterman 2018)*

Observational Astronomy

The Canada-France-Hawaii Telescope (CFHT) is located on the summit of Mauna Kea and is an important tool for astronomers to study astronomical objects of interest, even of astrobiological importance.

MSE: An astrobiological tool

- Maunakea Spectroscopic Explorer (MSE)
- instrument in development that will serve as an upgrade to the CFHT
- 4,000 astronomical objects studied at one time
- Dark matter and black holes
- first instrument of its kind to study the origins of elements on our periodic table
    - great implications for the study of the origin of life.
- study chemical evolution of our galaxy
- utilize spectroscopy to understand the origins of our own galaxy and planet
    - large-scale study of galaxy evolution and how this fits into the larger structure of the universe
    - opportunities to learn about the emergence of a potentially habitable world

Figure 4: *The Canada-France-Hawaii Telescope, soon to be upgraded with Hawaii's first instrument known as the Maunakea Spectroscopic Explorer that will have both astronomical and astrobiological relevance. (CFHT Hawaii 2023)*

References

Catling et al. (2018). Exoplanet biosignatures: a framework for their assessment. *Astrobiology*.

Field, D. (2005). Astronomy and astrobiology. *Europhysics news*, *36*(2), 51-55.

Hughes, S. S., Haberle, C. W., Kobs Nawotniak, S. E., Sehlke, A., Garry, W. B., Elphic, R. C., ... & Lim, D. S. (2019). Basaltic terrains in Idaho and Hawai ‘i as planetary analogs for Mars geology and astrobiology. *Astrobiology*, 19(3), 260-283.

Sakai, H., Casadevall, T. J., & Moore, J. G. (1982). Chemistry and isotope ratios of sulfur in basalts and volcanic gases at Kilauea Volcano, Hawaii. *Geochimica et Cosmochimica Acta*, 46(5), 729-738.

Schwieterman, E. W. (2018). Surface and temporal biosignatures. *arXiv preprint arXiv:1803.05065*.

https://www.cfht.hawaii.edu/en/

Beau Prince

Chain of Craters

The Chain of Craters is a series of volcanic craters that mark Kīlauea's upper East Rift Zone, running southeast from Kīlauea's summit caldera. The craters included in the Chain of Craters are thought to be very young (<400 years old) and formed by collapse [1]. Winding through the Chain of Craters is the aptly named Chain of Craters Road, which we will be traversing today. The route runs from Kīlauea Iki crater to the coast, ending where the road was covered in lava by the Pu`u`ō`ō eruption in 1986 [2]

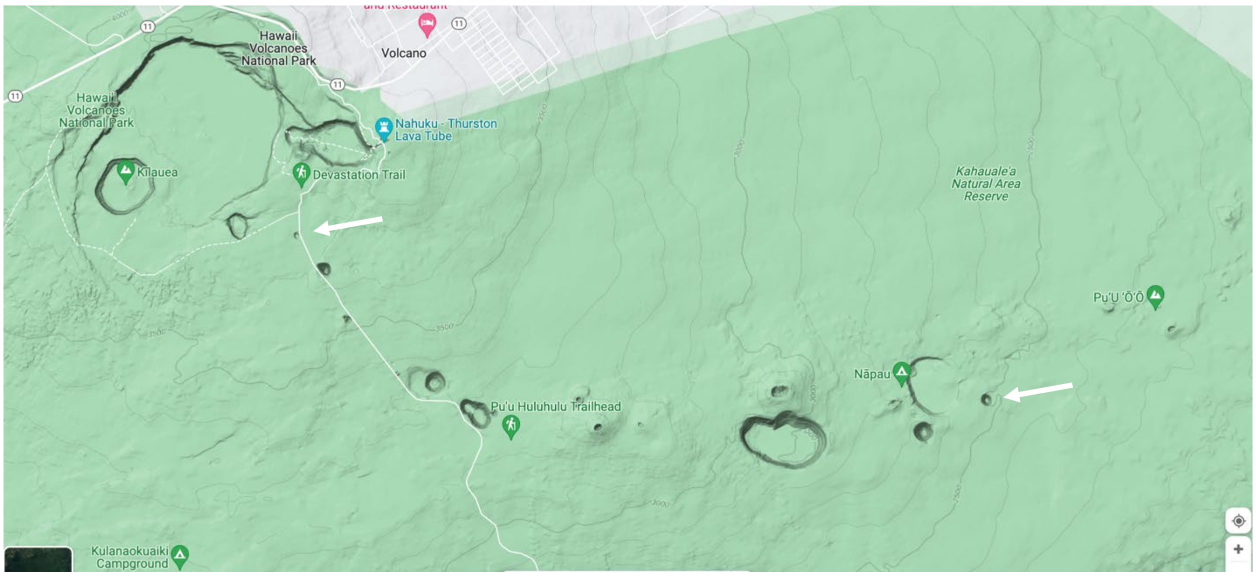


Figure 12: A screenshot from Google Maps showing the Chain of Craters curving southeast of the Kīlauea summit caldera. The first and last craters in the chain–Lua Manu and an unnamed pit, respectively–are labelled with arrows. The road running along the chain until the Pu`u Huluhulu trailhead is Chain of Craters Road.

Included in the Chain are the following craters (the craters we will be stopping at are in italics):

- Lua Manu
- Puhimau
- Ko`oko`olau
- Devil's Throat
- Hi`iaka
- *Pauahi*
- `Alo`i
- *Pu`u Huluhulu*
- *Maunaulu*
- `Alae

I'll provide a brief description of each to give us a sense of what we'll be seeing as we go.

Pauahi

Pauahi Crater is a pit crater (approximately 500m wide and 110 m deep) consisting of three pits: a main central pit, an eastern pit, and a western pit [3]. The crater has been the site of three eruptions. The first was in May 1973, in which a relatively small amount of lava was deposited on the crater's floor. This was quickly buried by the November 1973 eruption, in which an eruptive fissure formed at the bottom of the crater, diverting lava from the nearby, erupting Maunaulu. Shortly thereafter, fire fountaining from fissures along the walls of the crater created lava lakes in the western and central pits of the crater. After the lava lake had risen so high as to merge the two lava lakes, a large whirlpool formed, indicating draining through the bottom of the crater, despite eruptive fissures on the edge of the crater. A third eruption in November 1979 began in the western pit, destroying part of Chain of Craters Road as lava flowed westward from the crater [4].

Figure 13: Lava cascades from the eastern pit into the central pit of Pauahi Crater during its November 1973 eruption. Photo by Robert Tilling, USGS. (Public Domain)

Pu`u Huluhulu

Aptly named "Hairy Hill", Pu`u Huluhulu is a cinder cone due east of Pauahi and immediately northwest of Maunaulu. The cone and the inside of the crater are covered in dense vegetation, giving the cone a hairy appearance. The area surrounding the cone has been covered by several lava flows, including flows from the 1935-1936 Mauna Loa eruption [4] and the 1969-1974 Maunaulu eruption. In the latter eruption, flows from Maunaulu encountered a sudden reduction in slope where the shield of Maunaulu meets the rise of Pu`u Huluhulu, causing the lava to spread out and form its own levees. This created a perched pond of lava between Pu`u Hululu and Maunaulu [5]

Maunaulu

Maunaulu is a young volcanic cone just south of the much older Pu`u Huluhulu. The cone was created during the 1969-1974 eruption, which was the longest lasting and most voluminous eruption of Kīlauea for ~2200 years until the 1983-2018 Pu`u`ō`ō eruption. Starting as a gash in the ground, Maunaulu's shield now stands 121 m tall [6]. The eruption is perhaps best remembered for its fire fountains, which reached heights of 540 m. Lava flowed outward from Maunaulu and eventually filled the nearby `Alae, until fissures on the bottom of the crater drained the lake and created a cascade of lava over 250m into the empty crater below. The eruption continued nearly continuously until July 1974, leaving `Alo`i completely buried and `Alae nearly filled with hardened lava [7].

Figure 14: The orange gash is a one-day-old Maunaulu. This photo was taken by Don Swanson on May 25, 1969, one day after the beginning of the Maunaulu eruption. (Public Domain)

Formation of Chains of Craters

It is generally agreed that pit crater chains, such as the one here in the Upper East Rift Zone of Kīlauea, form by collapse into a subsurface cavity, but the exact mechanism of formation is still debated. Wilkes (1845) initially proposed a chain suggests the collapse of the roof of a lava tube. Similarly, Blevins (1981) suggested the Kīlauea chain formed from roof collapse of a large cavern under the ERZ. Others have suggested that pit chains form from a series of partially drained dikes (Favre 1993). In their survey of the Chain of Craters, Okubo & Martel (1998) proposed that pit chains form by stoping over a large rift zone fracture [3]. More recently, it has been proposed that dilational normal faulting may be the cause of pit crater chain formation [8, 9].

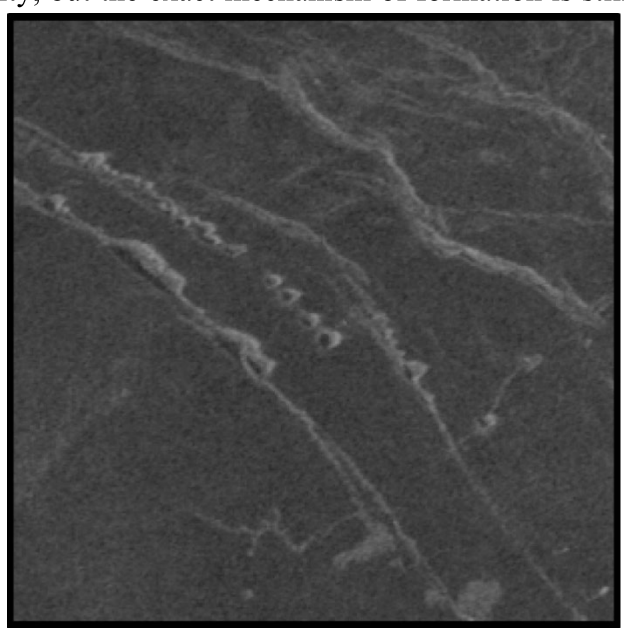


Figure 15: An image of a chain of pit craters near Idunn Mons, Venus, taken using Magellan Synthetic Aperture Radar. Adapted from Davey et al. 2013.

Chains of Craters in the Solar System

Chains of craters have been found on Earth, the Moon, Mars, Venus, Phobos, Eros, Gaspara, Ida, Enceladus, and Europa [10, and references therein]. While some chains, namely on the Moon, form by the tidal disruption of a weakly bound body immediately before impact [11], chains elsewhere, such as Venus and Mars, have apparently volcanic origins [12]. To gain a better understanding of these extraterrestrial chains, the ERZ Chain of Craters is often used as an analog. Oppositely, remote sensing observations of pit craters, especially on Mars, have proven useful in understanding the formation of pit craters on Earth (Wyrick et al. 2004).

References:

[1] USGS *Chain of Craters*. https://www.usgs.gov/news/volcano-watch-chain-craters-kilauea. Accessed 02/20/2022. [2] USGS *Pu`u`ō`ō Eruption Lasted 35 Years*. https://www.usgs.gov/volcanoes/kilauea/puuoo-eruption-lasted-35-years. Accessed 02/20/2022. [3] Okubo & Martel (1998) *Journal of Volcanology and Geothermal Research* 86, Pg 1-18. [4] Clague & Hazlett (1989) *Field Trip Guidebook T188/304.* [5] Wilson & Parfitt (1993) *Lunar and Planetary Science Conference Abstracts, Vol. 24.* Pg 1525-1526. [6] NPS *Eruption of Maunaulu*. https://www.nps.gov/havo/learn/nature/mauna-ulu-eruption.htm. Accessed 02/21/2022. [7] USGS *1969-1974 Maunaulu Eruption* https://www.usgs.gov/volcanoes/kilauea/1969-1974-maunaulu-eruption. Accessed 02/21/2022. [8] Farrill et al. (2011) *Lithosphere* 3 (2), Pg. 133-142. [9] Smart et al. (2011) *JGR: Planets* 114 (E4). [10] Wyrick et al. (2010) *Lunar and Planetary Science Conference Abstracts, Vol. 41.* [11] Bottke et al. (1997) *Icarus Vol. 126 (2),* Pg. 470-474. [12] Kling (2020) *Pit Craters Throughout the Solar System.* [13] Wyrick et al. (2004) *JGR: Planets Vol. 109 (E6)*. [14] Davey et al. (2013) *Canadian Journal of Earth Sciences Vol. 50.*

Magma Plumes and Chemical Zoning
Ong Iunn Jenn

Quick facts:
Magma plumes:

- Material + Energy exchange between planet's interior and crust → causing compositional heterogeneity (Chauvel *et al.* 1992; Hofmann and White 1982; Stracke *et al.* 2003; Weaver 1991)
- Proposed convection mechanisms:
    - steady-state plate tectonic dominated by upper mantle convection; results in sinking of cold plates of lithosphere
    - discontinuous/intermittent mantle overturn by plume convection carrying heat and material from the core mantle boundary (CMB) (Stein and Hofmann 1994; Storey 1995)

Observable trends (see ref. list):

- Loa vs. Kea
    - Isotopic difference (Th/U (), $^{87}Sr/^{86}Sr$; ε_{Nd}, ε_{Hf})
    - Major element difference
    - Minor element difference

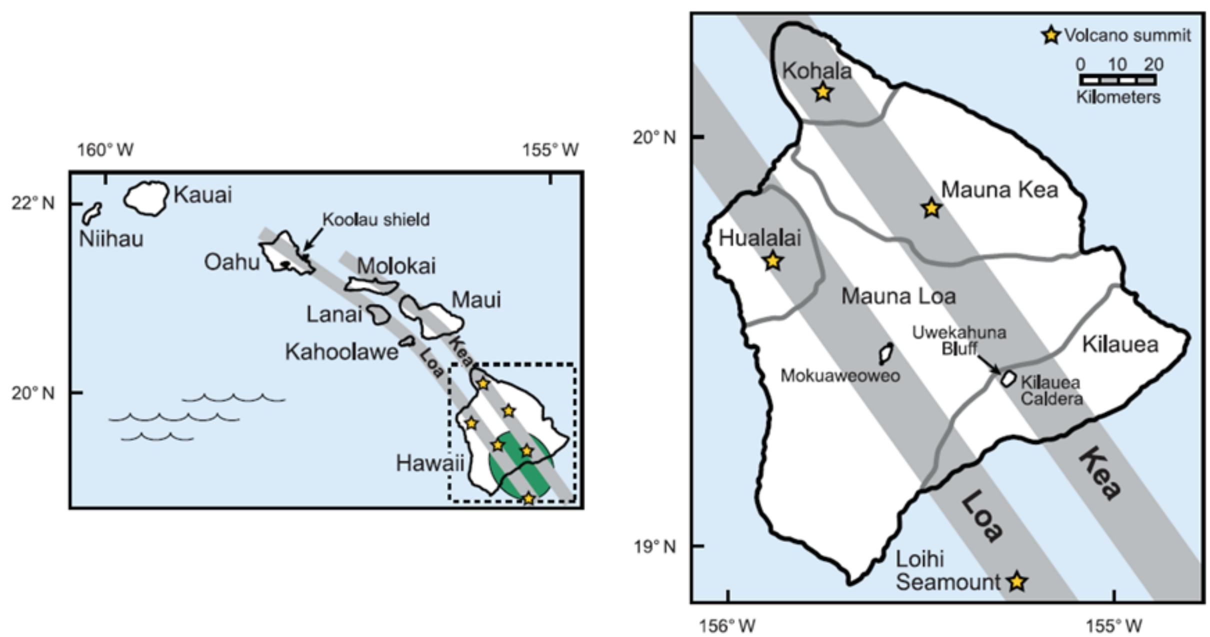


Figure 16. (Aaron *et al.* 2013) (left) map of the Hawaiian archipelago. (right) Map of the Island of Hawaii (Big Island) with the locations of the active volcanoes (Kilauea, Mauna Loa, Loihi) and extinct shields (Koolau). Members of the Loa and Kea trend are highlighted here.

The long-winded explanation:

The spatial dichotomy (a.k.a. "bilateral asymmetry" model) is based on the observations that can be seen in Fig 2. below. These are thought to have existed for the last 5 Myr.

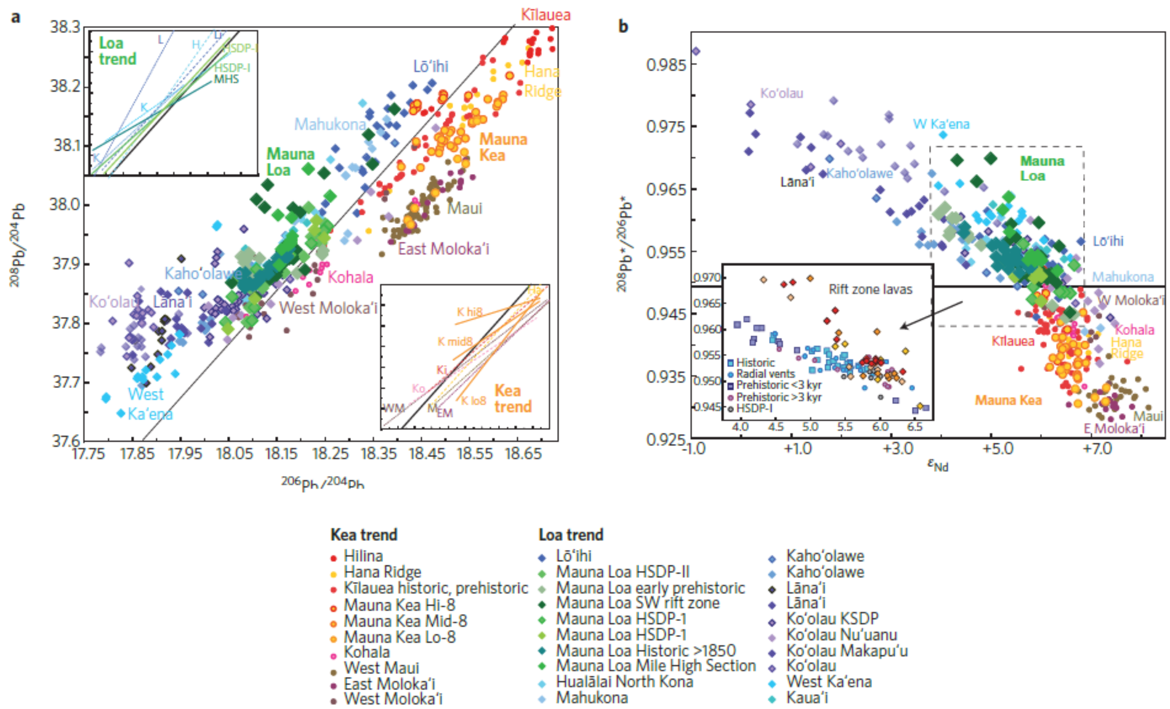


Figure 17. (Weis *et al.* 2011) Isotopic data for Hawaiian shield lavas. Volcanoes on Mauna Loa (diamonds and cool colours) and volcanoes on Mauna Kea (circles and warm colours) trends based on Pb isotopic composition. b) $^{208}Pb/^{206}Pb^*$ vs. ε_{Nd} data for Hawaiian shield lavas. Older samples (red, yellow, orange diamonds) traces a unique mixing line.

Loa – higher Th/U (evidenced from $^{208}Pb^*/^{206}Pb^*$), $^{87}Sr/^{86}Sr$; lower $^{206}Pb/^{204}Pb$, $^{143}Nd/^{144}Nd$, ε_{Nd}, ε_{Hf}

Possible explanations:

- Hawaiian plume concentrically zoned where Loa represents the centre and Kea the margins/sides (Bryce *et al.* 2005; Lassiter *et al.* 1996; Sobolev *et al.* 2005)
- Loa lies above the edge of the large low shear velocity province (LLSVP) of the Pacific while the Kea trend lies above the Pacific lower mantle (Weis *et al.* 2011)
- Two sources at the CMB (Harrison & Weis 2018; Harrison *et al.* 2017, 2020; Huang *et al.* 2011; Weis *et al.* 2011; Williamson *et al.* 2019)
- Due to thermal structure (Ren *et al.* 2005)
- Loa sampled shallow portions of the plume (pyroxenite melt zone), Kea is from the deeper peridotite melt zone in the centre

BUTTTTTTTTT…

Why the current proposed models might be wrong?

- None can explain why this geochemical anomaly only appeared 5 Mya and not before – the ever-changing drift direction of the Pacific plate do not always align with hotspot chains exhibiting this geochemical anomaly
- **Hawaiian plume concentrically zoned**: Very little compositional overlap = bilateral, non-concentric plume zones (Abouchami *et al.* 2005)

The BIGGER picture

NOT a unique phenomenon to the Hawaiian archipelago.

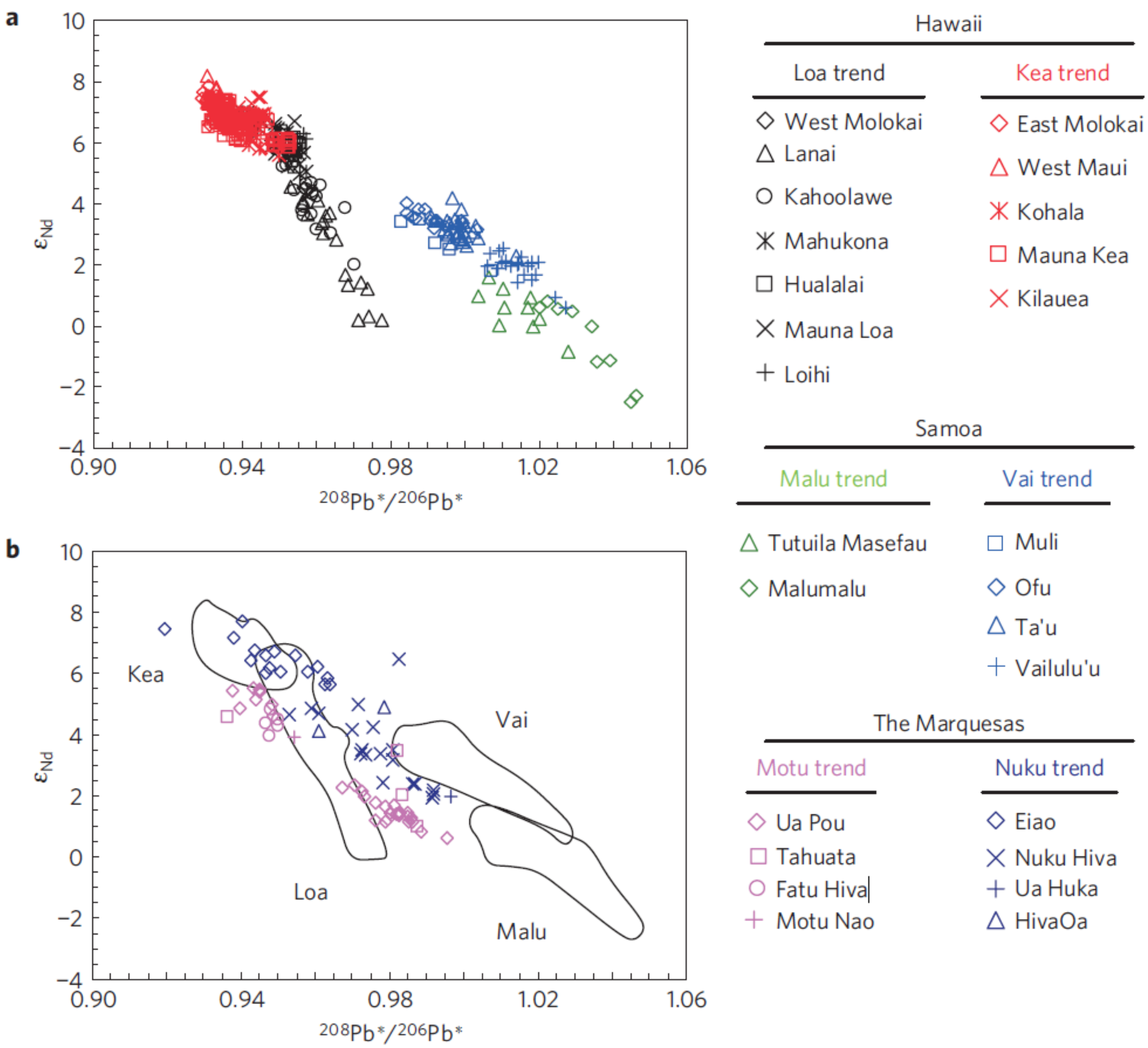


Figure 18. (Huang *et al.* 2011) Nd and Pb isotopic signals for: a, Hawaiian and Samoan lavas. b, The Marquesas lavas compared with the Hawaiian and Samoan lavas

Samoan and Marquesas (both also formed above mantle plumes upwelling in the Pacific) showed similar bilateral geochemical pattern within the regions (Fig 3).

References:

Abouchami W., Hofmann A.W., Galer S.J., *et al.* 2005. Lead isotopes reveal bilateral asymmetry and vertical continuity in the Hawaiian mantle plume. *Nature* 434: 851.

Bryce J.G., DePaolo D.J., Lassiter J.C. 2005. Geochemical structure of the Hawaiian plume: Sr, Nd, and Os isotopes in the 2.8 km HSDP-2 section of Mauna Kea volcano. *Geochem. Geophys. Geosyst.* 6.

Chauvel C., Hofmann A.W., Vidal P. 1992. HIMU-EM: the French Polynesian connection. *Earth Planet. Sci, Lett,* 110: 99-119.

Frey F.A., Huang S., Xu G., and Jochum K.P. 2016. The geochemical components that distinguish Loa- and Kea-trend Hawaiian shield lavas. *Geochimica et Cosmochimica Acta* 185: 160-181.

Harrison L.N. and Weis D. 2018. The Size and Emergence of Geochemical Heterogeneities in the Hawaiian Mantle Plume Constrained by Sr-Nd-Hf Isotopic Variation Over similar to 47 Million Years. *Geochem. Geophys. Geosyst.* 19: 2823-2842.

Harrison L.N., Weis D., Garcia M.O. 2017. The link between Hawaiian mantle plume composition, magmatic flux, and deep mantle geodynamics. *Earth Planet. Sci. Lett.* 463: 298-309.

Harrison L.N., Weis D., Garcia M.O. 2020. The multiple depleted mantle components in the Hawaiian-Emperor chain. *Chemical Geology* 532: 119324.

Hofmann A.W. and White W.M. 1982. Mantle plumes from ancient oceanic crust.

Huang S.C., Hall P.S., Jackson M.G. 2011. Geochemical zoning of volcanic chains associated with pacific hotspots. *Nat. Geosci.* 4: 874-878.

Lassiter J.C., DePaolo D.J., Tatsumoto M. 1996. Isotopic evolution of Mauna Kea volcano: Results from the initial phase of the Hawaii Scientific Drilling Project. *Journal of Geophysical Research – Solid Earth* 101: 11769-11780.

Ren Z.-Y., Ingle S., Takahashi E., *et al.* 2005. The chemical structure of the Hawaiian mantle plume. *Nature* 436: 837-840.

Sobolev A.V., Hofmann A.W., Sobolev S.V., Nikogosian I.K. 2005. An olivine-free mantle source of Hawaiian shield basalts. *Nature* 434: 590-597.

Stein M. and Hofmann A.W. 1994. Mantle plumes and episodic crustal growth. *Nature* 372: 63-68.

Storey B.C. 1995. The role of mantle plumes in continental breakup: case histories from Gondwanaland. *Nature* 377: 301-308.

Weis D., Garcia M.O., Rhodes J.M., Jellinek M., Scoates J.S. 2011. Role of the deep mantle in generating the compositional asymmetry of the Hawaiian mantle plume. *Nature Geoscience*: 831-838.

Williamson N.M.B., Weis D., Scoates J.S., *et al.* 2019. Tracking the Geochemical Transition Between the Kea-Domicated Northwest Hawaiian Ridge and the Bilateral Loa-Kea Trends of the Hawaiian Islands. *Geochem. Geophys. Geosyst.* 20: 4354-4369.

Extra notes:

LLSVPs – large low shear velocity provinces

Isotope notation:

$$\varepsilon_{\mathrm{Nd}} = \left(\frac{\left(\frac{^{143}\mathrm{Nd}}{^{144}\mathrm{Nd}}\right)_{sample}}{\left(\frac{^{143}\mathrm{Nd}}{^{144}\mathrm{Nd}}\right)_{CHUR}} - 1 \right) * 10\ 000$$

Epsilon (ε) is used for differences in the fifth decimal place. This is a common notation when dealing with radioisotopes. CHUR (Condritic Uniform Reservoir) – the mean chemical composition of chondrites (which formed from the Solar Nebula), is just a model used for this isotopic system. Each isotopic system has a commonly used standard (i.e. SMOW (Standard Mean Ocean Water for Oxygen) On a side note, delta (δ) is used for differences in the fourth decimal place (per mille).

$$\delta^{13}\mathrm{C} = \left(\frac{\left(\frac{^{13}\mathrm{C}}{^{12}\mathrm{C}}\right)_{sample}}{\left(\frac{^{13}\mathrm{C}}{^{12}\mathrm{C}}\right)_{std}} - 1 \right) * 1\,000$$

Xiaohang Chen
Magmatic eruptions

Magmatic eruptions are commonly referred to as volcanic eruptions, which describe the process of molten rock, volcanic ash, and gas being expelled from a volcano or fissure in the Earth's crust. This can result in a variety of volcanic activity, including lava flows, explosive ash clouds, pyroclastic flows, and lahars [1]. The type of eruption depends on several factors, including the composition of the magma, the amount of gas contained in the magma, and the type of volcano [3]. Magmatic eruptions can have significant impacts on the environment, including altering the landscape, releasing gases that can affect the climate and air quality, and posing a danger to human life and infrastructure. However, volcanoes also play an important role in the formation of new land and can provide valuable resources such as geothermal energy and minerals.

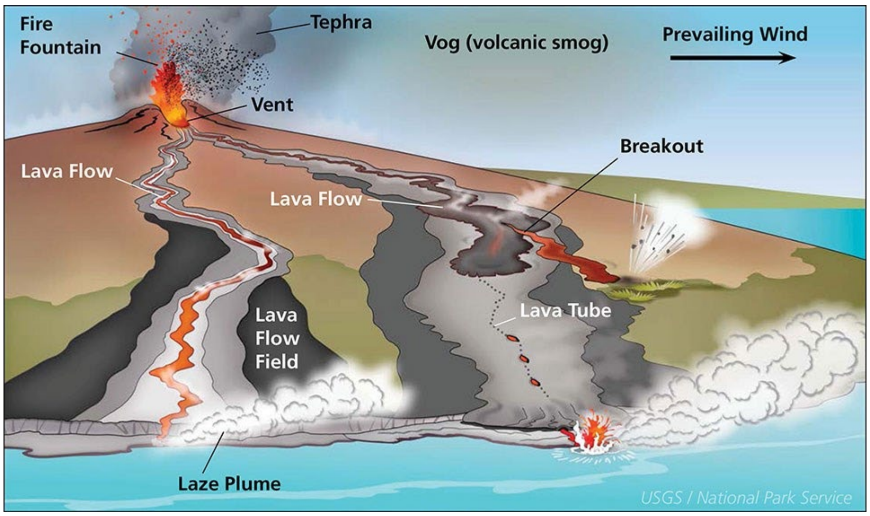


Figure 19 Diagram with feature labels. Credit: USGS illustration.

Hawaiian magmatic eruptions are a type of volcanic eruption that is characterized by the emission of very fluid lava [2]. They are typically not explosive and are relatively gentle. These eruptions are named after the Hawaiian Islands, where they are commonly observed.


Figure 20 Aerial photo captured during an overflight of the Northeast Rift Zone eruption of Mauna Loa volcano in Hawaii, U.S. November 28, 2022. Credit: USGS/Civil Air Patrol/Handout.

During a Hawaiian eruption, lava is extruded from the volcano in a steady stream or fountain. The lava flows downhill and can cover large areas of land, sometimes even reaching the ocean. Hawaiian eruptions are generally not accompanied by significant explosions or ash clouds. The lava produced during a Hawaiian eruption is typically basaltic in composition, which means it has a low viscosity and flows easily. This is due to the low silica content of the magma [4]. The low viscosity of the lava allows it to flow for long distances, creating extensive lava fields.

Hawaiian eruptions can last for weeks or months and may occur repeatedly over a period of years or decades. During an eruption, the lava flow may change direction, creating new paths and potentially threatening nearby communities. Although Hawaiian eruptions are generally considered to be less dangerous than other types of eruptions, they can still have significant impacts on the environment and nearby communities. The lava flows can destroy homes, infrastructure, and crops, and the volcanic gases emitted during an eruption can pose health risks to people and animals.

Reference

[1] National Academies of Sciences, E., and Medicine (2017), Volcanic Eruptions and Their Repose, Unrest, Precursors, and Timing, 134 pp., The National Academies Press, Washington, DC, doi:10.17226/24650.

[2] Powers, H. A. (1955), Composition and origin of basaltic magma of the Hawaiian Islands, GeCoA, 7(1), 77-107, doi:10.1016/0016-7037(55)90047-8.

[3] Huppert, H. E., and A. W. Woods (2002), The role of volatiles in magma chamber dynamics, Nature, 420(6915), 493-495, doi:10.1038/nature01211.

[4] Mangan, M. T., K. V. Cashman, and D. A. Swanson (2014), The dynamics of Hawaiian-style eruptions: A century of study, Report Rep. 18018, 323-354 pp, Reston, VA.

Namya 1

Namya 2

Namya 3

Namya 4

Kiana McFadden

Lava Cooling and Thermorheology

Lava Cooling

Active lava is defined as, “a mixture of molten rock (liquid), crystals (solids), gas (bubbles) and other voids[1]. This liquid can have temperatures ranging from about 700 to 1,300 °C [2]. As the lava cools, minerals can form. They form in a specific sequence, and this sequence is called the Bowen’s Reaction Series. The order in which the liquid can crystalize is illustrated in Figure 1.

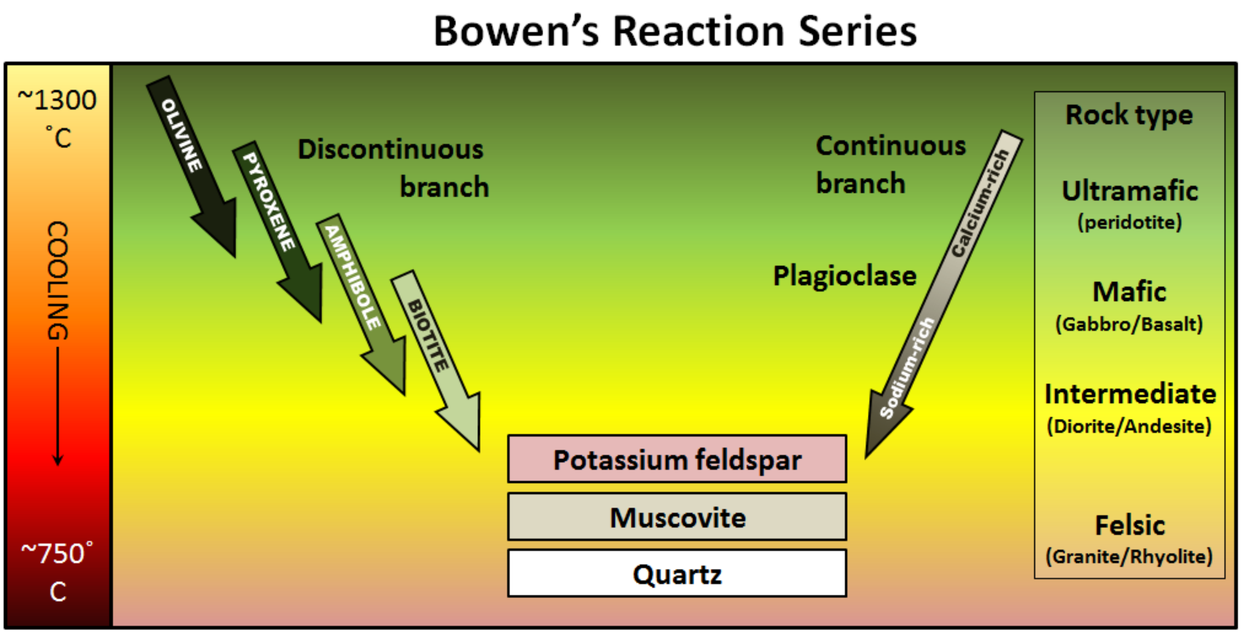


Figure 1: *This provides an illustration in the order in which molten lava can cool into different minerals. Picture credit: https://opentextbc.ca/geology/chapter/3-3-crystallization-of-magma/*

According to [3], the magma will react within the following ways:

- The first mineral to crystalize is olivine (silicate mineral) followed by pyroxene, amphibole, and biotite.
- Silica must remain in the magma and slow cooling must occur for the magma to crystalize in this series listed in Figure 1.
- When pyroxene starts to crystalize, plagioclase starts to crystallize. The plagioclase becomes more sodium rich as the temperature drops if there is sodium remaining in the magma.

As shown on the right-hand side of Figure 1, igneous rocks can be classified as ultramafic, mafic, intermediate, and felsic. Examples of these type of rocks can be found in Figure 2.

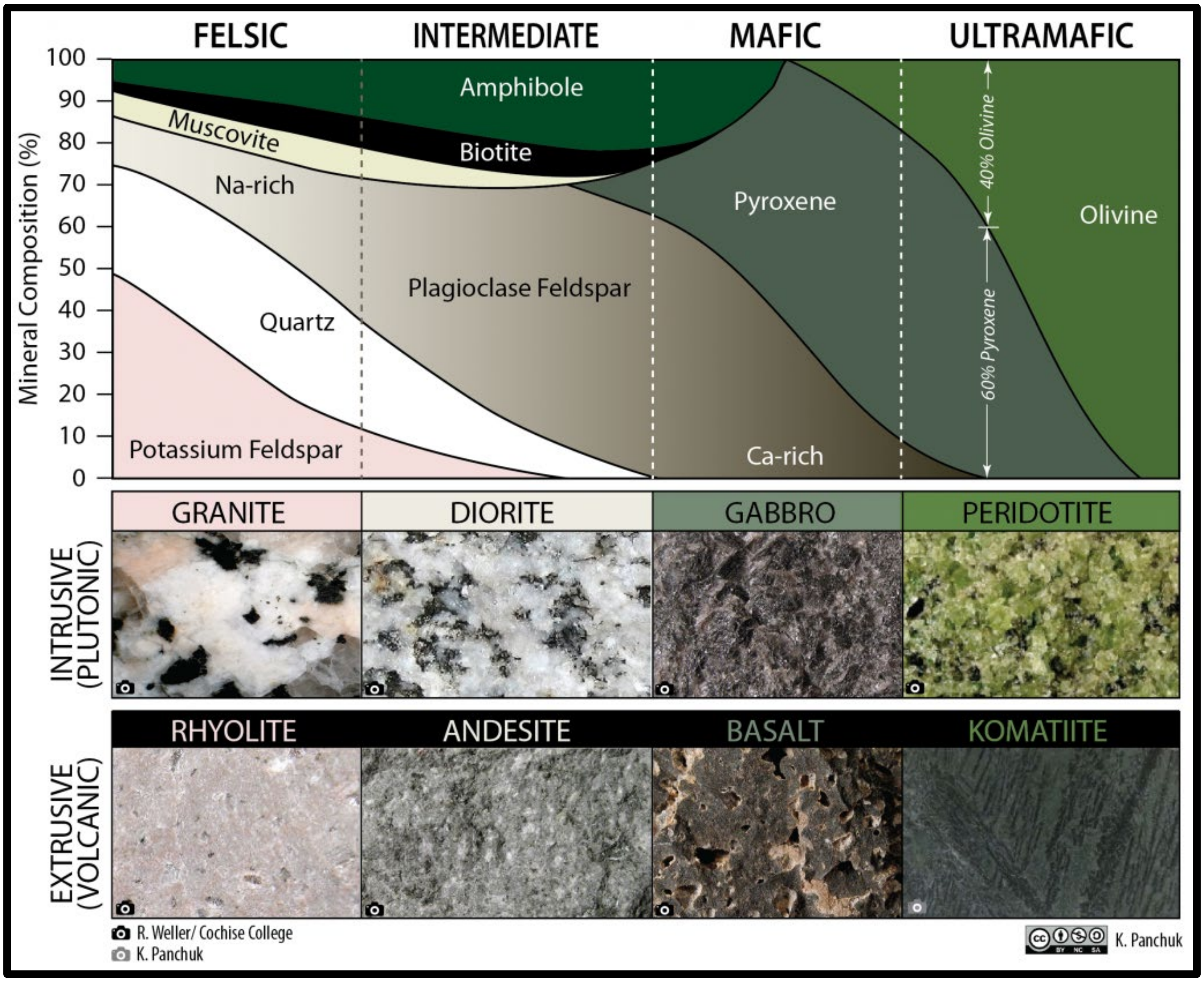


Figure 2. *This graphic presents examples of textures of the felsic, intermediate, mafic, and ultramafic rock types. Picture Credit: https://openpress.usask.ca/physicalgeology/chapter/7-3-classification-of-igneous-rocks-2/*

As stated by [4], each type of rock is classified by their mineral abundances and grain sizes. They can also be classified as an intrusive or extrusive igneous rock. Intrusive (cools within the Earth) and extrusive rock (cools on the surface of the Earth) have different grain sizes due to their rates of cooling [4].

Slow cooling = **BIGGER** crystal sizes

Fast cooling = **SMALLER** crystal sizes

According to [5], lava cooling rates can be influenced by the thickness of the flow and heat loss from the exterior of the flow (top and bottom of flow).

Figure 3: *This image depicts an ʻaʻā flow on the lower East Rift Zone of Kīlauea Volcano. This photo was taken on Jun 1, 2018 and highlights how the surface of the flow has solidified into crust, but the interior remains liquid and hot. Picture credit: https://www.usgs.gov/observatories/hvo/news/volcano-watch-how-do-lava-flows-cool-and-how-long-does-it-take.*

Thermorheology

According to [6] "rheology is the branch of physics in which we study the way in which materials deform or flow in response to applied forces or stresses." Lava rheology can be influenced by the volume fraction, shape, and distribution of bubbles and crystals within the lava. This volume fraction of crystals and bubbles can also vary by the thermal history and length of the lava flow [7]. According to [7], the rheology of lava flows allows us to make velocity estimates, but these estimates can be difficult to make if incorrect assumptions are made about the rheology. There is current technology such as PyFLOWGO which can "track downflow cooling and rheological responses for open-channel, cooling-limited flow" which is a necessary process to access the potential hazards stemming from the lava flow [8].

Puʻu ʻŌʻō Eruption

The eruption of Kīlauea Volcano began in 1983 and concluded in 2018. Eruptions began to focus at one vent (Puʻu ʻŌʻō) mid -June 1983 [9]. When the eruptions first began, ʻaʻā flows were produced. As the flows became less viscous, pahoehoe flows were produced [9].

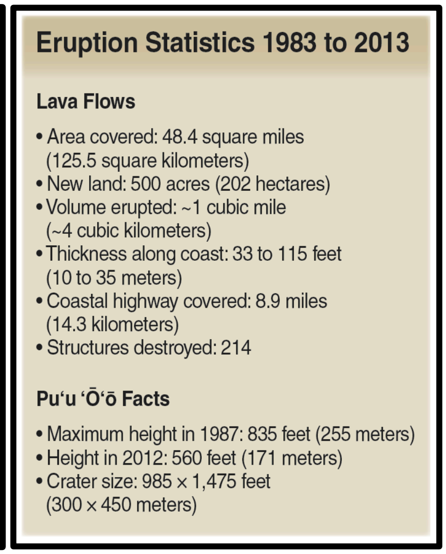


Figure 4: *The left image in this graphic show an eruption from the Puʻu ʻŌʻō cone. The right image provides some eruption statistics from 1983 and 2013. Picture credit for both images:*

References:

[1] Harris A. J. L. and Rowland S.K. (2015) *The Encyclopedia of Volcanoes, pg. 322.* [2] Rafferty, J. P, *Encyclopedia Britannica, https://www.britannica.com/science/lava-volcanic-ejecta*. Accessed 17 February 2023.[3] Earle, S., *Physical Geology, https://opentextbc.ca/geology/chapter/3-3-crystallization-of-magma/.* Accessed 17 February 2023.[4] Earle, S., *Physical Geology, First University of Saskatchewan Edition, https://openpress.usask.ca/physicalgeology/chapter/7-3-classification-of-igneous-rocks-2/.* Accessed 17 February 2023. [5] Hawaiian Volcano Observatory, *USGS https://www.usgs.gov/observatories/hvo/news/volcano-watch-how-do-lava-flows-cool-and-how-long-does-it-take.* Accessed 17 February 2023. [6] Figura, L. O. and Teixeira, A. A. (2007) *Food Physics: Physical Properties-Measurement and Applications, pg. 117.* [7] Lev, E. and James, M. R. (2014*) Bulletin of Volcanology, Vol. 76, pg. 829.* [8] Thompson, J. O. and Ramsey, M.S. (2021) Bulletin of Volcanology, Vol., 83, pg. 40. [9] USGS, https://pubs.usgs.gov/fs/2012/3127/fs2012-3127.pdf. Accessed 22 February 2023.

Allison McGraw

METEORITES, MANTLES, and MORBs- Oh my!

Ordinary Chondrites (OC) (**Fig. 1**) are the most common type of meteorite to arrive to Earth (86%) **[1]**. The OCs are dominated by silicate minerals, which contain varying amounts of iron (Fe) **[2]**. Despite silicate meteorites dominating our terrestrial collection, silicate asteroids do not dominate the Solar System (~17% of Main Asteroid Belt population).

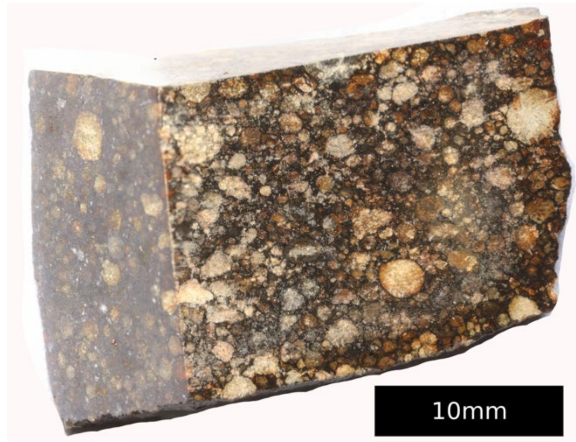


***Figure 21**: This is an example of an ordinary chondrite type of meteorite, L/LL chondrite North West Africa 487. Figure courtesy of U.Arizona Space Materials Collection.*

Nonetheless, Earth's mantle is dominated by silicate minerals (~70% volume of Earth). Hot spot volcanism delivers some of the most ultramafic and deepest mantle materials to the Earth's surface.

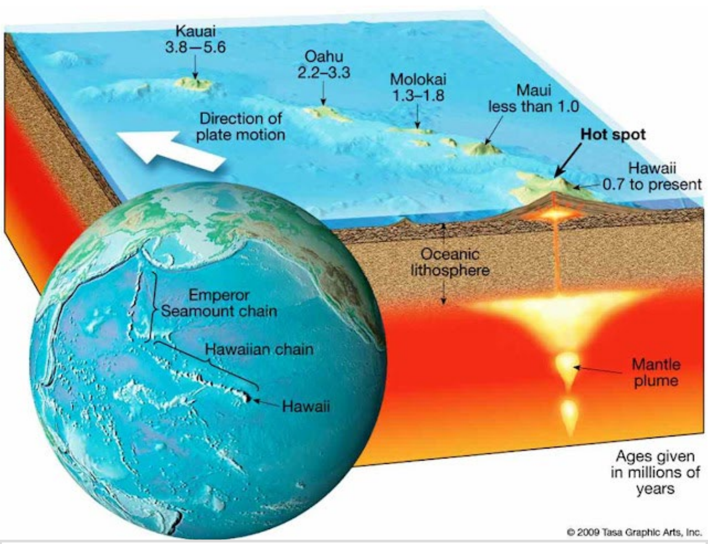


***Figure 2:** The hotspot volcanism of the Hawaiian Island chain. Image from GFZ GeoForschungsZentrum Potsdam, Helmholtz Centre.*

The Hawaiian Seamount chain describes ~6 Ma of tectonic history tracking **[3]** and also gives us an understanding of Earth's mantle (**Fig. 2**).

OCs are dominated by olivine, the mantle is dominated by olivine, and upper mantle volcanism from Mid-Ocean Ridge Basalts (MORBs) **[4]** is thus dominated by olivine silicates within the basalt (**Fig. 3**).

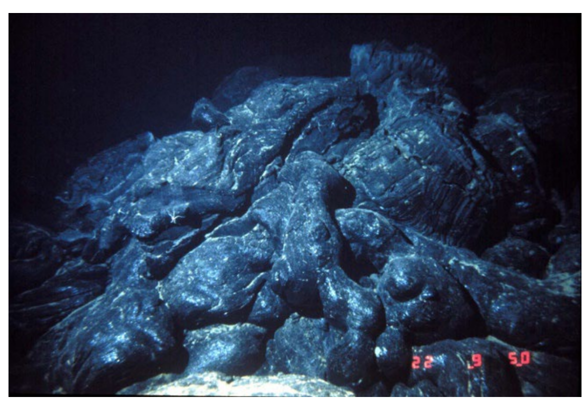


***Figure 3:** Pillow lava produced by submarine eruption located at a mid-ocean ridge. Slow oozey fissure flow located off the southern tip of the Juan de Fuca Ridge. Figure courtesy of Submarine Ring of Fire 2002,*

By comparing chondritic values of meteorites, mantles, and MORBs for basaltic chemistry we gain an understanding of bulk geochemistry for planetary materials **[5]**. However, only a certain selection of the true samples of the Solar System have arrived by dynamical delivery to the inner Solar System, including Earth **[6]**.

Terrestrial meteorites are an ancient window into our Solar System formation and history:

- Chondrules (~4.5647 Ga) **[7]** and Calcium Aluminum Inclusions (CAIs) (~ 4.5682 Ga) **[7, 8, 9]** are amongst the first solids to condense out of the solar nebula **[10]**
- Early solids capture pre-solar conditions as chondrules cooled near-liquidus temps., as splashing droplets during this timeframe **[11]** in a sea of sulfides and Fe-Ni
- Chondrules comprise of ~50% by volume of the OCs **[2, 10]**, hence, understanding their material properties aids in understanding the earliest Solar System formation

OC meteorites are the most common to arrive to Earth and comprise of 3 subtypes depending on Fe content in ultramafic silicate minerals olivine and pyroxene **[2]**.

OCs preserve chondritic values which are compared to measured values within terrestrial materials **[5]** that erupt onto the surface today via hot spot volcanism, sea-floor spreading (MORBs) and rifting volcanism (**Fig. 4**).

Iron meteorites are metal alloys of Fe-Ni and represent the extinct cores of planetesimals (**Fig. 5**).

Ni forces Fe isotopes to fractionate between metal silicate material. This results in an enrichment of isotopically light Fe in a mantle **[5]**.

At higher temperatures the effect on Ni diminishes, and it is possible that Earth maintained heavy Fe isotopes during massive mantle meltdowns. Mars, Vesta and primitive lunar basalts may have had isotopically light mantle melting (**Fig. 4**) **[5]**.

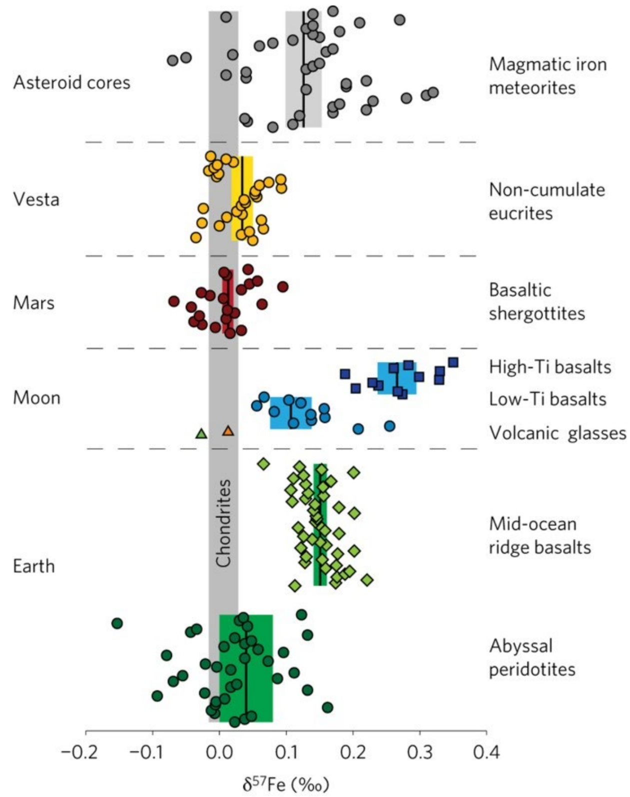


Figure 4: *MC-ICP-MS measurements of delta-^{57}Fe of chondritic meteorites and planetary sample groupings. The grey and colored bars show the error-weighted means and 95% confidence intervals. Figure from Elardo & Shahar (2017).*

Figure 5: *Iron meteorite image from U.Arizona Space Materials Collection.*

Figure 6: San Carlos olivine ~centimeter-sized crystals (left) collected by McGraw from Peridot, Arizona (right).

Figure 7: Seymchan Pallasite. Figure courtesy of ASU/CMS.

Mantles are the geologic engines of planets; 70% by volume and most abundant element is O:

- Dominated by olivine, very rarely do ultramafic mantle materials make it onto continental crust (**Fig. 6**), but oceanic plates are mainly basalt
- Pallasites represent boundary layers between ancient cores and mantles (**Fig. 7**)
- *Under the influence of Aluminum-26:* distribution of heating elements (^{26}Al) provided uniform heating of the oldest minerals within CAIs **[12],** the small inclusions are isotopic chronometers for ^{26}Al-^{26}Mg and ^{207}Pb-^{206}Pb systematic age modeling **[9],** also inducing planetary differentiation (**Fig. 8**)
- *What are the ages of a mantle?* For Earth- 4.5 Ga. For plume- 30-200 Ma **[13]**

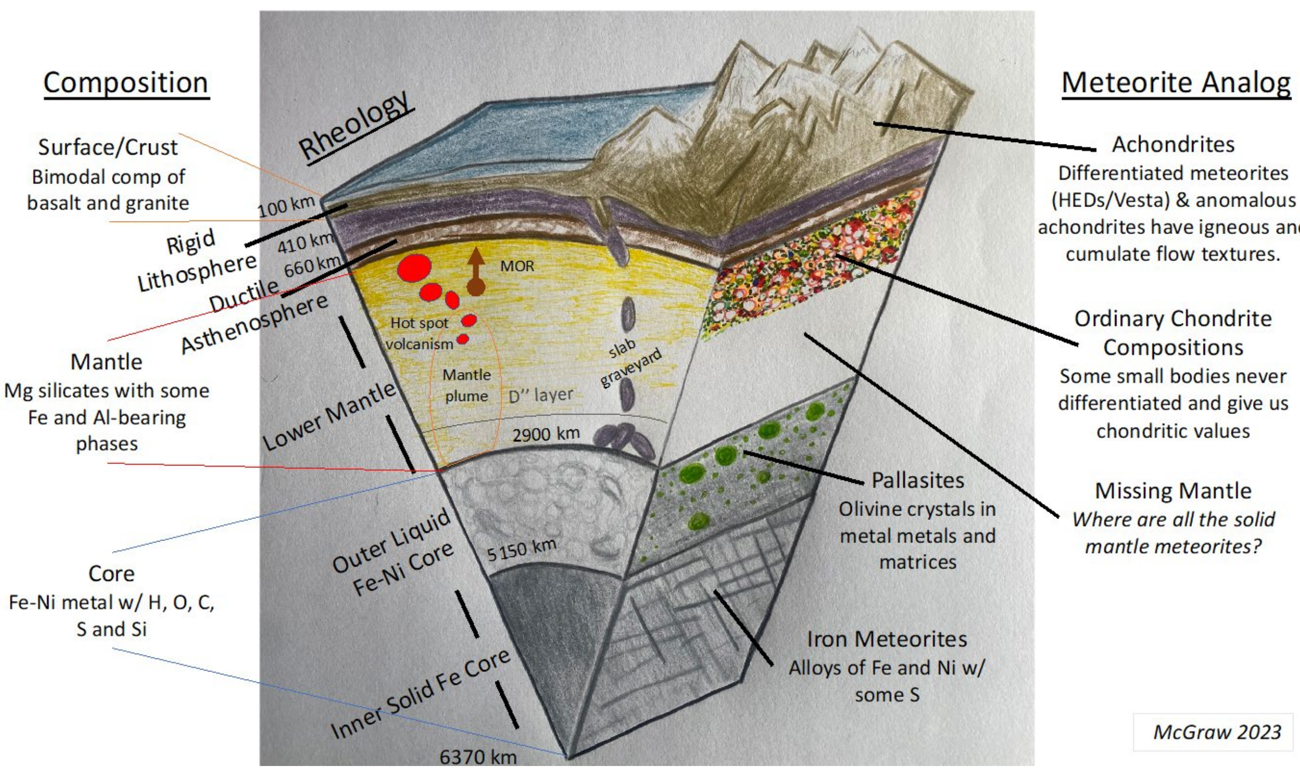


Figure 8: Schematic of Earth differential layers with compared meteorite analogs. Figure hand drawn by McGraw.

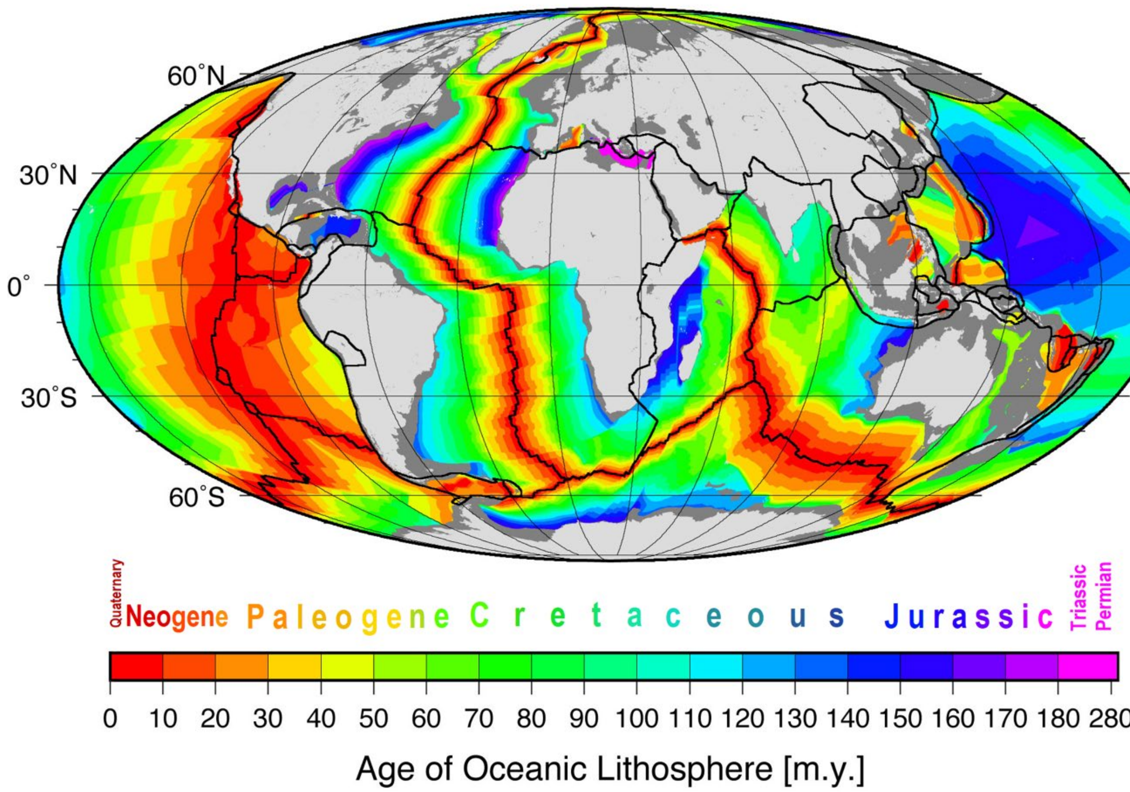


Figure 9: *The age of oceanic lithosphere, youngest is red. Image from Muller et al. (2008).*

MORBs create a window into Earth's upper mantle where we can get a sense of the mineralogy and geochemistry that Earth contains **[14]**:

- MORB is an erupted basalt that is a response due to sea-floor spreading (**Fig. 9**)
- Earth has an extensive mid-ocean ridge system, some ~65,000 km **[14]**
- Sea-floor spreading occurs where the basalt is released from various depths below oceanic plates, at divergent plate boundaries **[15]**
- MORBs are the most voluminous volcanic rocks on rock and they make up the topmost 1-2 km of oceanic crust, covering 2/3 of Earth's surface beneath the ocean
- Eruption rates are calculated at a global rate of over 500 m^3/second **[15]**
- Eruptions are through fissure eruptions which form sheeted dykes, pillow lavas, sheet-flows and lava tubes (**Fig. 3**) **[3, 15]**
- Destruction of sea floor at subduction zones results in the oldest MORB being no more than 200 Ma **[14]**

Achondrites are meteorites that lack chondrules **[16]** and have undergone geological changes due to due thermal metamorphism (MM'M). Achondrites maintain ancient igneous cumulate textures (**Fig. 10**) **[17]**, and may be representative of igneous surface flows on ancient asteroid surfaces (**Fig. 11**). Thermal MM'M took place on planetecimal surfaces as evidenced by achondrites **[17]**.

Thermally processed eucrite meteorites also reveal ancient surface flows on asteroid (4) Vesta **[18]**.

In summary, this topic:

- Relates the ancient asteroid outcrop pieces (meteorites) to how we understand the geologic evolution of the early Solar System and what bulk materials Earth acquired
- Explains how OC meteorites provide chondritic values where we can compare bulk planetary materials to gain a sense of planetary differentiation and how the formation of mantles may have occurred (or not occurred on some bodies)
- Discusses how hot spot volcanism and MORBs help describe the way in which Earth processes original OC material, and what occurs within the mantle at various depths
- Reveals how iron meteorites provide an insight to planetary cores and how pallasites may be a close touch to the extinct cores and silicate mantle boundary layers
- Examines how achondrite meteorites may be a link towards ancient asteroid surface and crustal flow activity

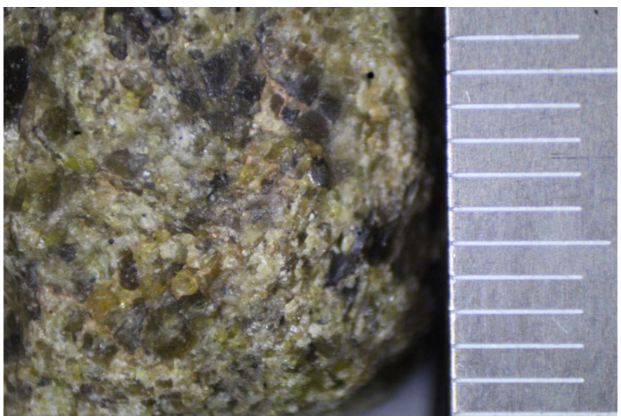


Figure 10: Anomalous achondrite meteorite NWA 6704 showing igneous cumulate textures, pyroxene crystals are submillimeter. Figure courtesy of U.Arizona Space Materials Collection.

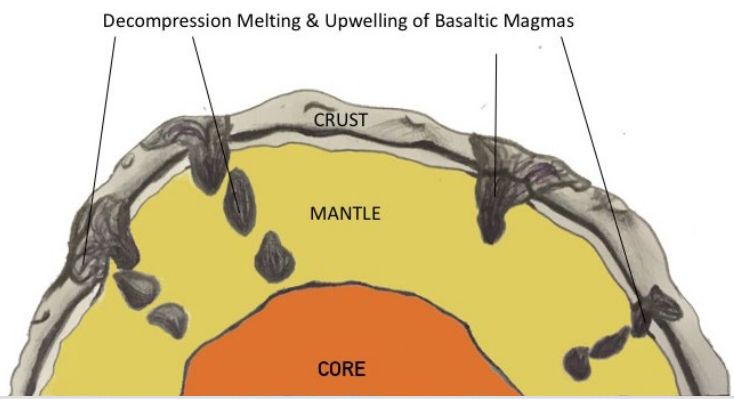


Figure 11: Example of an achondrite parent body that may have gone through planetary differentiation processes early in the Solar System history producing some of the igneous materials observed in anomalous achondrites. Figure by McGraw.

References

[1] The Meteoritical Bulletin, accessed Feb. 2023 **[2]** Weisberg et al. (2006). Meteorites and the early solar system II, 19, 19-52. **[3]** https://www.geologyin.com/2018/02/new-clue-for-fast-motion-of-hawaiian.html, Feb. 2023 **[4]** NOAA image gallery, Feb. 2023 **[5]** Elardo & Shahar (2017). Nature Geoscience, 10(4), 317-321. **[6]** Binzel et al. (2019) Icarus, 324, 41-76. **[7]** Amelin et al. (2002) Science, 297(5587), 1678-1683. **[8]** Amelin, et al. (2010). Earth and Planetary Science Letters, 300(3-4), 343-350. **[9]** Bouvier & Wadhwa (2010) Nature geo., 3(9), 637-641. **[10]** Lodders (2003) The Astrophysical Journal, 591(2), 1220. **[11]** Asphaug et al. (2011) Earth and Planetary Science Let., 308(3-4), 369-379. **[12]** Villeneuve et al. (2009) Science, 325(5943), 985-988. **[13]** Condie, in Earth-Evolving Planetary Sys. (3rd Edition), 2016 **[14]** Muller et al. (2008) Geochem. Geophys. Geosyst**.,** 9, Q04006 [**15]** le Roex (1998), Geochem. Encyclopedia of Earth Science. **[16]** Zinner, E. (2014) Meteorites, Comets and Planets, 17. **[17]** McGraw et al. (2020) The Astronomical Journal, 159(3), 107. **[18]** Hardersen et al. (2014). Icarus, 242, 269-282.

Mackenzie Mills

Morphology of Lava Flows

Lava flow morphologies depend on the interplay between processes that help the flow to advance and processes that hinder the flow [1]. The final form depends on:

- physical properties of the lava (i.e. viscosity)
- lava temperature
- the rate of lava extrusion
- the rate of crustal solidification
- external factors such as local gravity and topography.

Effusion rate has been suggested as the most important factor in controlling flow length and morphology [7] [8] [9]. Analyses of Hawaiian flows shows more of a dependence on eruption volume than rate [10]. This may be affected by the studied flows, most being lava tubes or channels. A clear distinction in flow morphology has been proposed between **volume-limited** (the studied Hawaiian flows [10]) and **cooling-limited** (large flows, i.e. from Mt. Etna [8] [9]). Volume-limited flows do not have enough volume to achieve their full length before they cool.

Generally, lava does not always behave as an ideal Newtonian fluid, but instead can behave as a Bingham fluid [1] [2] [7]. The interplay between two example parameters (viscosity and shear strain rate) is shown in Figure 1, along with how the parameters impact the resulting lava morphology type. **There is no single model that can predict the resulting flows of an eruption [1] [7].**

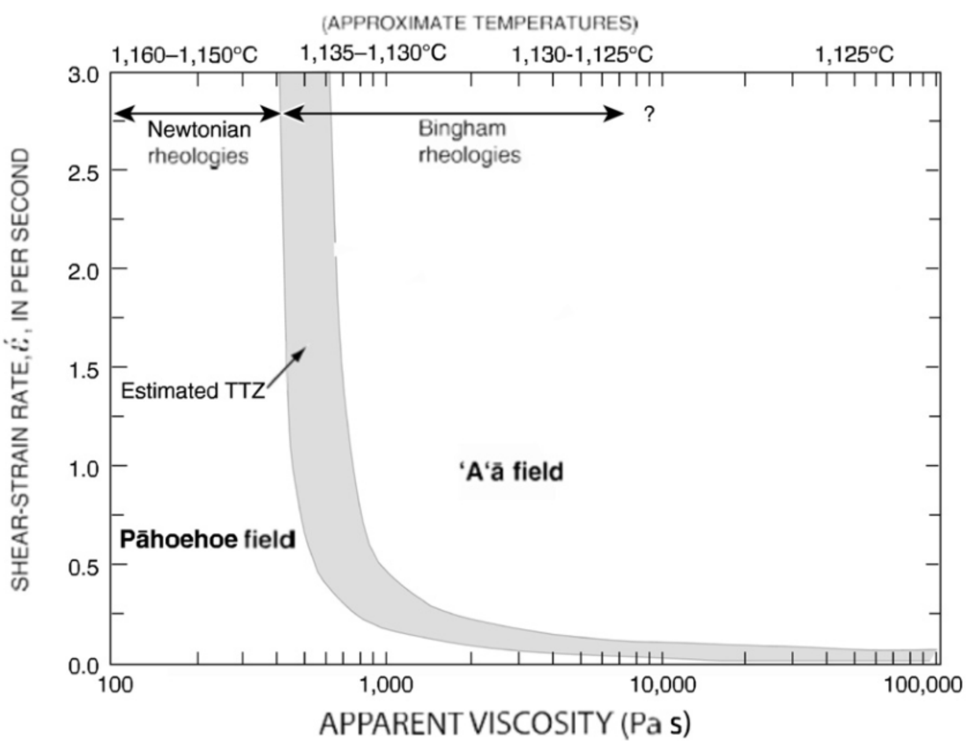


Figure 22: Effects of viscosity and shear-strain rate on lava type/morphology. Figure courtesy from [1].

First, two primary lava appearances generally occur in Hawaii: Pahoehoe and Aa. Pahoehoe has a smooth, sometimes folded, continuous surface with few breaks [1] [3]. It forms into lobes. This morphology is made as a molten core of magma flows, developing surface skins where it is cooling. Pahoehoe forms usually through many lobes advancing separately out of the main flow. There are multiple descriptors for different types of Pahoehoe: “toothpaste” lava, “slabby”, “shelly”, “spiny”, “ropey”, etc [1] [3]. Different types of Pahoehoe form because of initial flow viscosity, shear rate, and the growth rate of the crust. Figure 2, from [1], shows a Pahoehoe breakout (being sampled in the foreground) from the margin of an active Aa flow (in the background). The shiny, also silvery color of the lava lobes can be seen. Also visible are the lobate structures, and “ropey” structures (right at the scientist’s feet).

Figure 23: Pahoehoe breakout (being sampled in the foreground) from the margin of an active a'a flow (in the background). Image courtesy of the USGS.

Figure 24: Margin of an advancing Aa lava flow erupted from Kilauea volcano, Hawaii, advancing over an older pahoehoe flow. Image width ~ 3 m in the foreground. Image courtesy of USGS.

Alternatively, Aa has a very rubbly surface, with chunks of very vesicular lava crust [1]. These chunks are called clinkers. Aa advances through one primary lobe instead of multiple like Pahoehoe. As the flow advances, clinkers fall off the top and in front of the flow. These get incorporated into the lobe edges, forming layers of rubble-like rock chunks above and below the flow lobe, much like the tread on heavy machinery. In Figure 2, from [1], the rubbly-looking flow behind the pahoehoe breakout point is an Aa flow. Figure 3, also from [1], shows a close-up image of an Aa flow.

Another process that affects final lava flow morphology is lava inflation [1] [3]. This is when more magma is pumped into an existing flow system. 1) A flow spreads, the surfaces of the lobes undergo cooling and thicken over time. 2) More magma flows into the system, “inflating it” and pushing the existing lava crust outwards. Figure 4 shows the fractures and bulge that occurred from a flow inflating. This has been applied to many lava flows, including the Columbia River Flood basalts, and proposed for flood basalts on Mars [4].

Off the islands of Hawaii, lava morphologies don’t follow these two primary types as well. Morphology depends strongly on lava type, and parameters such as viscosity [1],[2]. More evolved lavas with higher silica contents have a higher viscosity and often a higher volatile content, and these factors affects the morphologies the flows present. More viscous lavas have more explosive eruptions with large ash clouds, pyroclastics, and growing bulbous lava domes [2] [5] instead of instead of long-running lava flows.

Another example is "pillow" lava, which forms primarily at mid-ocean ridges. This type of lava morphology happens when molten lava suddenly contacts liquid water [6]. The flash solidification develops into pillow-like lumps, shown in Figure 5.

Flood basalts have been proposed on Mars based on morphologies of lava flows observed in surface images [4]. Images revealed 'platy–ridged' flood lava flows, named after the large rafted plates and ridges formed by compression of the flow top (Figure 6). Similar flows have been found in the Columbia River Basalts on Earth. [4] proposes such flows "form with a thick, insulating, but mobile crust, which is disrupted when surges in the erupted flux are too large to maintain the normal pahoehoe mode of emplacement."

Figure 25: A pressure ridge atop a lava flow, where inflating lava has pushed the solidified surface upward. Image courtesy of the "Pressure ridge (lava)" Wikipedia page.

Figure 26: Pillow lavas on the seafloor. Image courtesy of the "Lava" Wikipedia page.

References:

[1] Gregg, T. K. P. (2017) *Journal of Volcanology and Geothermal Research, 342*, 3-12 (review paper).

[2] Griffiths, R. W. (2000) *Annual Review of Fluid Mechanics, 32*, 477-518.

[3] Hon, K. et al. (1994) *Geological Society of America Bulletin, 106*, 351-370.

[4] Keszthelyi, L. (2006) *Journal of the Geological Society, London, 163*, 253-264.

[5] Anderson S. W. and Fink, J. H. *Part of the IAVCEI Proceedings in Volcanology book series, Volcanology, 2*.

[6] Kennish, M. J. and Lutz, R. A. (1998) *Earth-Science Reviews, 43*, 63-90.

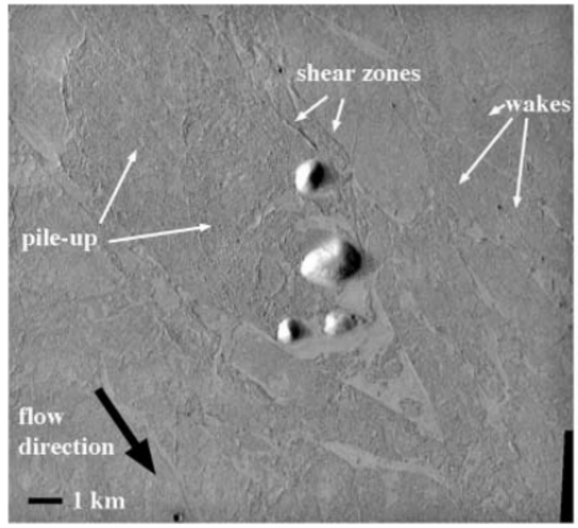
[7] Pinkerton, H. (1987) *Endeavour, New Series, 11*, 2.

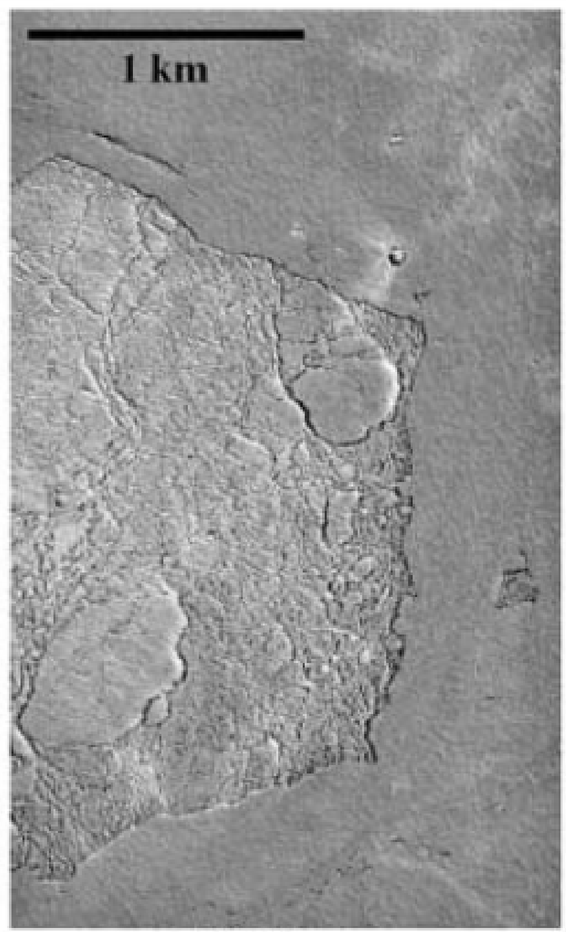
[8] Walker, G. P. L., Phil. Trans. R. Sot. London, 274A, 107, 1973.

[9] Wadge, G., Geology, 6, 503, 1978.

[10] Malin, M. C., Geology, 8, 306, 1980.

Figure 27: (top) Lava shows shear structures, wakes, and pile-up of debris due to topography. The flow direction and some properties of the translating upper crust can be determined from this observation. Image resolution is 18 m per pixel; north is to the top. (bottom) Shown is a rough ridged section of "plates" in an otherwise "smooth" lava flow. Image resolution is 100 m per pixel; north is to the top.





Name: Fuda Nguyen

A History of Hawai'ian Ethnography Through Time.

Figure 28. Traditional Polynesian Canoe.

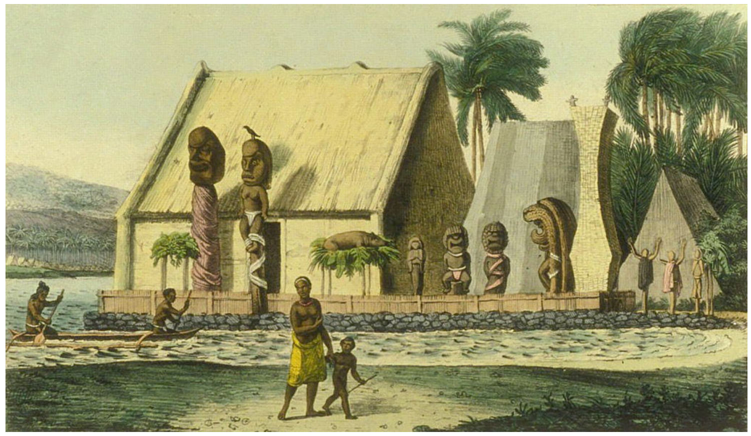


Figure 29. A depiction of a royal heiau (Hawai'ian temple) at Kealakekua Bay, c. 1816, Jean-Pierre Norblin de La Gourdaine.

I. A thousand years of Polynesian Voyage and settlement: The Native Hawaiian

Hawai'i has histories spanning over a thousand year as part of the Polynesian geographic area (*poly* 'many'; *nēsoi* 'islands') and the Polynesian ethnographic group. Human settlement in Hawai'i represents the best feats of ocean navigation in the world: through archaeological evidence, it is believed that the first Polynesian voyagers arrived in Hawai'i about 1200 to 1700 years ago. Through expert wayfinding, such as the usage of the night-sky and constellations to make sense of direction on the vast Pacific Ocean, to their unique wooden canoes design, Polynesian sailors voyaged all the way from South East Asia and settled on the distant Hawai'ian island chain. **[1]**

By the 14th century, the Hawai'i islands chain has developed into several kingdoms governed by chiefs with complex cultural customs, languages and religions that are distinctively Hawaiian. Like many Polynesian societies, ancient Hawai'i developed complex social hierarchies with ranked lineages and powerful chiefs. The four biggest islands, the island of Hawai'i, Maui, Kaua'i and O'ahu were ruled by their own chiefs. Children were born into large and warm families. Education in ancient Hawai'i consisted of training in special crafts and skills, such as canoe making or tattooing. The priests were educated in society's traditions, mythology, and genealogies. Their societies were highly-stratified.

When the Polynesians first migrated to the Hawai'ian Islands, almost no edible plants were available. They brought many different plants such as taro, bananas and sweet potatoes. The most important food eaten was taro, which was used to make poi; which was a big part of their everyday diet. They also brought pigs, chickens, and dogs and bred them on the islands. Still, the sea provided most of the protein in the traditional Polynesian diet. Fishing was done by individuals, with spear, line, or net, and also by groups. In the latter case, large numbers of men sometimes spread and hauled in huge nets in bays or lagoons and at other times drove fish toward shore, where they could be captured in nets held in shallow water.

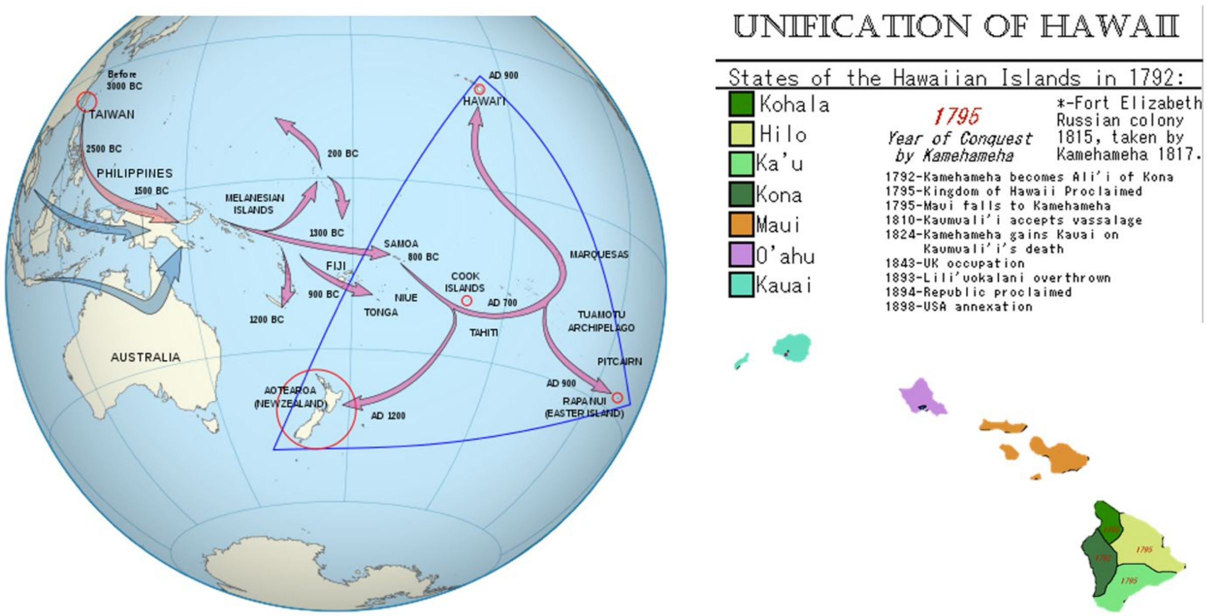


Figure 30. Left: Settlement and voyaging archeological pattern of the Polynesians to Hawai'i. Right: The timeline of the unification of various island chiefdoms into the Hawai'ian kingdom by King Kamehameha the Great.

In Hawai'ian mythology, the great gods Kane, Lono, Ku and Kanaloa existed before the creation of the world. Kane created light to push against darkness, and with light Lono and Ku follows. Lono, or Lono-makua (Lono the Provider) - was linked with rainfall and agriculture. Ku, or Kukaʻilimoku (the Snatcher of Land) god of politics and war. Kanaloa is the god residing over the ocean, complimentary to and is a divine duality of Kane. (William Hamblin and Daniel Peterson). These gods create all the lesser gods in Hawai'ian mythologies, most prominently the fire and volcano goddess Pele.

Understanding the deity in Hawai'ian culture helps explain their relationship with the land. Natural forces and geological activities represent manifestation of their gods. People don't 'own' their land, they merely dwell on it. In the Native Hawai'ian culture, the dormant volcano Mauna Kea is one of the most sacred and prominent summits in Hawaiʻi. The name Mauna Kea comes from Mauna O Wakea (which means mountain of Wakea, the "Sky Father"), as commonly referred to by Native Hawai'ian **[2].**

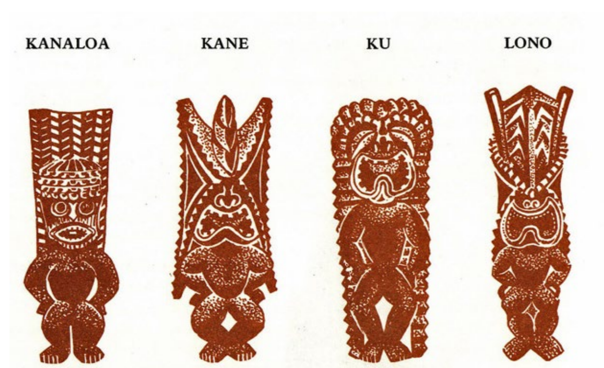


Figure 31. Illustration of the four most important Hawai'ian deities: Kanaloa, Kane, Ku and Lono.

The separate chiefdoms on each of the major Hawai'ian islands were eventually united by King Kamehameha, with canon supplied by the Americans. He waged a military campaign lasting 15 years to unite the islands, and established the Hawai'ian Kingdom in 1795 with advising from Westerners. The unification ended the ancient Hawai'ian society, transforming it into an independent constitutional monarchy **[3]**.

European contact in Hawai'i bought many disruptive changes to the Hawai'ian society. **The most fatal demise to the Native population is diseases**. The death rate among Native Hawaiians accelerated devastatingly fast after their first contact with Western foreigners. Over the years, many other infectious diseases and illnesses such as measles, chicken pox, polio and tuberculosis killed thousands of Hawaiians. 1-in-17 Native Hawaiians had died within two years of Captain Cook's arrival. By 1800, the population had declined by 48% since Cook set foot on Hawaii. Just 40-year later, it declined 84%. **[4]**

Figure 32. – Kona-Kailua. Drawn by James Arago at the Sandwich Island. (Antiquated name). Circa 1819

The weakened native population led to greater foreign dominance. This period is marked by the increased business and trade across the Pacific and Western interference to the monarchy and local politics in Hawai'i. Foreigners increasingly concentrated power and land ownership on the island. This was when the first experiment of American imperialism took place, which ultimately led to the illegal coup of the monarchy by the sugar plantation owners, the forced signing of the "Bayonet Constitution", and the annexation of the Hawai'ian Kingdom by the United States. **[5]**

II. The Natives, The Locals, and The Haole.

Fast forward 200 years later, the faces of Hawai'i have changed dramatically. **Immigrants from Asia-Pacific are now collectively the largest population group**. Here in Hawaii, they are referred to as 'locals'.

The history of Asian immigration to Hawai'i to work on sugar plantations is a complex and important aspect of Hawaii's history. During the 19th century, Americans and Europeans saw the profit potential in the island nation's sugar cane plantations and hired contract laborers from Asia due to the lack of native labor. Imported workers from China were the first the come, followed by Japanese workers. In 1890, the Chinese and Japanese made up a third of the population, with the Chinese population being restricted onwards following the Chinese Exclusion Act of

Key Timeline in Hawai'ian Recent History
1810: King Kamehameha I unifies and establishes the Kingdom of Hawaii.
1820: The first group of American Protestant missionaries arrive in Hawaii.
1893: American businessmen illegally overthrown Queen Liliuokalani.
1898: Hawaii is annexed by the United States and becomes a territory.
1920s-1930s: Large immigration wave from Asian Pacific for sugar plantations.
1941: The attack on Pearl Harbor by the Japanese brings the US into World War II.
1960s-: Resurgence of Hawaiian sovereignty movement, reclaiming traditional cultures.
1993: The United States Congress apologize for the overthrow of Hawaiian monarchy.

Figure 33. Timeline of Hawai'ian history post-European contact.

1882. The immigrants eventually settled in Hawai'i and established their own businesses and communities. **[6]**

Figure 34. Chinese contract laborers on a sugar plantation in 19th century Hawaii

By 1900, Asian Americans were 65% of the population, while Native Hawaiians shrank to just 24%. **Asian Americans were not exempted from the racial discrimination and distrust from white Americans.** In an 1894 commission, American colonizers raised concern that the growing Asian population was "undesirable" but nevertheless necessary because of their labor. After the Pearl Harbor bombing by the Japanese, the US military imposed martial law on the island and control the daily life of people. In this period, 40% of the Hawai'ian population is Japanese Americans, which put them into the difficult position bearing the "face of the enemy" **[7]**. Swift and racist mass hysteria erupted with the help of wartime propaganda campaign. On the mainland, over 100,000 Japanese Americans were incarcerated in internment camps. Though only less than 2000 were incarcerated in Hawai'i, this mass hysteria campaign nonetheless created lasting effects on second and third-gen Japanese Americans, leading some to intentionally stop learning the Japanese language or bearing Japanese names.

Figure 35. Japanese Immigrant's Assembly Hall in Hilo, Hawaii, built in 1889, today located in Meiji Mura museum, Japan.

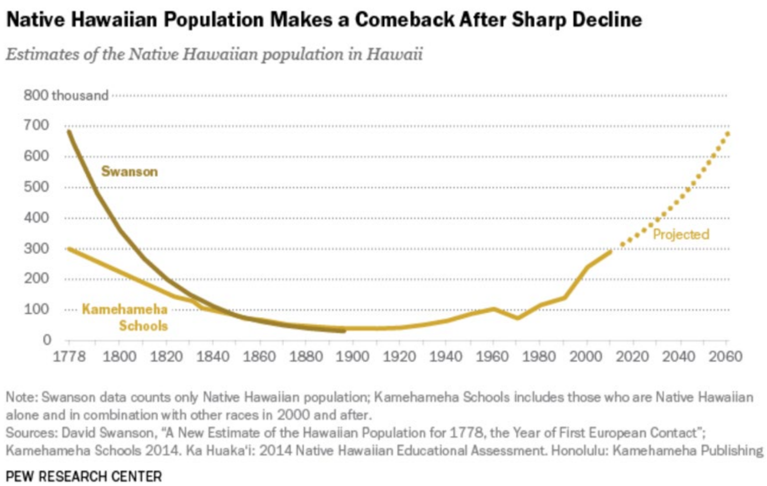
However, by mid-20th century, Asian Americans had become a majority of the population, while the white population ("haole"[1], meaning "no breath") became the minority. This shift in the population allows Asian Americans to wield significant political power. The island-wide strikes of 1954 led to the overthrow of white minority rule and better working condition for the Asian American locals.

The original Native population of Hawai'i, compared to Asian Americans, suffer more from lower income, higher poverty, incarceration, and high school dropout rates or don't attend college. Due to their limited access to land, they are disenfranchised economically and socially. The Native Hawai'ian sovereignty movement continues to seek to reclaim the lost land and culture of the native people. In 1921, the Hawai'ian Homes Commission Act allowed the homesteading for people of 50% or more Hawai'ian ancestry. In the 1970s, a local movement began to reinvigorate Hawai'ian culture and restore it to a central role in Hawaii. Hula is widely practiced, immersion schools teach the Hawai'ian language, Hawai'ian foods and dishes are popular and available, and cultural

1. Whereas native Hawai'ian great by touching foreheads and breathing into one another, the first European sailors interpreted this as a hug without knowledge of the breath, and thus the term 'haole' arise.

practioners pass traditions to succeeding generations and educate others about the rich history of the islands **[6]**.

The annexation of a kingdom and the imperialist exploitation for economic gains of Hawai'i and its people remains one of the only five crimes that the United States had to officially apologize for. Discussion of this history sometimes focus too much attention on the colonialist perpetrators while sidelining the native Hawai'ian as passive victims: however, they are anything but. Digging of archival and print evidence provided records of native Hawai'ian fiery resistance to political, economic and cultural domination. This resistance can still be felt in our cultural fabrics until today and it has intensified during the past couple decades: the fiery protest to stop US military bomb testing on Kahoʻolawe **[8]**, the protest over environmental destruction and poor water management on the Maui island, or the blockage of new telescope construction on top of Mauna Kea.



After 200 years, demographer predicts that Native population are finally making a comeback. The Native Hawai'ian population has been growing in recent decades because of a higher fertility rate **[9]**. These all points to the importance of celebrating the Native Hawai'ian culture and resurrecting the pride in being Native Hawai'ian in pop-culture, for example, with movies like Moana. Understanding the histories of what it means to be Hawai'ian will be a foundation for future native inhabitants of Hawai'i to make their own decisions about important issue facing them today: the status of Hawai'ian society, revitalization of Hawai'ian language, combating over-tourism on the islands, management of water and natural resources, and preservation of the Aloha ways of life.

References

1. **Kahn & Suggs & Kiste, 2021.** "*Polynesian culture*", Brittanica.
2. **Hamblin & Peterson, 2018.** "*The four great gods of ancient Hawaii Religion*", Desert News.
3. **Archer, Seth, 2018.** "*Sharks upon the Land: Colonialism, Indigenous Health, and Culture in Hawai'i, 1778–1855*", Cambridge University Press.
4. **Goo, Sara, 2015.** "*After 200 years, Native Hawaiians make a comeback*", Pew Research.
5. **Siler, Julia Flynn, 2012.** "*Lost Kingdom: Hawaii's Last Queen, the Sugar Kings and America's First Imperial Adventure*", Atlantic Monthly Press.
6. "*Native Hawaiian Sovereignty Movement*", **2021**, The Asian American Education Project.
7. **Tanigawa, 2016.** "*Face of the Enemy*", Hawaii Public Radio.
8. **Doulton-Lee Ho, 2021**. "*Lessons from the Bombings of the Island of Kahoʻolawe*".
9. **Swanson, 2014**. "*A New Estimate of the Hawaiian Population for 1778*".

The Flora and Fauna of Hawaii
Maizey Benner

Hawaii is located at approximately 20° N latitude, giving it a mild tropical climate with relatively uniform length of day and temperature (Price, 1983). The temperature at sea level varies by only 6° seasonally and 1-2° from day to night (Price, 1983). This warm, tropical climate and the extreme isolation of the islands supports a diverse range of flora and fauna. The Hawaiian islands are home to more than 10,000 species that are found nowhere else in the world, and upwards of 25,000 total species (DLNR, 2023).

Figure 1.
Top: Hawaiian Hoary Bat (from USGS)
Bottom: Hawaiian Monk Seal (from the Marine Mammal Center)

Fauna

Mammals

There are only two mammals native to the Hawaiian islands: the Hawaiian Hoary bat and the Hawaiian Monk seal (Fig. 1), both of which are endangered and rare to observe. At the right time, the Monk seal may be observed on the beaches of the main islands sunbathing, however only 100 or so regularly make the trip from the Northwestern islands. Hoary bats roost in a variety of habitats throughout the main islands, but are a solitary subspecies with little research on their ecology.

Upon settling in Hawaii between 500 to 700 AD, the Polynesian people introduced pigs and chickens to the islands. Then, in the late 18th century and early 19th century, English sow/boar, cattle, and sheep were introduced by English and American settlers (Hugh et al., 1986). Over time, the introduced livestock have become feral and contributed to damage to native flora and the spread of disease. The feral livestock are more aggressive and agile than livestock in the continental US.

Fig 2. Spinner dolphins with a distinct long-beak and tripartite

The islands are home to a large number of marine mammals, including sea turtles, whales, dolphins, and sharks. The most common sea turtle is the Green Sea Turtle, however they are relatively rare on the main islands, save for isolated beaches, and instead nest on the Northwest islands. These sea turtles have shells 2-3 feet in length and are dark brown in color. Humpback whales can be seen off the coast singing and carrying on (breaching, leaping, and tail slapping). The Humpback whales visit Hawaiian waters during the winter months for mating, giving birth, and nursing their young. There are 18 dolphin species found in Hawaiian waters, however the spinner, spotted, and bottlenose dolphins are the most common. Spinner dolphins are frequently found near the shore in shallow bays and have a characteristic long beak (fig. 2), while the Spotted dolphins prefer the channels between islands and have a distinct spotted pattern on their body. Bottlenose dolphins are much larger than spinner and spotted dolphins and are uniformly grey in color (Hawaii Wildlife Fund).

Birds

There are at least 113 avian species native to the Hawaiian archipelago, 71 of which have become extinct since human colonization on the islands (DLNR, 2023). The introduction of nonnative plants, diseases, and insects have altered the habitats of forest birds and pushed them to higher elevations or remote islands.

The nēnē (fig. 3) is the only surviving Hawaiian goose species and is the state bird of Hawaii. Nēnē are mostly brown in color, with a black face and feet, cream cheeks, and black and cream striped neck. They nest in a variety of habitats and feed on leaves, seeds, flowers, and fruits, depending on their location.

Fig 3. An adult nēnē (right) with two goslings (from DLNR Hawaii).

The Hawaiian owl, or pueo, is an endemic species of owl that was likely introduced to the island upon the arrival of the Polynesians. Peuo are active during the day and are commonly found in grasslands, shrublands, and montane parklands.

The ‘arapane is a deep red-colored species (fig. 4) of Hawaiian honeycreeper and is the most widely distributed of the family. They fly above the canopy pollinating ōhi'a in flocks, feeding on insects in the upper canopy. They are in competition with ‘i’iwi and ‘amakihi, other species of honeycreeper, to nest and pollinate ōhi'a. The ‘i’iwi is a vermillion red color with a black tail and wings, and a distinct pink curved bill (fig. 4). The ‘amakihi is a small, yellow-green to olive colored bird that are most commonly found in subalpine scrub and māmane/naio forests.

There are also a large number of introduced avian species including the northern and red-crested cardinal, brush-tailed wallaby, Japanese white-eye, common myna, and the house finch, to name a few.

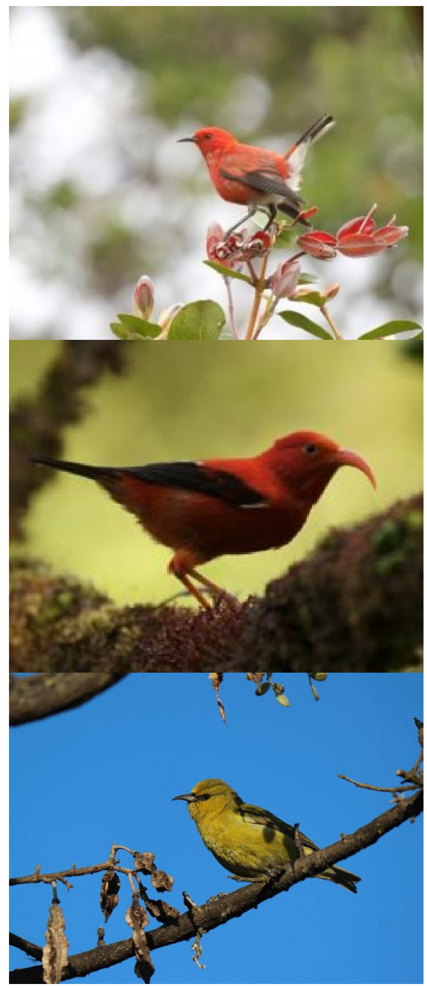


Fig. 4.
Top: ‘Arapane bird with deep red color and black bill.
Middle: ‘I’iwi bird with long curved bill.
Bottom: Yellow-green ‘Amakihi with black curved bill.
from DLNR Hawaii

Flora

There are at least 1,207 native species of flora in the Hawaiian archipelago, with 88% being endemic. There are three primary mechanisms for the arrival of plant species to Hawaii: wind, water, and birds. Some species, such as ferns, have spores that are light enough to be transported by the wind. Other species with buoyant parts drifted to the islands via water currents, and some were deposited by birds carrying seeds in their systems or in their feathers.

Ferns

Fig. 5
Left: Hāpu'u tree fern
Middle: Uluhe, or staghorn fern
Right: Palapalai fern

The humid climate of the islands is particularly suited to ferns. Hawaii boasts 200 species of native ferns with 65% being endemic. 5 genera of ferns comprise 41% of the native species. The spores of ferns are spread amongst the islands via wind from the trade winds and northern subtropical jet stream. The 'Ae fern is the first species to colonize lava flows with short, narrow fronds. Hāpu'u ferns form large trees near the summit of Kīlauea (fig. 5). They have soft fibers that have been used as stuffing for pillows and mattresses. The palapalai (fig.5) and Pala'ā ferns are indigenous to the islands and often used in hula and lei as adornments for the head and wrists. The uluhe (fig. 5), or staghorn fern, is also common in Hawaii and forms thick mats along the forest floor that create a soil that fuels the growth of other rainforest flora.

Fig. 6 'Ohi'a tree growing from a recent lava flow.

Trees

There are two major endemic tree species in Hawaii that we will encounter: 'ohi'a and koa.'Ohi'a lehua grow in fresh lava flows between 1,000 and 9,000 ft in elevation. They are characterized by metallic green leaves and pom-pom flowers that range from bright red to yellow in color (fig. 6). 'Ohi'a are the most abundant native Hawaiian tree and comprise half of all native trees on the big island. The 'ohi'a tree is sacred to the Hawaiian goddess of the volcano, Pele, and the goddess of hula, Laka, and plays a key role in many aspects of Hawaiian culture. There is a fungal disease rapidly spreading among ‘ohi’a trees called rapid ‘ohi’a death, which clogs the vascular system of the tree. The tree may have branches of dead but still attached leaves with dark sap and fruity odor. The NPS recommends cleaning your shoes before and after entering the forest with 70% rubbing alcohol and washing gear in hot soapy water.

The koa tree (fig. 7) is the largest native Hawaiian tree, growing up to 115 ft in height. It is found at elevations of 200-6,500 ft in recent lava flows along with the ‘ohi’a tree. They have a large canopy spread between 20-40 ft. The wood of the koa tree is extremely valuable and historically has been used to build canoes, surfboards, furniture, and instruments. Many native species of birds, including the species mentioned above, use koa as habitat.

Fig. 7 Koa tree leaves with a long curved shape. (Source: DLNR Hawaii)

Habitat Destruction on the big island

Much of the mesic (moist) forests, lowland and montane dry forests have been cleared by human activity on the island (fig. 8). In addition to human activity, the invasive plants, animals, and disease introduced to the island have modified the natural flora and fauna. The geographical isolation and wide range of habitats make the island susceptible to nonnative species.

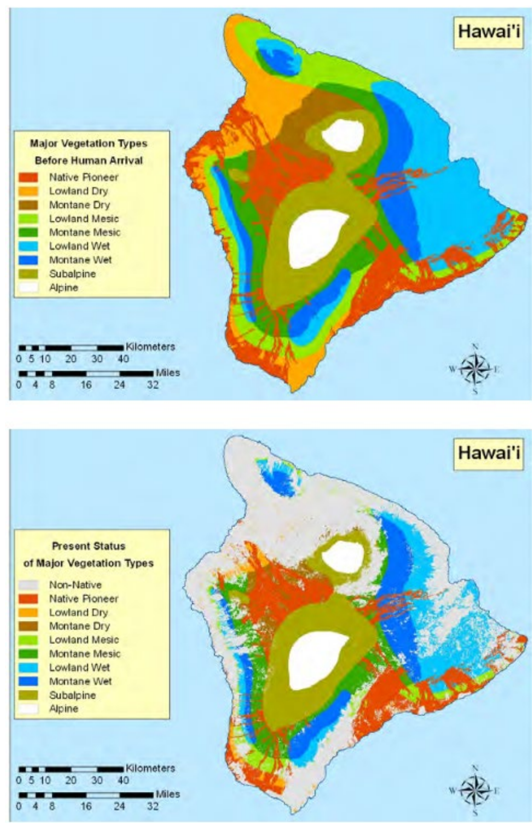


Fig. 8: Map of vegetation types on the big island of Hawai’i before and after the arrival of humans.

References

Department of Land and Natural Resources. (n.d.). *Issue 6: Conservation of native biodiversity - Hawaii*. From https://dlnr.hawaii.gov/forestry/files/2013/09/SWARS-Issue-6.pdf

Dolphins. Hawai'i Wildlife Fund. (2020, October 6). Retrieved February 14, 2023, from https://www.wildhawaii.org/wildlife/dolphins/

Hugh, W.I., T. Tanaka, J.C. Nolan, Jr., and L.K. Fox. 1986. The Livestock Industry in Hawaii. HITAHR Information Text Series 025. College of Tropical Agriculture and Human Resources, University of Hawaii

Price (1983) *Hawaii’s Climate*, University of Hawaii Press

Rocío Jacobo

Hawaiian–Emperor Seamount Chain

The Hawaiian–Emperor Seamount Chain (more than 6000 km in length) consists of approximately 130 volcanoes, and it is formed of the islands of the Hawaiian chain and the Emperor Seamounts (from the submarine volcano Kamaʻehuakanaloa near Hawaii to the Detroit (81–75 Myrs old) and Meiji (82 Myrs old) seamounts in the northwest Pacific). The most distinctive feature of the Chain is the Hawaiian-Emperor bend (HEB), where the two chains form an angle of about 120° (Figure 1) [4] [6].

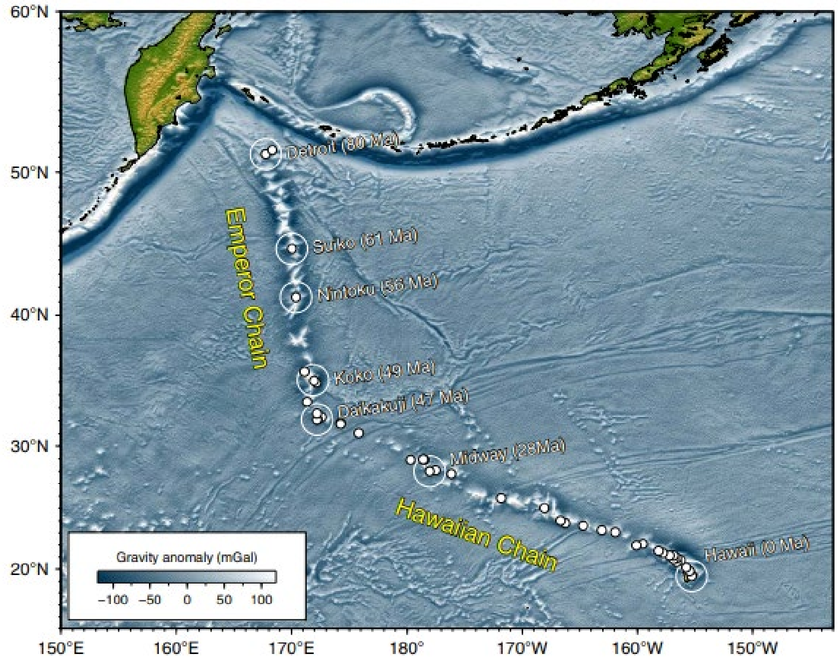


Figure 36. Hawaiian-Emperor Chain. [4]

Table 1. Summary of weighted mean 40Ar/39Ar ages for Hawaiian-Emperor seamounts. [2]

Seamount	Age ± 2σ (Ma)	*n*	Stage	Distance from Kilauea (km)
Suiko	60.9 ± 0.3	3	Shield and postshield	4860
Koko (north)	52.6 ± 0.8	1	Shield	3812
Koko (south)	50.4 ± 0.1	5	Postshield	3758
Kimmei	47.9 ± 0.2	1	Postshield	3668
Diakakuji	46.7 ± 0.1	3	Shield	3493
Abbott	41.5 ± 0.3	1	Shield	3280
Colahan	38.7 ± 0.2	4	Rejuvenated	3128
Unnamed	31.0 ± 0.2	1	Postshield	2600

Theories of formation

In 1840-1841, James Dwight Dana directed the first geologic study of the Hawaiian Islands. He determined that the islands were getting younger to southeast based on their different degrees of erosion. He also established the Loa and Kea series for two trends of volcanoes. Dana proposed that the alignment of the Hawaiian Islands reflected the localized volcanic activity along segments of a major fissure zone [7].

Tuzo Wilson, in 1963, and Morgan in 1971, explained that the time-progressive volcanism along the Hawaiian Chain was created by the lithosphere moving across o stationary hot spot in the mantle [5] [7].

The theory of the HEB was generated by a change in motion of the Pacific Plate at ~47 Ma, from a nearly northward direction (parallel to the Emperor Chain) to a north-westerly direction (corresponding to the Hawaiian Chain has been the most popular and accepted one. The lack of tectonic events along the margins of the neighboring plates leads to the theory that the bend must reflect the motion of a non-stationary hotspot. Another piece of evidence for this theory comes from paleomagnetic data where is shown that the Hawaiian Islands were formed close to the present-day Kamaʻehuakanaloa volcano latitude, paleolatitudes increase progressively from ~2° at Koko, through ~8° at Suiko, to ~19° at Detroit, implying that the hotspot may have migrated south during the emplacement of the Emperor seamounts [4] [3].

There is a big debate in the scientific community about whether the movement of the Pacific Plate or the migration of the plume created the Hawaiian–Emperor Seamount Chain. Some authors question the presence of the mantle plume that generates the islands and if the Hawaiian Island Chain and the Emperor Seamount Chain are even related [1]. Some of the arguments they present to question the existence of a mantle plume that created the Island Chain are:

- The Emperor Chain began near a spreading ridge based on $^{86}Sr/^{87}Sr$ ratios.
- The bend does not result from a change in direction of motion of the Pacific plate, because the direction of plate motion cannot change rapidly, but local stresses can.
- There is no evidence of the plume head (large igneous province).
- They present studies where seismic tomography does not show the presence of low wave speed anomalies under the big island (Figure 2), although there are others that show it (Figure 3).

- There is no heat flow anomaly.
- The origin of the melts of Hawaii is from the base of the lithosphere instead of a deeper source.

These are some points presented that question the origin of the Hawaiian–Emperor Seamount Chain, although most of the scientific community agrees with the mantle plume origin of it.

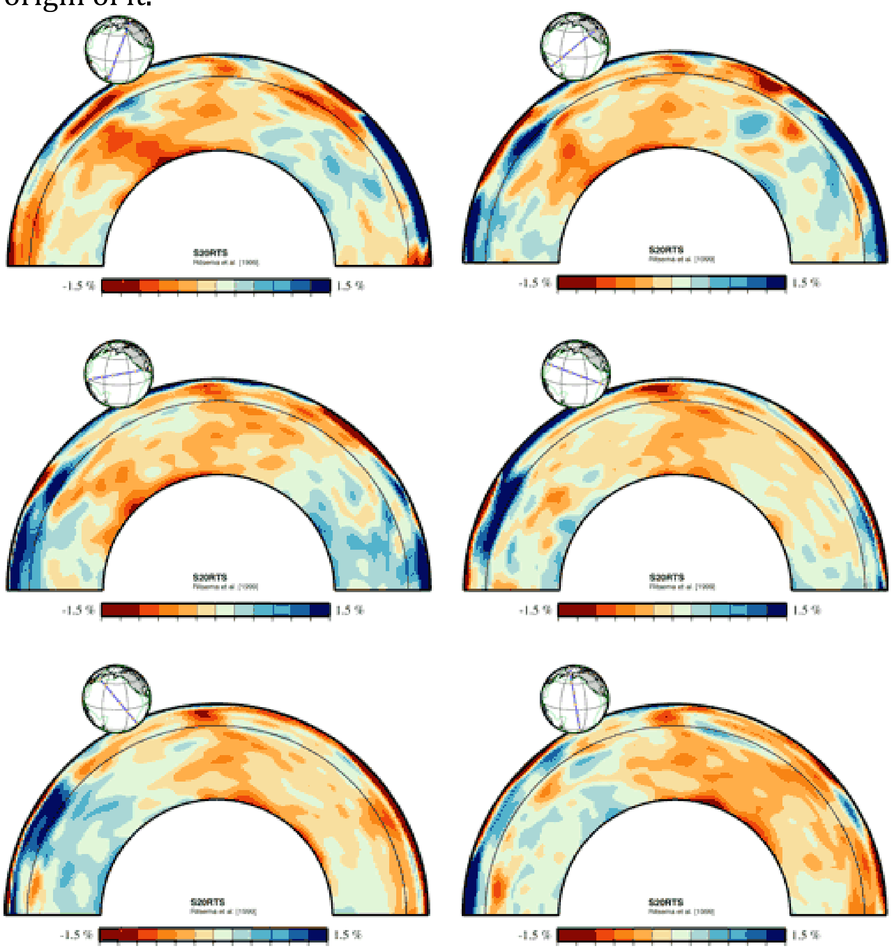


Figure 2. Six cross-sections passing through the big island of Hawaii. [7]

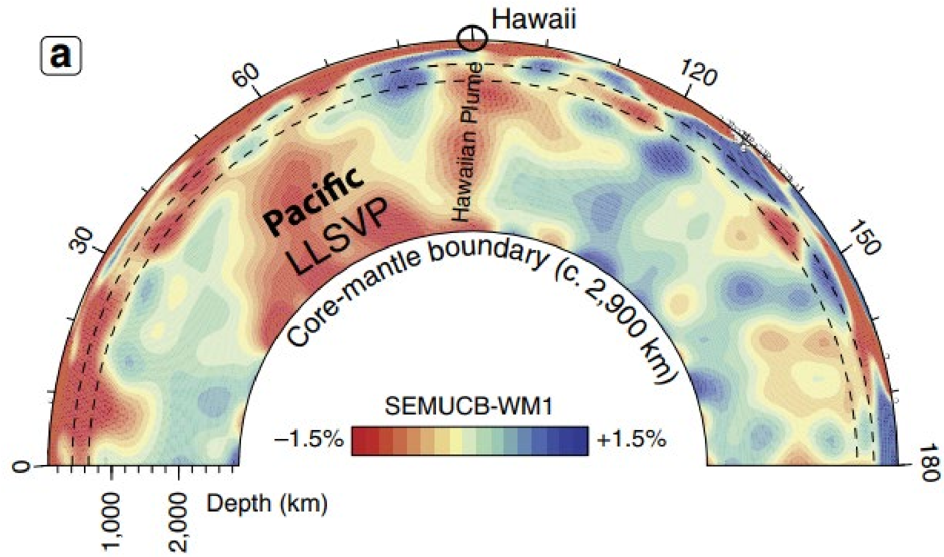


Figure 3. North-south vertical slice of the SEMUCB-WM143 mantle tomography model. [4]

References:

[1] Foulger, G. R., Anderson, D., Natland, J. H., & Julian, B. R. (2003, August). The Emperor and Hawaiian volcanic chains. In Penrose Conference Plume IV: Beyond the plume hypothesis (pp. 25-29).

[2] Sharp, W. D., & Clague, D. A. (2006). 50-Ma initiation of Hawaiian-Emperor bend records major change in Pacific plate motion. Science, 313(5791), 1281-1284.

[3] Sun, W., Langmuir, C. H., Ribe, N. M., Zhang, L., Sun, S., Li, H., ... & Sanan, P. (2021). Plume-ridge interaction induced migration of the Hawaiian-Emperor seamounts. Science Bulletin, 66(16), 1691-1697.

[4] Torsvik, T. H., Doubrovine, P. V., Steinberger, B., Gaina, C., Spakman, W., & Domeier, M. (2017). Pacific plate motion change caused the Hawaiian-Emperor Bend. Nature Communications, 8(1), 15660.

[5] Watts, A. B., Grevemeyer, I., Shillington, D. J., Dunn, R. A., Boston, B., & Gómez de La Peña, L. (2021). Seismic structure, gravity anomalies and flexure along the Emperor Seamount chain. Journal of Geophysical Research: Solid Earth, 126(3), e2020JB021109.

Web pages

[6] Hawaiian–Emperor seamount chain. (2023, February 3). In Wikipedia. https://en.wikipedia.org/wiki/Hawaiian%E2%80%93Emperor_seamount_chain

[7] Foulger, G. R., Anderson, D. (2006). The Emperor and Hawaiian Volcanic Chains: How well do they fit the plume hypothesis? http://www.mantleplumes.org/Hawaii.html

Nathan Hadland

Phreatic and Phreatomagmatic Eruptions

Phreatic Eruptions: Phreatic eruptions result from rapid heating and vaporization of water. Consequently, magmatic processes are not the principal driving mechanism of the event and are rather broadly generated by hydrothermal processes. By definition, phreatic eruptions only contain nonjuvenile particles (e.g., preexisting rock from the volcanic conduit). Phreatic eruptions encompass steam-driven explosions generated by:

- Magma intruding fluvial sediments and aquifers (e.g., the groundwater table or meteoritic water percolating downward)
- Lava or pyroclastic flows interacting with surface water
- Geyser like explosions driven by depressurization of near boiling-point subterranean geothermal water
- Volcanic eruptions expelling hydrothermal systems formed during periods of repose

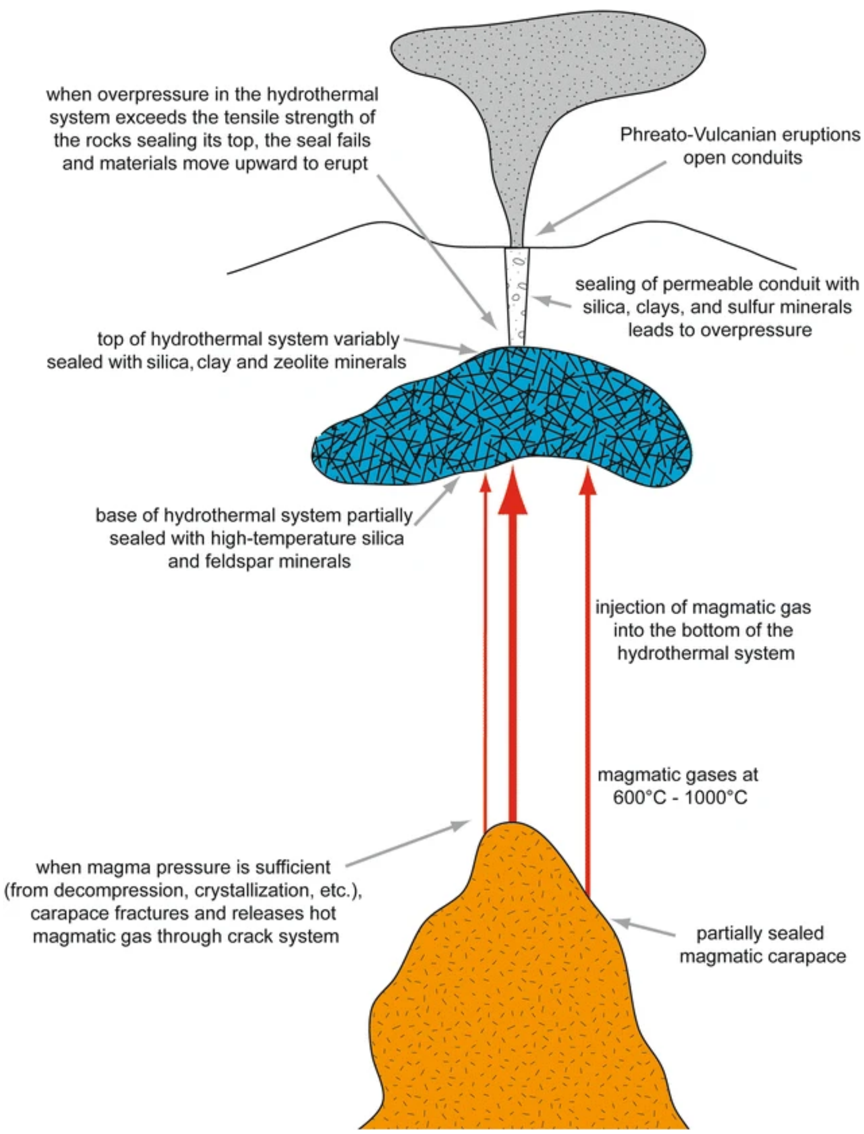


Figure 37: A magma chamber releases gasses into the overlying hydrothermal system above. If the hydrothermal system is sealed at its top, the system will become pressurized from the addition of hot magmatic gasses and rock, leading to an explosion[1].

The expansion of steam combined with volcanic outgassing builds up pressure within a hydrothermal system. When the overpressure exceeds the tensile strength of the overlying rock, the upper seal will rupture, allowing gases and lithic debris to be transported through a

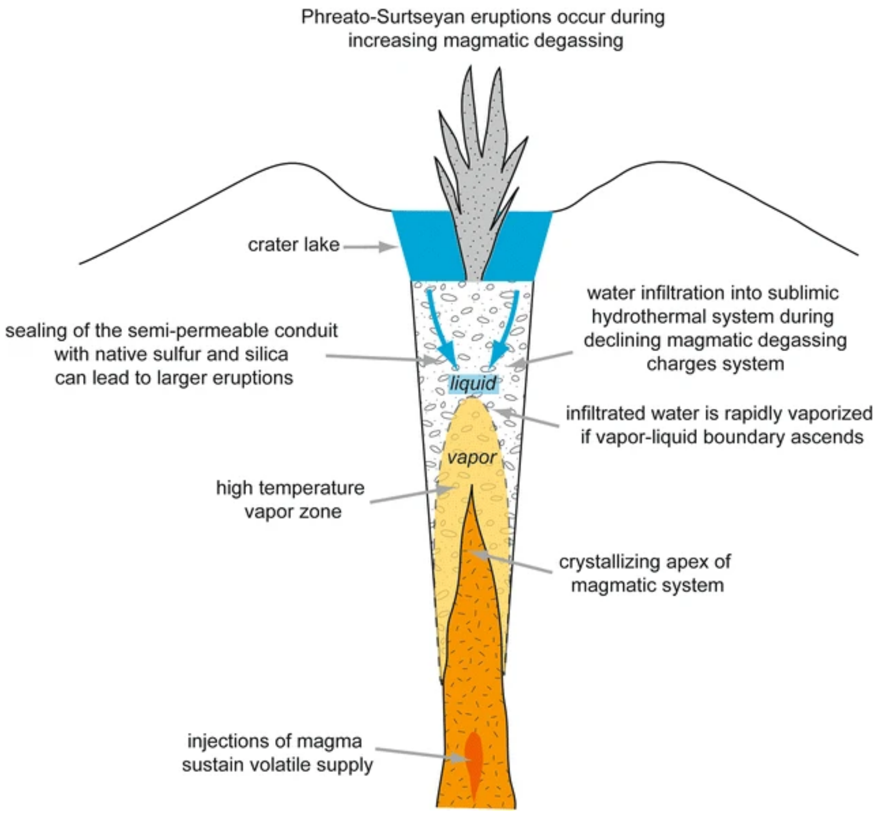


Figure 2: Increasing gas input into an overlying body of water raises the vapor–liquid boundary, resulting in vaporization of confined liquid water, generating volume change, pressurization, and eruption (Stix & Moor, 2018).

conduit system and erupted at the surface. These eruptions can be extremely hazardous due to their explosivity, as the ash, water, and volcanic bombs ejected during the eruption can cause injuries or damage to buildings and infrastructure. Additionally, the rapid changes in pressure during a phreatic eruption can generate seismic waves that may cause earthquakes.

Phreatomagmatic Eruptions:

Phreatomagmatic eruptions are similar to phreatic eruptions, but they involve the direct interaction of magma and water and contain juvenile clasts in the explosive column, rather than purely steam explosions. When magma encounters groundwater or surface water, the water is rapidly vaporized, creating steam and gas that drives an explosive eruption. The interaction of magma and water can also lead to the formation of volcanic bombs and ash, as well as the creation of craters or explosion pits. Phreatomagmatic eruptions can be much more powerful than phreatic eruptions and can cause widespread damage and destruction.

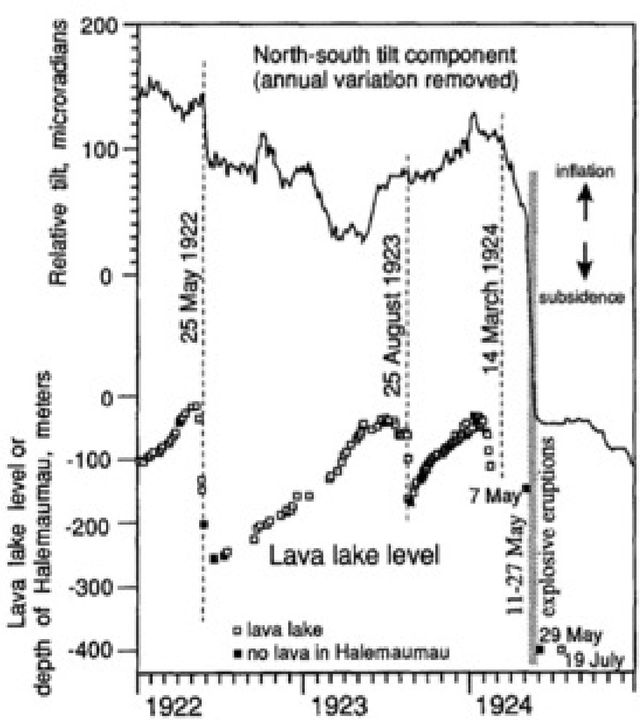


Figure 3: North/south tilt measured at the caldera rim on Kilauea, providing a indicator of inflationary and deflationary processes. The bottom plot shows the relative level of the lava lake. The phreatic explosion events occurred in May 1924 [2].

Figure 3: (a) Largest explosion of the eruption, May 18, 1924. Note clouds forming from condensation of steam. (b) Explosive eruption column from Halema'uma'u 11:15 am May 18, 1924. (c) Spectators from steamships view an eruption plume before getting told to move away by then director of HVO. 9:13 am May 24, 1924. (d) Eruption debris thrown out ~2000 feet from the crater rim during an explosion on May 18, 1924 [3].

Typical products include hyaloclastite which is typically a breccia consisting of glass fragments formed by quenching and fragmentation of chilled magma either during the explosion or due to thermal shock and spallation during rapid cooling. They typically form during subglacial eruptions, shallow submarine conditions, and in the deep sea. Hyalotuff deposits can also form via explosive fragmentation of glass, and form tuff rings, tuff cones, or maars.

Phreatic/Phreatomagmatic Eruptions in Hawaii: Explosive phreatic and phreatomagmatic eruptions on Hawaii are rarer than traditional Hawaiian styles of magmatic eruptions. The most recent event occurred in 1924. In that case, the sudden drop in the lava lake level to within a hundred meters of the elevated water table in the summit region combined with a massive

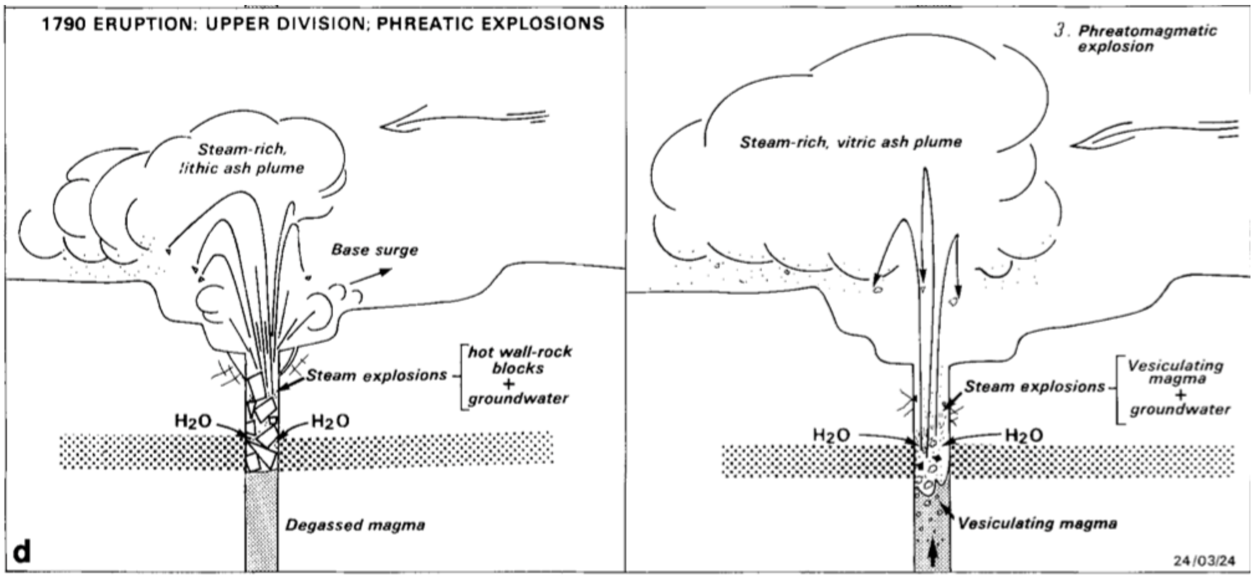


Figure 4: Comparison of phreatic and phreatomagmatic explosions during the 1790 Kilauea eruption. Phreatomagmatic explosions in earlier phases could have weakened the vent walls and allow for abundantly available lithic debris for subsequent phreatic eruptions. The phreatic eruptions occured when the magma levels had significantly dropped in the lake [4].

withdrawal of magma from the summit reservoir to the east rift zone. As a result, groundwater was able to flow rapidly into conduits of very hot rock previously heated by magma that connected the lava lake and magma chamber. Small explosions started around May 11th and by May 13th, rocks were hurled 2000 feet into the air. The ash and rocks were derived from old lithic blocks from the walls of the crater, indicating that the eruption was strictly phreatic [2].

A similar event occurred in in 1790 but had both phreatic and phreatomagmatic components. The first phase of the eruption involved typical

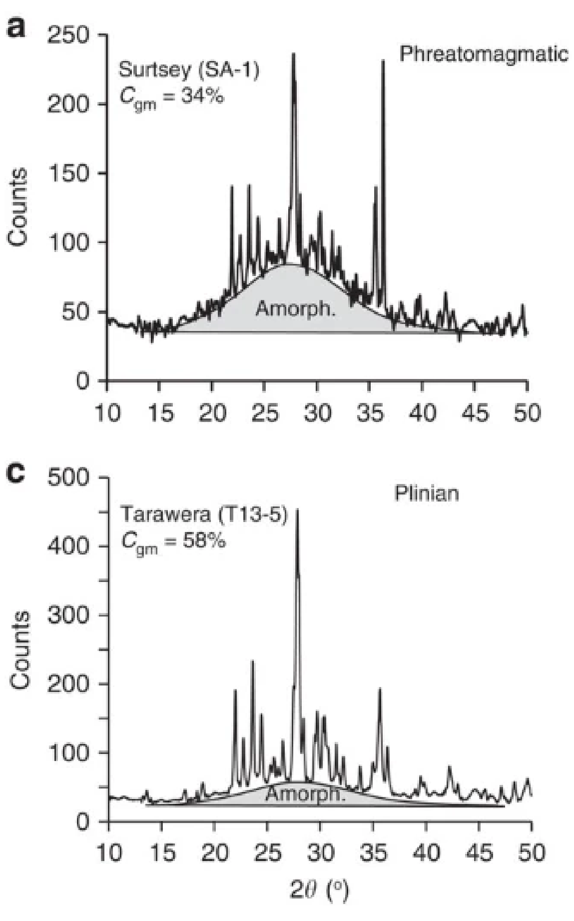


Figure 5: Representative groundmass diffraction patterns for a phreatomagmatic eruption (Surtsey) and a basaltic Plinian eruption (Tarawera). Grey areas under the diffraction pattern represent the area associated with amorphous content while Bragg peaks represent diffraction off various lattice planes within the sample (e.g., crystallinity) [5].

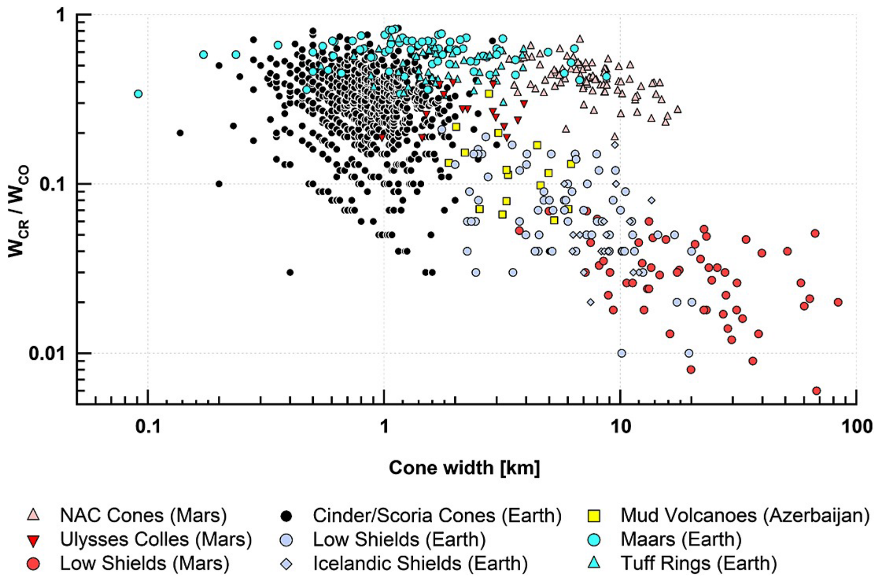


Figure 6: Morphology Nephentes-Amenthes Cones (NAC) south of Utopia Planitia and east of Isidis (originally interpreted to be mud volcanoes), and pitted cones in Ulysses Colles, Tharsis. These are compared with terrestrial examples of cones, maars, mud volcanoes, and shields and display the ratio between crater diameter (W_{CR}) and cone diameter (W_{CO}) versus W_{CO} [6].

magmatic-volatile-driven fountaining at the summit. In phase two, magma was withdrawn to the East Rift zone and groundwater was free to infiltrate close the summit conduit where it interacted with magma in the lava lake. Later phreatic eruptions during the third phase resulted from the interaction of groundwater with older lithic rock that had been heated by the degassed magma [4]. This eruption was recorded in Hawaiian oral traditions, since it resulted in the deaths of warriors traveling in the area. In both the 1790 and 1924 eruptions, a precise balance between magma withdrawal rates, groundwater supply, and reservoir hydrostatic pressure was required to generate the explosive activity.

Planetary Examples: Most volcanism on Mars have been interpreted to be formed predominantly by effusive eruptions. However, the evidence for a hydrologically active past should have generated frequent opportunities for magma/water interactions, potentially leading to explosive phreatomagmatic eruptions. One method for determining whether the eruption was magmatic or phreatomagmatic is to evaluate the relative level of crystallinity in the sample using X-Ray Diffraction (e.g., CheMin instrument) [5], or other compositional information. For example, brines in Gusev Crater have been suggested to be the trigger for phreatomagmatic explosions that were later overprinted by hydrothermal alteration materials [7], though this remains controversial [5]. Another method involves the morphological interpretation of landforms. Evidence for pyroclastic cones have been reported frequently on Mars, but generally have been concluded to be a result of magmatic degassing, rather than steam explosions. However, [6] identified pitted cones along the southern margin of Utopia Planitia that shares similar characteristics to terrestrial tuff cones and rings and is consistent with the hydrological history of the regions. An issue with this method is that tuff rings are difficult to distinguish from impact craters based solely on orbital imagery.

References: [1] Stix & de Moor (2018) *Earth Planets Space,* 70, 83. [2] Dvorak (1992) *Bull Volcanol,* 54, 638-645. [3] USGS, https://www.usgs.gov/volcanoes/kilauea/may-1924-explosive-eruption-kilauea Accessed 17 Feb 2023. [4] McPhie *et al*. (1990) *Bull Volcanol,* 52, 334-354. [5] Wall *et al*. (2014) *Nat Commun*, 5, 5090. [6] Brož, P., & Hauber, E. (2013), *Geophys. Res. Planets*, 118, 1656– 1675 [7] Schmidt *et al*. (2008) *J. geophys. Res.*, 113, E06S12.

Weigang Liang

Weathering Environments

Weathering is a process in which a rock structure interacts with the environment, and is altered into a more fundamental state. Such processes are ubiquitous throughout the Solar System, and are one of the main processes through which planetary surfaces evolve over time. Weathering can be categorized into roughly two types (Fig. 1): **mechanical** and **chemical**. Mechanical weathering alters the physical properties of the structure, such as its mass and shape, but does not affect its chemical makeup. On the other hand, chemical weathering modifies the chemical composition of the structure, and the end products are usually more fundamental, less reactive products.

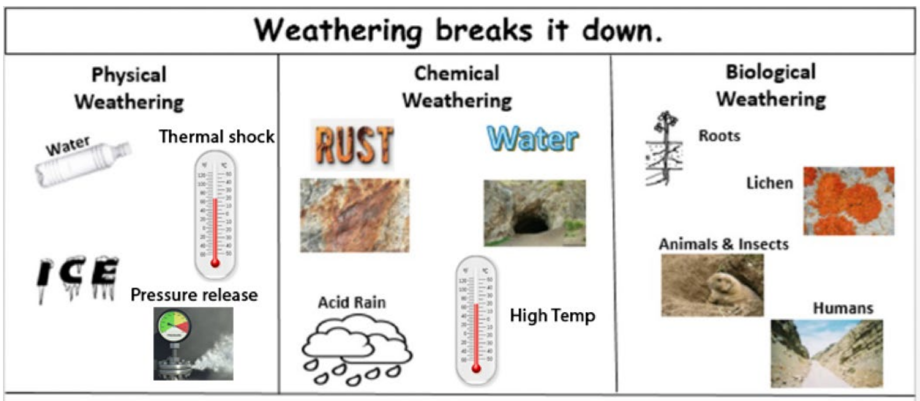


Figure 38: Illustration showing the different modes of weathering. Figure courtesy of Arnine W

On Earth, there is an addition agent of weathering, biological weathering, driven by bacteria, plants, and most importantly, *us*.

****Weathering, unlike erosion, does not usually involve transport of material***

Mechanical Weathering

There are many processes in which the environment can modify a structure without affecting its chemical makeup (Fig. 2):

Frost weathering

When water seeps into cracks in a rock structure, if the temperature cools to below freezing, the water will freeze. The conversion from water to ice usually involves a 9% volume increase, producing a force of up to 207 MPa, which is greater than the tensile strength of typical rocks on Earth's surface [1].

Frost/thaw weathering can result in formations such as stone stripes (Fig. 2), in which clasts are separated from more fine-grained material.

Figure 39: Stone stripes on Mauna Kea, 4000m elevation. [2]

Thermal stress weathering

Upon exposure to large variations in temperature, the thermal expansion and contraction of the rock structure can induce significant stress, and break the rock apart. Thermal stress weathering is most common in areas such as deserts/Antarctica [3], or airless bodies, in which diurnal temperature contrasts are significant.

Pressure release weathering

When deeply buried rock structures are exhumed, the absence of the overlying pressure results in the expansion of the of the buried structure. As a result, the stress may induce the fracturing and breakage of rocks along the surface, in a process known as exfoliation, or sheeting (e.g., Fig. 3). Such a process can smooth exposed rock, and result in structures such as the Half Dome in Yosemite.

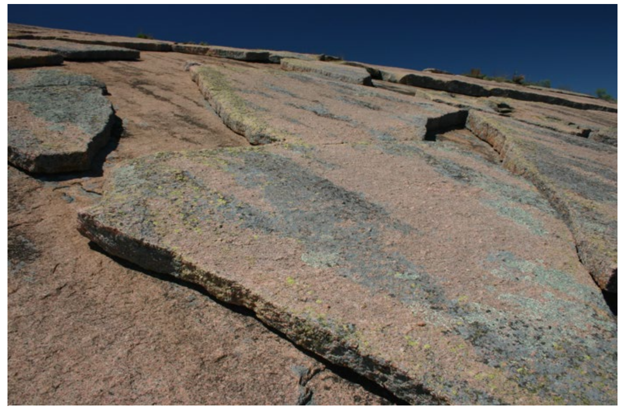


Figure 40: Exfoliation of granite in Texas. Figure courtesy to Wing-Chi Poon

Chemical Weathering

Chemical weathering involves the alteration of the chemical makeup of a rock body. Some of the principal agents of chemical weathering on Earth are water, oxygen, and carbon dioxide.

Figure 4: Makauwahi limestone Cave, Kauai [4]

Dissolution

The polar nature of water molecules allows it to readily separate molecules with weaker bonds. Water by itself is capable of quickly dissolving minerals such as halites (salts) and transform them into aqueous solutions, while the timescale in which water can dissolve material with stronger bonds like quartz will be magnitudes greater than that for halites.

In the presence of dissolved carbon dioxide, water, in the form of carbonic acid, can convert mostly insoluble material like calcium carbonate into the soluble calcium bicarbonate. Structures of limestone can be heavily weathered in this manner, and result in formations such as karsts and caves (Fig. 4) .

Oxidation

Under the presence of oxygen, iron forms a surface layer of iron (II) oxide FeO, preventing its interiors from further reactions with oxygen. However, under the presence of both oxygen and water, iron minerals are converted to iron (III) oxides (rusting, ~Eq. 1), which have low tensile strength, and do not protect the iron layer beneath from further oxidation. Similar reactions with oxygen and water occur as well for many other metallic ores such as pyrite (FeS_2).

$$4Fe(s) + O_2(g) + 7\,H_2O(l) \rightarrow 2Fe_2O_3 \cdot \frac{3}{2}H_2O(s) + 8H^+(aq) \quad \textbf{(1)}$$

Hydrolysis

Hydrolysis is the process where upon interaction with water, a modified portion of the original mineral is incorporated into the aqueous solution, and the remaining portions of the mineral form a new end product (e.g., Eq. 2). *Acid hydrolysis* occurs when acidic water interacts with a mineral, and the protons attack the chemical bonds within the minerals, and an alternate end product is formed (e.g., Eq. 3). Acid hydrolysis is a very important process on Hawaii due to its warm temperatures, high rainfall, and low pH of rain due to high concentrations of SO_2 in the local atmosphere (e.g., Fig. 5).

Figure 5: Spheroidal weathering of benmoreites, Maui [5]

$$Mg_2SiO_4 + 4\,H_2O \rightleftharpoons 2\,Mg(OH)_2 + H_4SiO_4 \quad \textbf{(2)}$$

forsterite + water ⇌ brucite + silicic acid

$$Mg_2SiO_4 + 2\,CO_2 + 2\,H_2O \rightleftharpoons 2\,MgCO_3 + H_4SiO_4 \quad \textbf{(3)}$$

forsterite + carbon dioxide + water ⇌ magnesite + silicic acid in solution

Punalu‘u Black Sand Beach

Weathering of Basalt

The sand in Punalu‘u Black Sand Beach (below) is primarily composed of basaltic material sourced from local volcanic eruptions. Basalt is not a stable mineral on the Hawaiian shores, and it will be chemically weathered into compounds that are closer to chemical equilibrium with the surroundings.

Basalt is composed of > 65% plagioclase feldspar ($NaAlSi_3O_8 - CaAl_2Si_2O_8$), and < 20% quartz [6]. Plagioclase feldspar is chemically weathered into kaolinite (Eq. 4) in the presence of carbon dioxide and water, while quartz is relatively very stable, and does not chemically weather readily.

$$\text{Plagioclase feldspar} + \underset{\text{carbonic acid}}{H_2CO3} + H_2O \rightarrow \underset{\text{kaolinite (clay)}}{Al_2Si_2O_5(OH)} + \underset{\text{soluble carbonates}}{Na_2CO_3 + CaCO_3} + \underset{\text{quartz}}{SiO_2} \quad \textbf{(4)}$$

References: [1] Matsuoka et al. (2008) *Permafrost Periglac. Process.,* 19: 195-210 [2] Feuillet et al. (26014) Encyclopedia of Planetary Landforms pg. 1-9 [3] Lamp et al. (2017) *JGR Earth Surf*, 122, 3-24. [4] https://poipubeach.org/blog/makauwahi-cave-poipu, Accessed 02-21-23. [5] Sinton, J. (2019) *SOEST Hawaii.* [6] Streckeisen, A. (1976) *Earth-Science Rev.* 1-33.

Chengyan Xie

Seeing and telescope site selection

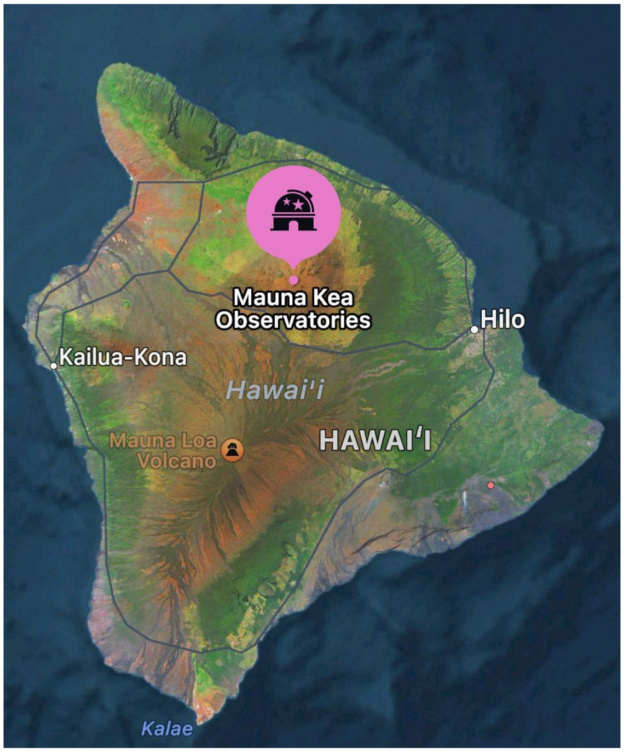


Figure.1 Landform of big island in Hawaii and the location of Mauna Kea Observatories.

Selecting a site for a telescope is an important decision for astronomers. Seeing condition is one of the most important factors in telescope site selection and has a major influence on the quality of observations. Here I'm going to discuss why Mauna Kea in Hawaii is one of the best sites in the world for telescopes. I'll first explain what seeing means and why it's important, then show how the topography of Mauna Kea influence the climate there and thus making the seeing conditions great. At last, I'll summarize the advantages of building telescopes on Mauna Kea.

The resolution of a telescope is mainly restricted by two factors: the diameter of the lens and the seeing. The angular resolution formular can be written as $\delta\theta = \frac{\lambda}{2D}$. When D is small, this decides the resolution of the telescope. However, when you build the telescope large enough that the $\frac{\lambda}{2D}$ is very small, the seeing will restrict the resolution. In astronomy, "seeing" refers to the blurring or distortion of images caused by the Earth's atmosphere. When we observe celestial objects from the ground, light from these objects passes through different layers of the atmosphere, which can cause the light to become scattered or refracted, leading to a distortion of the image. The turbulence and the density of atmosphere both have an influence. As a result, to build a 'best' telescope requires a site with the best seeing conditions.

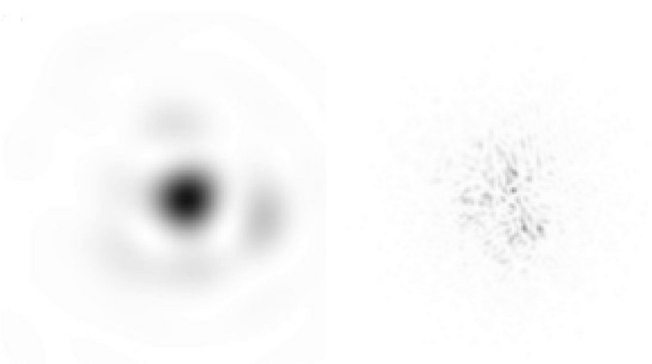


Figure. 2 Resolution restricted by lens size (left) and seeing (right).

How to choose a site with better seeing conditions? First, the elevation should be high. The thin, high-altitude air is less turbulent than the thicker air at lower elevations. The landscape and the weather will also influence the atmosphere turbulence. Flat landscape and temperature consistent with surrounding regions can make the atmosphere stable. No air pollution is also an important factor because the impurity in atmosphere will make the atmosphere unclear and unstable.

Mauna Kea is a dormant volcano on the island of Hawaii with a peak of 4207 meters above sea level. From the landscape map we can see there's a large plateau at the peak area. Located at the center of Pacific Ocean and the tropic area, the climate there is mild and warm. Mauna Kea is in the Northeasterly Trades region, where wind blow constantly from the Northeast, minimizing the turbulence of the atmosphere.

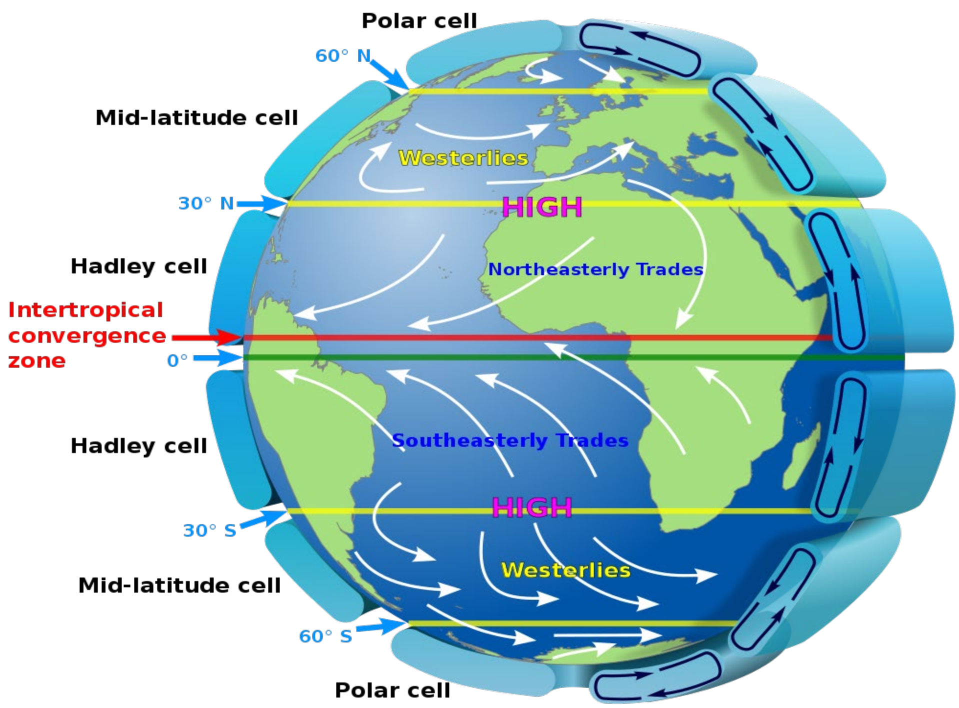


Figure. 3 Trade wind region sketch.

The elevation and trade wind also contribute to the low rainfall at Mauna Kea, which is another important factor influencing telescope site choosing. As the trade winds blow across the island, they are forced to rise over the steep slopes of the island's mountains, including Mauna Kea. As the air rises, it cools and the moisture in the air condenses into clouds and precipitation, which falls on the windward side of the island. By the time the air reaches the leeward side of the island, where telescopes are located, it has lost much of its moisture and is relatively dry.

In all, the unique geographic features of Mauna Kea make the climate and atmosphere excellent for telescope observations, especially on the aspect of seeing.

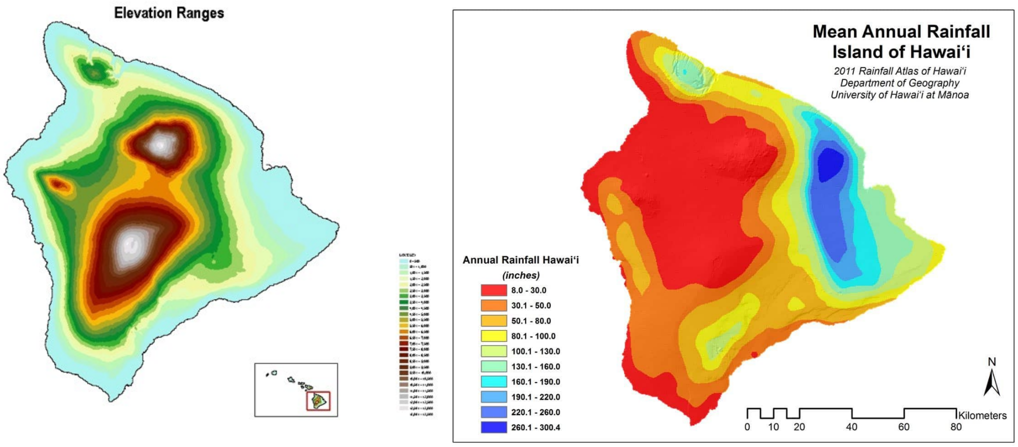


Figure. 4 Left: Elevation contour of Big Island of Hawaii; Right: Rainfall contour of it.

References:

[1] K.Cowles(1989). Site selection criteria for the optical atmospheric visibility monitoring telescopes. TDA Progress Report 42-97.
[2] Wikipedia page, https://en.wikipedia.org/wiki/Mauna_Kea Access date: Feb.19 2023
[3] Wikipedia page, https://en.wikipedia.org/wiki/Astronomical_seeing. Access date: Feb.19 2023
[4] Figure Source: http://lureofhawaii.com/topo.html; https://www.lovebigisland.com/weather/; Access date: Feb.19 2023
[5] Glossary of Meteorology (June 2000). "Trade air". American Meteorological Society. Archived from the original on 2011-06-06. Retrieved 2009-10-28.

Mauna Loa: 2022 Eruption

David Cantillo

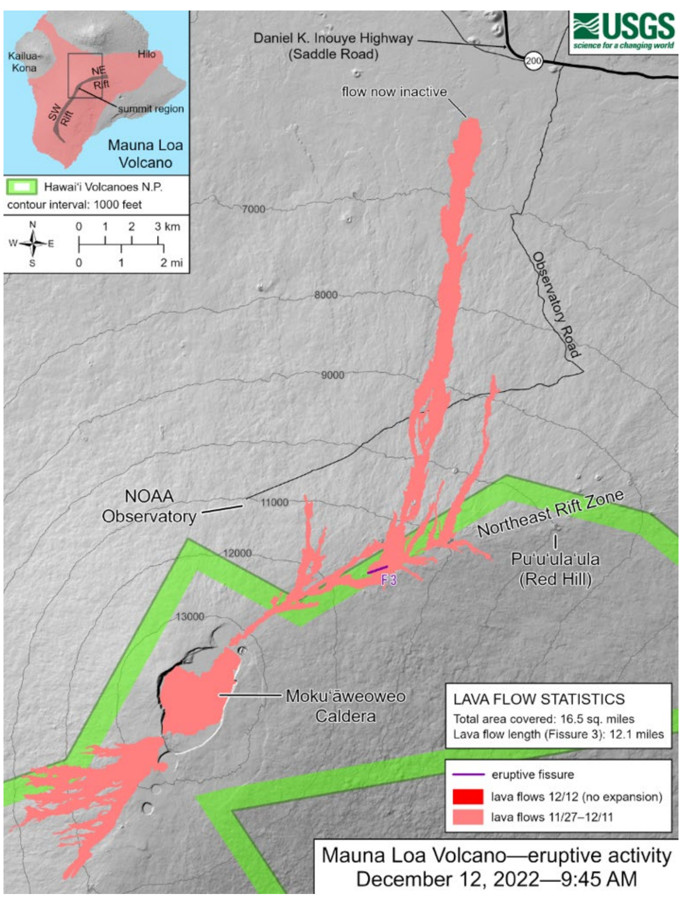
On November 27, 2022, a fissure opened at the summit of Mauna Loa and began a two-week eruption centered in Mauna Loa's Northeast rift zone. As the first eruption on Mauna Loa since 1984, this eruption offered a fascinating glimpse at the volcanic processes that shaped the Hawai'ian landforms and ultimately created the islands we see today.

Volcanic Context

Despite its peak being slightly shorter than Mauna Kea, Mauna Loa is more massive and is considered the largest shield volcano on the Earth [1]. Its lava flows are generally effusive and can vary in speed depending on slope. The last eruption prior to 2022 took place in 1984.

	Mauna Loa	Mauna Kea
Elevation	13,679'	13,803'
Volume (km^3)	75,000	32,000
Last Eruption	2022 (1984)	2600 BCE

Table 1. Largest Hawai'ian shield volcanoes.



2022 Eruption Timeline

1. October 5th: NPS closure of Mauna Loa summit due to heightened seismic activity (2-3 times more) [2]
2. October 30th: Volcano advisory
3. 11:30 pm Nov. 27th: Eruption begins at Moana Loa summit in caldera [3]
4. 6:30 am Nov. 28th: Lava flows migrate out of the caldera into the Northeast rift zone [3]
5. 7:30 pm Nov. 28th: Four total fissures are observed with lava fountains up to 200 ft. in height; road to Mauna Loa covered [4]
6. December 5th: A single flow approaches the saddle road though begins slowing down due to slope
7. December 13th: Eruption ends [5]

Figure 1 (left). USGS map of volcanic flow originating from the Mauna Loa summit [6]

Figure 2. Landsat-9 image of the 2022 Mauna Loa eruption taken on December 2nd, adapted from [4]

Figure 3. HI-SEAS habitat with the fissure 3 flow approximately half a mile to the west [4]

Eruption Hazards

Fortunately, the Mauna Loa 2022 eruption did not result in any injuries or casualties. The largest concerns in the Northeast Rift Zone were the flow proximities to the Saddle Road, Mauna Loa Observatory, and HI-SEAS [4] (Hawai'i Space Exploration Analog and Simulation).

<u>Saddle Road</u>

The Saddle Road, or Daniel K. Inouye Highway, serves as the fastest route between Kona and Hilo while also providing access to the slopes of Mauna Kea and Mauna Loa. By the end of the eruption, the fissure 3 flow was 1.7 miles from the road, providing viewing access to more than 100,000 people over the course of two weeks [4].

<u>Mauna Loa Observatory</u>

Mauna Loa Observatory is an atmospheric data collection station. On the night of the 28th, the fissure 3 flow crossed the road leading to the station, resulting in the loss of power and access to its CO_2 detector used in the famous Keeling curve.

<u>HI-SEAS</u>

The Hawai'i Space Exploration Analog and Simulation (HI-SEAS) facility serves as an analog environment to the Moon and Mars. Within three days of the eruption, fissure 4 was heading toward HI-SEAS, though quickly cooled. Instead, the more dominant fissure 3 passed close by to the west [4].

Figure 5. Aerial image of 1984 Mauna Loa flow [5] *Figure 6. Aerial image of 2022 Mauna Loa flow [5]*

Comparison with 1984 Eruption

The 38-year period between the 1984 and 2022 eruption was the longest record of quiescence in Mauna Loa's recorded history, with most eruptive events occurring every few years since the 1800s. In many ways, the 2022 eruption on Mauna Loa was similar to the last eruption in 1984, with both events originating in the summit caldera and propagating towards the Northeast rift zone [5]. With this, the two eruptions began in the middle of the night with only about thirty minutes of warning, prompting quick decision-making from scientists, government workers, and residents on the best approaches for possible evacuation [5]. Fortunately, both eruptions resulted in minimal damage with no human casualties.

Since 1984, technology has rapidly improved in the monitoring of eruptions and distribution of information to residents [5, 6]. More accurate digital terrain models have allowed researchers to create accurate flow models that can predict that rate of transportation and assess risk, and the internet has allowed for real-time views of the lava with webcams that can be easily shared [5].

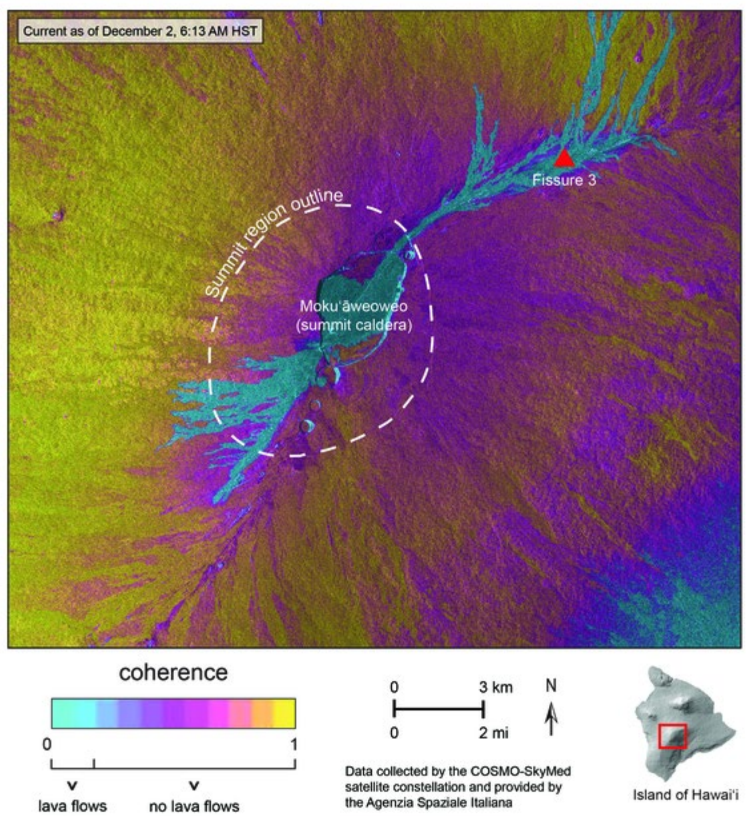


Figure 7 (right). Map of November 16th – December 2nd 2022 surface change detected by the COSMO-SkyMed satellite constellation [6]. Areas in light blue show the least coherence, illustrating new flow features. The main summit region of Mauna Loa is represented by the dashed white line.

Planetary Science Analog: Mars

While the Hawai'ian shield volcanoes may be the largest on the Earth, shield volcanoes can be found on many other planetary bodies such as Venus, Mars, and Io. The largest shield volcano in the solar system is Olympus Mons, which is found in the Tharsis region of Mars and is more than five times larger than Mauna Kea [7].

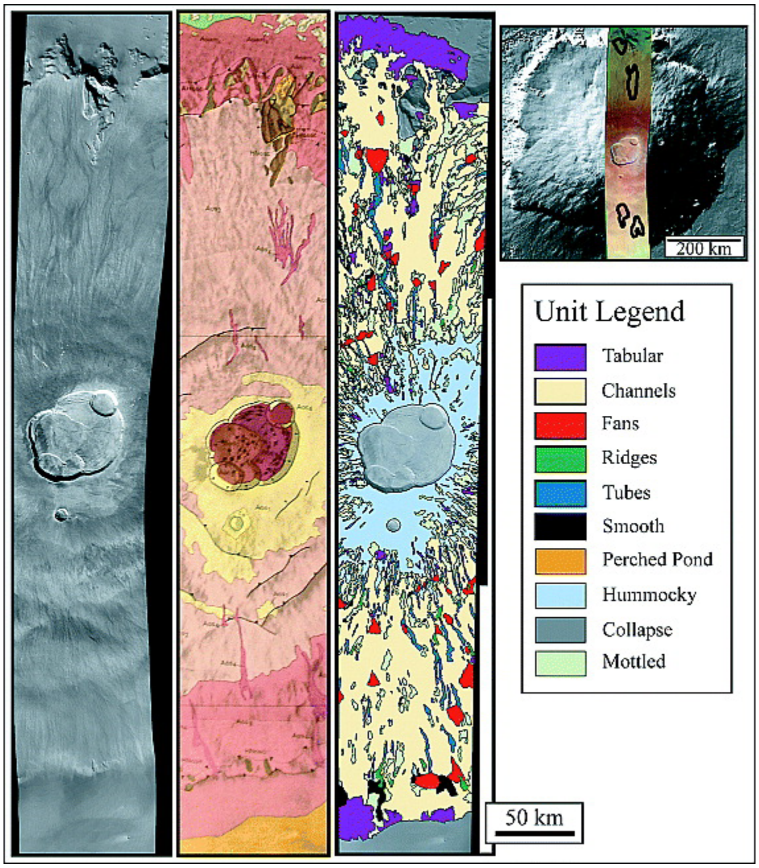


Figure 8. Nadir image of Olympus Mons (left), with geologic map from Morris and Tanaka 1994 (middle) and lava flow map [7]. Hummocky flows are centered near the summit while channels make up the dominant flow type downslope.

Unlike the Hawai'ian shield volcanoes, Olympus Mons is no longer erupting. Impact crater density estimates have shown that the last major eruption likely occurred in the late Amazonian (~300 Ma) [7]. Bleacher et al. (2007) performed geologic mapping and found that Olympus Mons likely began erupting with stable, tube-forming flows in the Noachian, then switched to chaotic channel-forming eruptions in the late Amazonian. They note that a similar trend is observed in the Hawai'ian islands today [7].

While no shield volcanoes have erupted on Mars recently, there is evidence of young (46-222 ka) pyroclastic deposits in Elysium Planitia based on stratigraphic relationships and crater counting [8]. This may be evidence of multiple planets with active volcanics.

References

[1] USGS. "Mauna Loa." U.S. Department of the Interior, USGS, 2021. [2] National Park Service. "Mauna Loa Summit Closed Due to Increased Seismic Activity." Hawai'i Volcanoes National Park, U.S. Department of the Interior, 5 October 2022. [3] USGS. "Van/Vona: Mauna Loa Red/Warning Eruption Moved to Northeast Rift Zone." Hawaiian Volcano Observatory, U.S. Department of the Interior, USGS, 28 November 2022. [4] NASA Earth Observatory. "Living the Lava Life on Mauna Loa." Earth Observatory, NASA, 29 Nov. 2021. [5] USGS. "Volcano Watch: Comparing Crises at Mauna Loa in 1984 vs. 2022." Hawaiian Volcano Observatory, U.S. Department of the Interior, USGS, 16 February 2022. [6] USGS "Photos and Video Chronology – Mauna Loa – December 3, 2022." Hawaiian Volcano Observatory, U.S. Department of the Interior, USGS, 3 December 2022. [7] Bleacher et al. (2007) *Journal of Geophysical Research (Planets),* 112, 4003. [8] Horvath et al. (2021) *Icarus*, 365, 114499.

Claire Cook

Mauna Kea: Glacial History

Introduction

Glacial records can provide insight into aspects of paleoclimate, like precipitation and temperature [1]. In the Pacific Ocean region, the Hawaiian Islands have the only evidence of former glaciation, with several summits, including Mauna Kea's, above the snowline during previous glaciations [2]. The record of glaciation on these volcanoes is therefore important for assessing the past climates of this region [2].

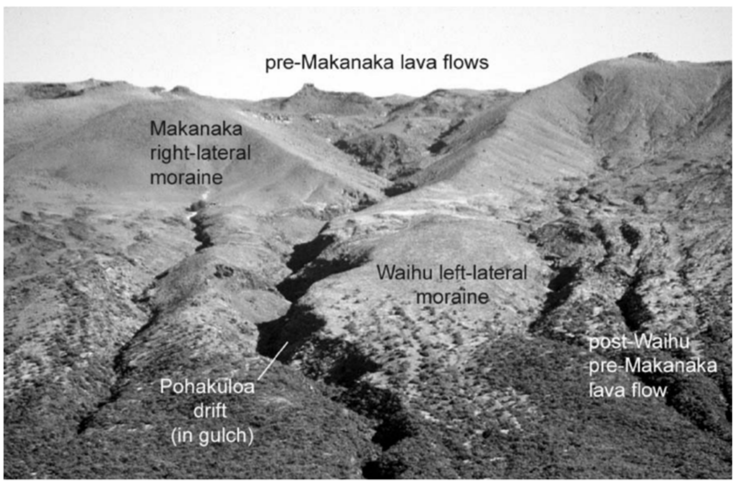


Figure 41: View looking northeast towards Mauna Kea summit. Shows Makanaka and Waihu moraines. From [2].

Glacial Geology of Mauna Kea

Following is a brief summary of the relevant volcanic and glacial geology (based on [2] and [3]). See Fig. 1 and the geologic map in Fig. 2.

- Hamakua volcanics: alkali and transitional basalt, aged 250 ka to 65 ka.
- Laupahoehoe volcanics: hawaiite lavas and associated pyroclastic deposits, overlying Hamakua volcanics, aged 65 ka to 4 ka.
- Makanaka Formation: the last glaciation, with two units separated by lava flows. The older unit, extending as low as ~3200 m, forms broad moraines with max slope angles of 10 to 25°. The moraines of the younger unit, which extent to as low as 3420 m, are sharper, with slope angles of 20 to 30°. Both till and outwash facies are present and have a max thickness of 50 m. Striated and abraded lava surfaces are found within the boundary of these moraines. The moraines delineate a ~10 km diameter ice cap on the upper slopes of the volcano. They are overlain by postglacial lava flows and overlie volcanic rocks and deposits related to two previous glaciations.
- Waihu Formation: second to last glaciation, with moraines exposed discontinuously along the southwestern flank of the mountain downslope from the Makanaka moraines, with a lower limit of ~3000 m. These moraines have slope angles 5 to 20° and have been lowered ~3 m or more by erosion. This unit includes both tillite and outwash facies and has a max thickness of ~30 m. In many places, tillite overlies abraded and striated lava flows.

- Pokahuloa Formation: exposed only in a few locations, near the top of the Hamakua lavas. It seems to reach approximately the same downslope limit as the overlying Waihu formation. Again, till and outwash facies are exposed with the former resting on abraded rock surfaces. It has a max exposed thickness of 40 m.

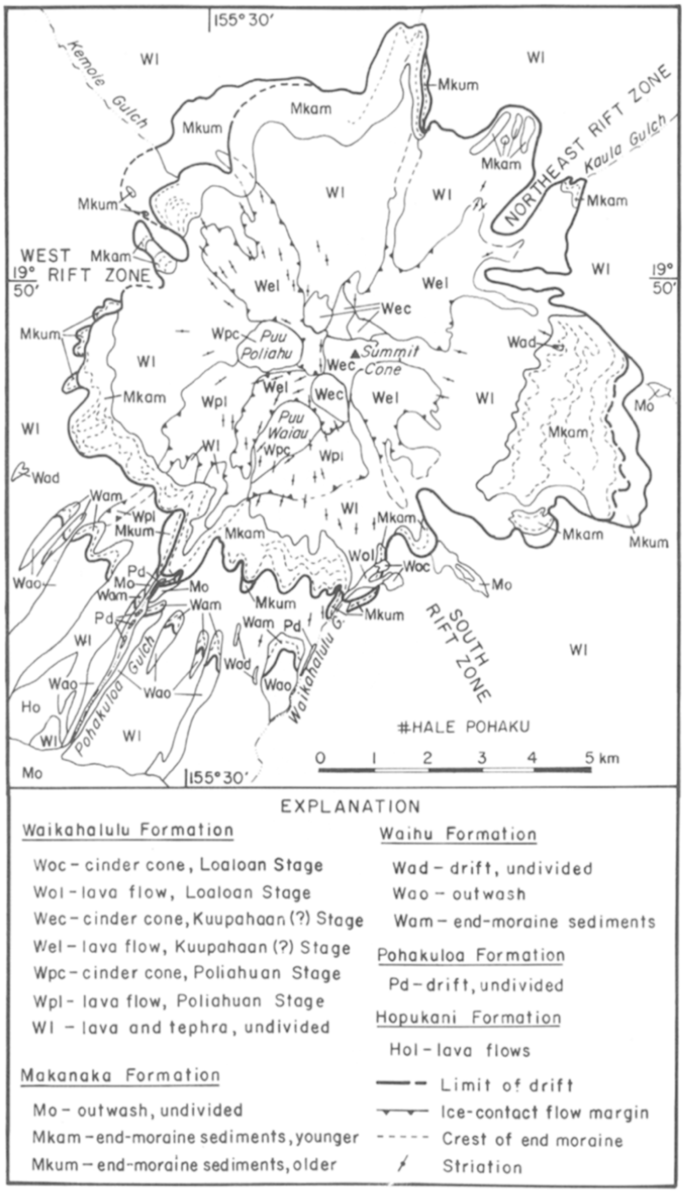


Figure 42: Glacial geological map of upper slopes of Mauna Kea, from [3].

Porter 2005 also considered reconstructions of these ice caps and their equilibrium line altitudes (ELA) [2]. See Fig. 3.

- Makanaka ice cap at last glacial maximum (LGM): Reconstructed based on profiles of glacier using moraines, the height of overridden cinder cones, and the upper limit of glacial erratics on the cinder cones. The area of the glacier was ~70 km^2, the average thickness was ~70 m (up to ~100 m). The estimated ELA, including a correction for island subsidence due to the load of erupted lava, was 3785 m.
- Waihu ice cap: Full reconstruction not possible because ice limit is only known for the southwest sector and there are no data that allow for a thickness estimate up-glacier from the end moraines. However, based on just the SW part and an assumption of a steady state profile similar to Makanaka: ELA (corrected for subsidence) was 3680 m.
- Pohakuloa ice cap: not enough information to be reconstructed, though the limit on SW slope of volcano is close to that of the Waihu ice cap.

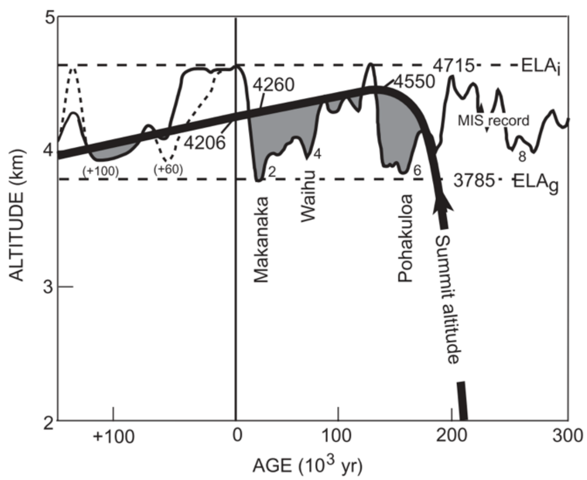


Figure 43: Summit-altitude curve for Mauna Kea (showing increase and decrease in altitude due to volcanic activity and subsidence) along with standard marine oxygen isotope curve used a proxy for snowline variations, scaled based on ELA at present interglacial and at LGM. Shaded areas represent times when the summit rose above the snowline, corresponding to glacial formations observed. From [2].

Chronology of Mauna Kea Glaciation

Porter 2005 summarizes the glacial chronology [2] (See Fig. 4), and additional data points are added by Anslow et al 2010 [1], giving a more complex picture of the deglaciation of the Makanaka ice cap.

- Pohakuloa: large error; likely older than 100 to 150 ka, but younger than 150 to 200 ka.
- Waihu: younger than Pohakuloa, dated (based on overlying and underlying volcanics) to be most likely ~100 ka to 150 ka, but possibly as young as ~70 ka.
- Makanaka: Anslow et al 2010 [1] derived new cosmogenic ^{3}He ages on glacial boulders and bedrock. Their ages are based on a time dependent production rate scaling scheme that incorporates the impact of changes in the magnetic field on the cosmic ray flux (more pronounced at high altitude tropical sites), the inclusion of boulder geometry corrections, and topographic shielding. Using this scaling for their own measurements and measurements from previous work, their results are generally consistent with previous measurements, within errors.
    - Age of initial deglaciation, using ages of two moraines near the mapped extent of the LGM + recalculated ages from previous measurements: 20.5 ka.
    - Age of final deglaciation, using another moraine (in Waikahalulu Gulch): 14.6 ka.
    - Ice cap fluctuation between LGM initial and final deglaciation: this was inferred based on the age (18.6 ka) of bedrock surfaces upslope from the Waikahalulu Gulch moraine. The ~4 kyr of prior exposure suggests a fluctuation in the ice cap margin following initial deglaciation: the ice retreated from the LGM position to upslope of the dated bedrock surface, with a readvance at ~16 ka, followed by the final deglaciation at 14.6 ka.
    - Measurements from another moraine and flood deposit suggest that at ~12 ka, one of the moraines was breached by a lake dammed behind it. This indicates a wetter climate at that time than present.

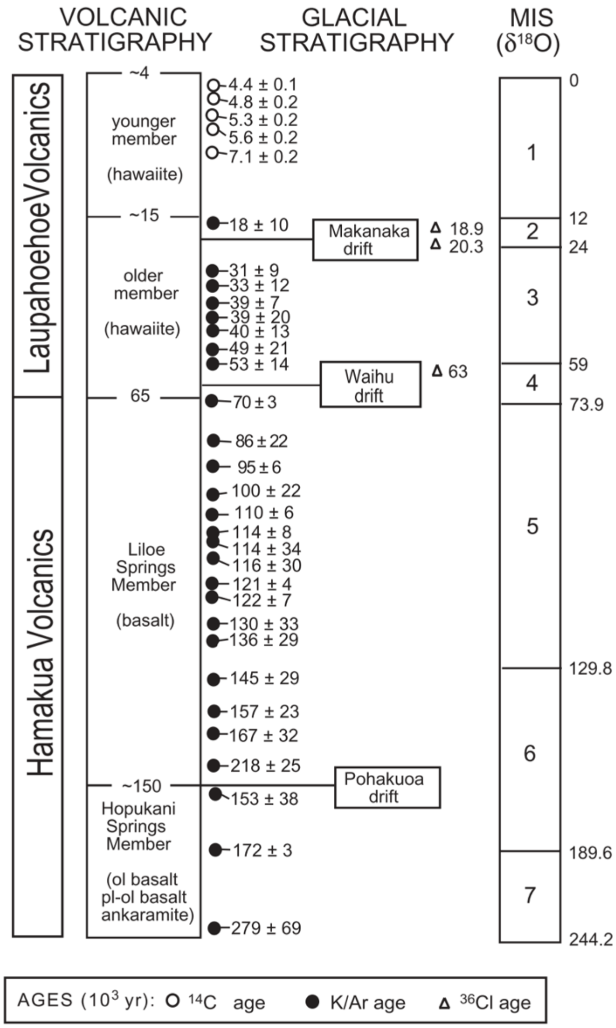


Figure 44: Volcanic and glacial stratigraphy and chronology of Mauna Kea. From [2].

Paleoclimate Interpretation

Anslow et al 2010 also used an ice dynamics model to find paleoclimate conditions that best fit the observations [1]. They used a cost function based on the location of the moraine crest at LGM to find what model most closely matched the ice cap extent. They consider 4.5°C cooling at LGM relative to present and find that the best fit is with precipitation three times higher than present. They also find that the timing of readvance and subsequent rapid deglaciation may correspond to particular changes in circulation and the onset of a warm interval, respectively.

Planetary Connection: Tropical Mountain Glaciers on Mars

The Tharsis Montes (volcanoes) on Mars have Amazonian-aged fan-shaped deposits on their northwestern flanks that have been interpreted as cold-based glacier deposits [4, 5].

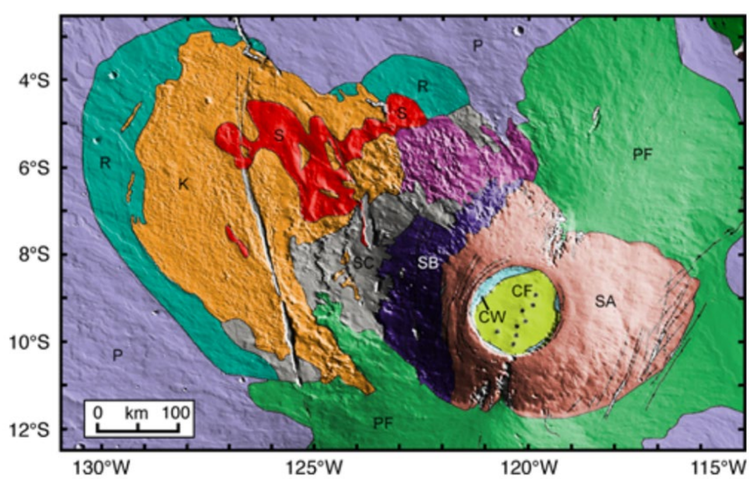


Figure 45: Geologic map of Arsia Mons fan shaped deposit. From Head and Marchant 2003.

Shean et al 2005, describing Pavonis Mons [4], as well as Head and Marchant 2003, describing Arsia Mons [5], describe similar characteristic facies interpreted as glacial in origin, based in part on similarities to terrestrial analogues in the Dry Valleys of Antarctica.

- ridged: multiple arcuate and parallel ridges around the margins of the deposits. Interpreted as drop moraines formed around the margins of a retreating cold based glacier.
- knobby: hills/hummocks/knobs. Interpreted as sublimation till derived from downwasting of cold based ice.
- smooth: convex lobate features, elongated downslope, that superpose all other units within the deposits. Interpreted as extant debris covered glacial ice.

Modeling has shown that these deposits may be formed at high obliquity, when polar ice sublimation is enhanced [6, 7].

References

[1] Anslow, F. S. et al. (2010) *EPSL, 297*, 234-248. [2] Porter, S. C. (2005) *Quaternary International, 138-139,* 118-128. [3] Porter, S. C. (1986) *Quaternary Sci. Rev., 5,* 181-182. [4] Shean, D. (2005) *JGR, 110*, E05001. [5] Head, J. W. & Marchant, D. R. (2003) *Geology, 31*, 641-644. [6] Forget, F. et al. (2006) *Science, 311,* 368-371. [7] Fastook et al. (2008) *Icarus, 198,* 305-317.

Astronomy, Telescopes, and Related Cultural Issues
Arin Avsar

- The history of astronomy in Hawaii far outdated the building of giant telescopes on Mauna Kea and surrounding peaks
    - Early Polynesians used the stars to navigate (wayfinding) through large swaths of the Pacific, without instruments of any kind.
    - After first contact with Europeans in 1778, the Polynesian style of wayfinding was largely replaced by European forms of navigation, using charts, spy glasses, clocks, etc
    - For the last 50 years, there has been a movement to bring back Polynesian astronomy/wayfinding. This movement was spearheaded by Nainoa Thompson.

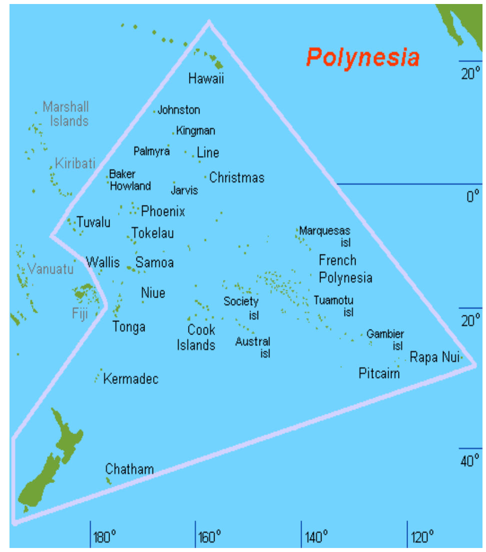


Figure 1 - Map of Polynesia

<u>Modern Astronomy on the Hawaiian Islands</u>

- Observatories on Mauna Kea
    - There are currently 11 operating telescopes on Mauna Kea, with 1 (TMT) planned for construction
    - Some Notable Observatories: W.M. Keck Observatory, Subaru Observatory, Gemini Observatory (North)
- Why put telescopes on Mauna Kea?
    - The geography, climate, and location of Mauna Kea makes it one of the most ideal locations for ground-based astronomy in the Northern hemisphere
        - The flat mountain top at 13,000 ft makes the construction of multiple large telescopes at the peak easy compared to other mountains.
        - The gentle winds at the peak also provides for good seeing, while the low humidity allows for less instrument shutdowns and telescope time cancellation and observing at longer wavelengths

Figure 2 - View of the Mauna Kea Observatories from the peak.

Importance of Mauna Kea to Hawaiian Culture

- In Hawaiian culture, Mauna Kea is considered to be the altar of Wākea, the Sky/Celestial Father. He is wed to Papahānaumoku, the Earth Mother.
    - Due to their marriage, Mauna Kea is considered to be the *piko* (umbilical cord) that connects the Earth to the Cosmos.
    - Being Wākea's altar, it is considered to be the guardian of the graves of Hawaiian chiefs, who are said to be the descendants of Wākea and Papahānaumoku.
    - Additionally, in Hawaiian folklore, the two are considered to be the creators of the islands of Hawaii, Maui, and Kauai.
    - For these reasons, desecration of the mountain through the construction of telescopes is considered deeply offensive to Hawaiian culture and people.

Construction of the TMT and Ensuing Protests

- The Thirty Meter Telescope (TMT), if completed on Mauna Kea, will be the largest telescope in the world.
    - Construction of the TMT began in 2014 and was immediately followed by protests, including picketing and blocking roads leading to the summit
    - The protests were successful in stalling the construction of the TMT and receiving concessions from the government of Hawaii.
        - Then Gov. David Ige demanded that the University of Hawaii must: decommission 4 existing telescopes by the time the TMT is operational, TMT must be the last telescope built on Mauna Kea, and must return all unused land on Mauna Kea to the State of Hawaii by 2033.
    - The concessions were not enough and protests continued. The Supreme Court of Hawaii then stepped in, invalidating the land permits for TMT and stopping construction.
        - The permits were then reinstated by the court in 2018, sparking protests in 2019 and stopping construction. **It has not since restarted**

Figure 3 - Left: Concept Image of the TMT on Mauna Kea. Right: Protestors blocking the roads leading to the peak of Mauna Kea in 2019

Other Locations For TMT

- Mauna Kea is not the only location in the Northern hemisphere suitable for astronomical observations and the TMT
- La Palma, Canary Islands, Spain
  - **TMT already has a back-up lease secured on the Canary Islands to build the TMT, if need be.**
  - Located at an elevation of ~8,000 ft, the Canary Islands are home to over a dozen telescopes on its peaks.
  - Due to its peak being 5,000 feet lower than Mauna Kea, many astronomers and those on the TMT team still want to push for Mauna Kea, since TMT will operate in the infrared
  - The Canary Islands would be a much less controversial place to build the TMT, with no sacred land that will be desecrated to build the telescope.

The Role of Gerard Kuiper and LPL on the Mauna Kea Observatories

- Gerard Kuiper is widely credited with popularizing Mauna Kea and discovering the capabilities for modern astronomical instruments to be placed on the peak while he was the director of LPL in 1963.
- Kuiper shifted attention from Haleakala (10,000 ft peak located on Maui) to Mauna Kea for its higher elevation, less cloud cover, and less precipitation.
- Shortly after, the first telescope (UH88), a 2.4 meter reflector, was built on the summit of Mauna Kea

Astronomy and Indigenous Rights

- The protests in Mauna Kea are not an isolated incident, especially in the US.
  - Mount Graham International Observatories, Arizona
    - Home to the Western Apache, the peak is called “The Southwest Home”, it is very sacred for being home to the Apache mountain spirits.

        - The Large Binocular Telescope (LBT), one of the largest telescopes in the world and operated by Steward Observatory, is located on the peak.
        - The Apache people must now obtain permits from the state in order to conduct ceremonies and have been arrested for not doing so.
    - Haleakalā, Maui, Hawaii
        - Home to the Advanced Technology Solar Telescope. Protests, similar to those on the Big Island, erupted in 2015.
        - The protests were ultimately unsuccessful, with the telescope seeing first light in 2019

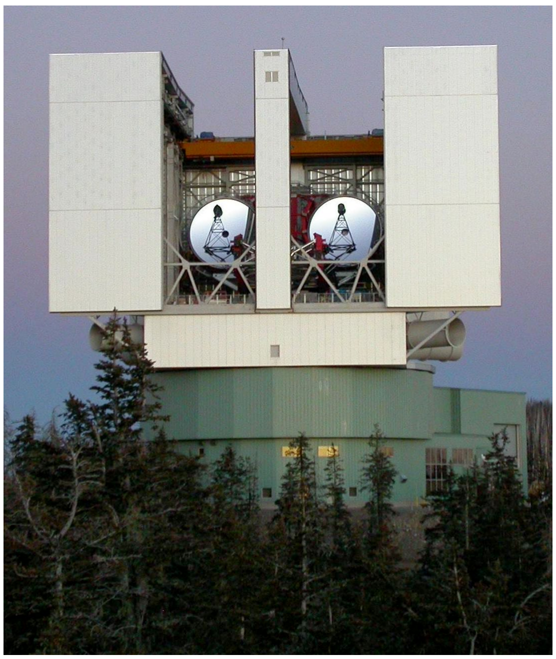


Figure 4 - Left: Large Binocular Telescope located on Mount Graham. Right: Mount Graham Sacred Run. This event is put on by the Western Apache Tribe to bring awareness of the desecration of Mount Graham by American educational institutions and the Vatican.

References

1. https://en.wikipedia.org/wiki/Polynesia (Image, Accessed: 02/20/2023)
2. https://about.ifa.hawaii.edu/origins-of-astronomy-in-hawaii/&sa=D&source=docs&ust=1676922901194644&usg=AOvVaw0IchJY6UrPHszOxzrmutno (Accessed: 02/20/2023)
3. Ciotti et al. (2011), Hawaiian Journal of History, Volume 45, 2011
4. https://www.npr.org/2022/07/31/1114314076/hawaii-mauna-kea-telescope-space-observatory#:~:text=The%20mountain%27s%20flat%20shape%2C%20gentle,of%20Hawaii%27s%20Institute%20for%20Astronomy (Accessed: 02/20/2023)
5. https://www.tmt.org/page/mission-vision (Accessed: 02/20/2023)
6. https://www.nytimes.com/2019/07/22/us/hawaii-telescope-protest.html (Accessed: 02/20/2023)
7. https://www.azcentral.com/in-depth/news/local/arizona/2021/08/20/mount-graham-sacred-space-apaches-stolen-defiled/7903881002/ (Accessed: 02/22/2023)
8. https://ictnews.org/the-press-pool/31st-annual-mount-graham-sacred-run-begins-as-vatican-continues-decades-long-occupation-of-apache-holy-land (Accessed: 02/22/2023)

Dingshan Deng

The Climate and Atmosphere of Hawaiian Island

The Climate in the Hawaiian Islands

The weather in Hawaiian Islands is generally considered pretty good and pleasant. The temperature in Hawaiian Islands tends to range between 75-85 °F (24-30 °C) throughout the year. There are only two seasons: Summer (*kau*) from May to October and Winter (*ho'oilo*) from November to April. The average daytime summer temperature is 85 °F (29 °C) while the average daytime winter temperature is 78 °F (26 °C). The nighttime temperature is about 10 °F lower than that of daytime (Figure 1).

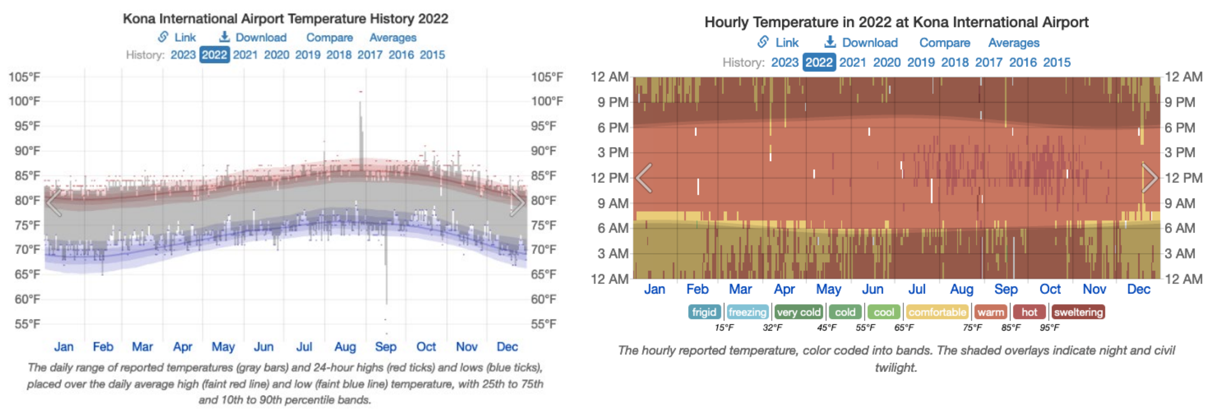


Figure 46: Weather history at Kona International Airport [1]

The consistency of the Hawaii weather benefits from a few factors.

- First, Hawaiian Islands locates in the **middle of the Pacific Ocean** means that it is often surrounded by warm ocean currents, which help to maintain the temperature of the ocean water around, thus reduce the temperature variations.
- Secondly, the islands also **locate in the subtropical high-pressure zone**, which helps to prevent the formation of storms and other extreme weather events.
- Thirdly, the **trade winds (Figure 2)** are easterly winds consistently blow from the northeast, helping to moderate the temperatures and humidity levels.

The trade winds also help to keep the air quality in Hawaii clean and fresh even on the big island where there are active volcanoes. The consistent winds help to blow away pollutants and keep the air circulating. The winds disperse the volcanic gases and prevent them from building up in one place.

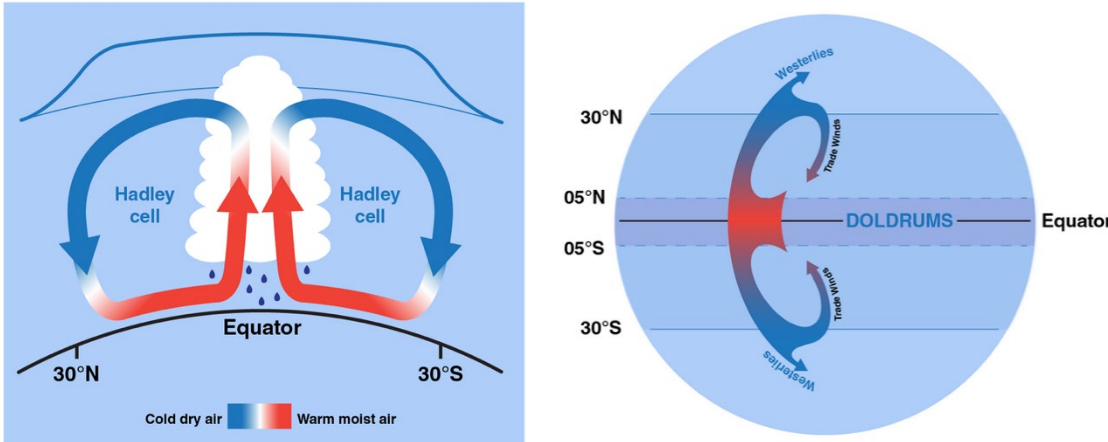
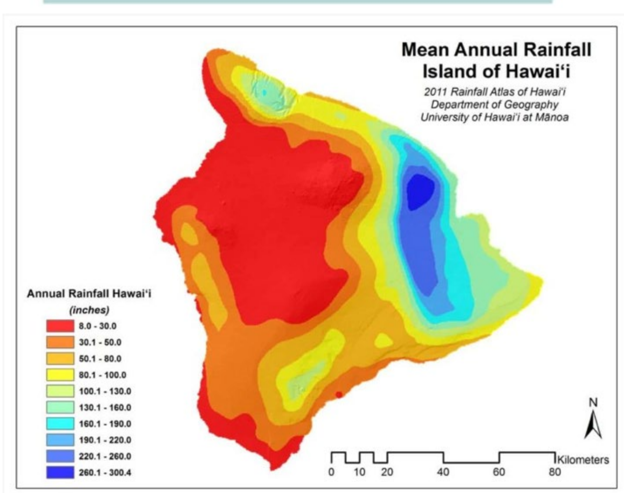


Figure 2: The air eventually cools and sinks a bit further north in the tropics. This phenomenon is called the Hadley cell. Right: Earth's rotation causes the trade winds to curve toward the west in the Northern Hemisphere and the east in the Southern Hemisphere. The area of almost no wind at the equator is called the Doldrums. (NASA/JPL-Caltech [2]).

The trade winds also help create different microclimates on the islands: The islands have an incredible collection of diverse micro-environments with quite unique climate (10 out of 14 world's climate zones). As the trade winds are easterly winds consistently blows from the northeast, **there are clear difference between the windward sides and the leeward sides**. This difference helps create the lush rainforest on the windward sides while the leeward sides are more arid and drier (Figure 3).

Figure 3: Top: the trade wind at Hawaii Island [3]. Left: the mean annual rainfall on Hawaii Island at the year of 2011 [cite]. Right: Hawaii Island climate zones: Humid Tropical Climates in green, Arid and Semi-arid Climates in red, and the ice or alpine climate in black [4].



The Atmosphere over the Islands and the Volcanoes

One of the most notable specialties of the atmosphere over Hawaiian Islands is the presence of volcanic gases produced by the active volcanoes on the islands. These gases, which include water vapor (H_2O), sulfur dioxide (SO_2), carbon dioxide (CO_2) and small amounts of other gases, such as hydrogen sulfide (H_2S), can have an impact on the atmosphere of Hawaii, especially when there is an eruption (such as the one happened on Nov 28, 2022, see Figure 4).

However, the overall impact of the volcanic gases on the atmosphere of Hawaii is relatively small. This is because the volcanic activity is typically localized and the trade winds help to disperse the gases over a wide area, preventing them from building up in one place. Additionally, the volcanoes in Hawaii tend to produce relatively low levels of harmful gases, compared to other volcanoes around the world. *Further discussions see volcanic section in the field guide* :-)

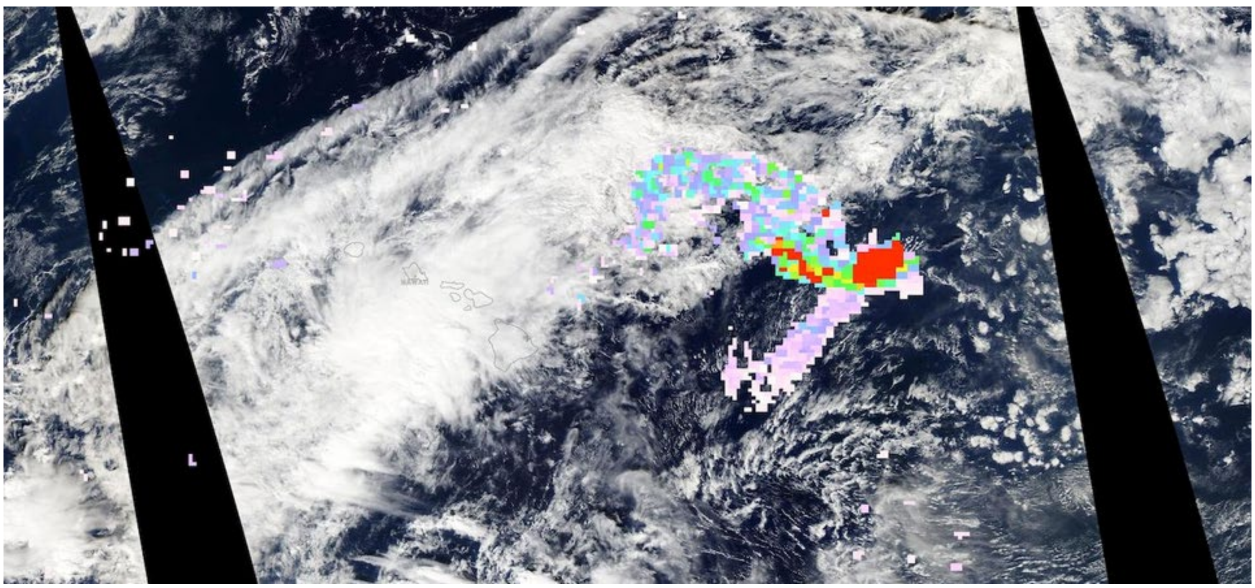


Figure 4: This true color corrected reflectance image is overlaid with the Prata Sulfur Dioxide (SO_2) Index (Day) layer showing the Sulfur Dioxide plume from the Mauna Loa Volcano eruption on November 28, 2022. The corrected reflectance image was acquired by the Moderate Resolution Imaging Spectroradiometer (MODIS), and the sulfur dioxide layer is from the Atmospheric Infrared Sounder (AIRS) instrument; both instruments are aboard the Aqua satellite [5].

Detect Volcanism through Exoplanet Atmosphere

The volcanic activities on exoplanets can produce gases and aerosols that could be detected using variety of techniques: **Now the most realistic method is spectroscopy observations by large telescopes** such as JWST, which provides information about the composition of the atmosphere to trace the presence of volcanic gases. However, not all volcanoes produce the same types or amounts of gases and aerosols, so some volcanic activity may be difficult to detect.

Majority of volcanic gas released on Earth is through non-explosively processes near the surface, such as the continuous non-explosive eruption of Kilauea. But for exoplanet observations, the explosive volcanos that have the potential to inject material into a planets' stratosphere will have the chance to be detected. For example, the eruption of Mount Pinatubo in the Philippines in 1991 June is the one we could observe by a telescope with diameter > 6.5 m, the size of JWST within 10 parsecs (the closest sun-like stars). 17 ± 2 Mt of SO_2 were injected into the stratosphere over 4 days [6], and left H_2SO_4 aerosols reside in the stratosphere for 1-3 years [7]. Considering the frequency of having a large eruption with Volcanic Explosivity Index (VEI) > 6 mag is 3% per year [8], and assuming all Earth like exoplanets have Earth like activity, **the probability of observing a Pinatubo class explosive eruption is about 1% if an Earth-like planet is observed for 1 year** (see the Table 2 in [7], attached below). Even larger events will be rarer to happen but requires smaller telescope to observe. Therefore, there is a chance to capture the volcanic eruptions on exoplanets in the future observations.

Table 2
Frequency of Explosive Volcanic Events

Name	El Chichón	Pinatubo	Krakatau	Tambora	Taupo	Toba/Yellowstone
$\sim \times$ baseline	0.5×	1×	2×	10×	100×	500/1000×
Year	1982	1991	1883	1815	23500 y.a.	73000/6e5 y.a.
VEI/Mag	5	6	7	7	8.1[a]	8.8[a]/8.7–8.9[a]
Stratospheric SO_2 (Mt)	7–8	17	30–50	~200 est.	~2000 est.	~1e4/2e4 est.
Frequency estimate, f (yr^{-1})	0.05–0.2[b]	0.03	0.002	0.001	1e-4–1e-6[b]	1e-6–1e-8[b]
Planet-years to achieve $P = 1\%$	1	1	6	11	1e2–1e4	1e5–1e6
10%	1–3	4	53	106	1e3–1e5	1e6–1e7
90%	11–45	76	1151	2302	2e4–2e6	2e7–2e8
Signal duration, Nd (days)	n/a	2	30	170	170	170
Observations to achieve $P = 1\%$	n/a	183	73	24	2e2–2e4	2e5–2e6
10%	n/a	730	645	228	2e3–2e5	2e6–2e7
90%	n/a	13870	14003	4943	5e5–5e6	5e7–5e8

Notes. Frequency comparison of various magnitude volcanic events to the 1991 Pinatubo baseline adopted in this paper. Probabilities assume Earth-like behavior and may be higher for younger or more tidally active planets. SO_2 to the stratosphere for events larger than Krakatau are highly uncertain. For Toba and Yellowstone, magnitudes are well known but frequencies are highly uncertain and span the same effective range for both events. Note the smaller number of observations needed for a Tambora-class 10× event due to a detectable signal surviving longer in the atmosphere. Observations to achieve P assume minimum detectability is 1× baseline.
[a] Magnitudes directly measured from the mass of ejecta deposits.
[b] Frequencies extrapolated from the scaling laws and historical evidence presented in Mason et al. (2004).

References:

[1] 2022 Weather History at Kona International Airport: (02/10/2023) https://weatherspark.com/h/y/145043/2022/Historical-Weather-during-2022-at-Kona-International-Airport-Hawaii-United-States#Figures-Temperature. [2] What Are Trade Winds? (02/10/2023): https://scijinks.gov/trade-winds/ [3] Volcanic Air Pollution—A Hazard in Hawai`i. (02/10/2023): https://pubs.usgs.gov/fs/fs169-97/ [4] Giambelluca et al. (2014) Evapotranspiration of Hawai‘i. Final report submitted to the US Army Corps of Engineers—Honolulu District, and the Commission on Water Resource Management, State of Hawai ‘i. [5] Sulfur Dioxide Plume from the Mauna Loa Volcano Eruption, Hawaii. (02/10/2023) https://www.earthdata.nasa.gov/worldview/worldview-image-archive/mauna-loa-eruption-so2-28-nov-2022 [6] Gerlach et al. (1996) FIRE and MUD: Eruptions and Lahars of Mount Pinatubo, Philippines, ed. C. G. Newhall & R. S. Punongbayan (Seattle, WA: Univ. Washington Press), 400 [7] Mason et al. (2004). The size and frequency of the largest explosive eruptions on Earth. Bulletin of Volcanology, 66(8), pp.735-748. [8] Kaltenegger et al. (2010). Detecting volcanism on extrasolar planets. The Astronomical Journal, 140(5), p.1370.

Naman Bajaj

Dr. Gerard Kuiper and his expedition at Mauna Kea!

Based at the University of Arizona, the Dutch–American planetologist, Dr. Gerard Kuiper, was interested in collecting the low-energy, infrared light that planets emit. Most infrared light is absorbed by the water droplets present in the lower layers of the atmosphere, therefore infrared observation is best performed at a high altitude. For some years, Kuiper had been exploring peaks in California, New Mexico and Chile to determine which would be best suited for such an observatory.

Hawai‘i was not unknown to him. Kuiper was used to working with Alika Herring, an astronomer famous for the quality of the mirrors he crafted, who held Native Hawaiian ancestry. At the beginning of the 1960s, Kuiper and Herring had worked together for the US Department of Defence to test the observational quality atop Haleakalā. More generally, the Hawaiian archipelago was of particular interest to Kuiper because of its relatively low latitude (around 20° north), which made much of the heavens accessible to observation. Later, they received an invitation from Hawaii Chamber of Commerce to consider Mauna Kea as an observing site.

In January 1964, Kuiper came for a five-day trip to Hawai‘i Island. He discovered that Akiyama’s offer had solid backing from the state government, and this obviously mattered a lot to him. One meeting with Governor John A. Burns was enough to secure the construction of a graded and oiled ‘Jeep track’, which would almost reach the summit of Mauna Kea. In April 1964, a Hilo company built a ‘very crude road’ [1], but a road, nevertheless, opening opportunities for future development. Kuiper easily won a National Aeronautics and Space Administration (NASA) grant to observe the Moon (in preparation for the Apollo missions).

This gave him a pretext to test Mauna Kea’s quality. Herring brought over from Haleakalā the mirror which he considered his best: ‘Of excellent quality, the use of these optics not only made it possible to assign any image deficiencies entirely to the state of seeing but permitted an exact comparison with the results previously obtained at Haleakala’ [2]. It was decided that the mirror would be housed in a dome at Mauna Kea’s summit. On 20 July 1964, the new telescope was dedicated in the presence of the governor. Though tests had just started, Kuiper did not contain his enthusiasm:

> “I do not recall an occasion in my professional career that had the excitement and the promise of this moment. Here we stand on the highest mountain in the Pacific in the clearest and purest air that astronomers have found for making observations in support of the greatest of all human ventures: travel to the moon – hopefully by 1970 – and later possibly to Mars. [...] Hawaii is probably the best laboratory from which to study the Earth: its forces, its growth, its history, and the chemistry and history of its atmosphere. This mountaintop is probably the best site in the world – I repeat – in the world, from which to study the Moon, the Planets, the Stars. [...] Mr. Governor, as a scientist who has worked in Europe, Java, the Mainland, Chile, and on Haleakala, I want to tell you that, to use the words of Mr. Alika Herring, our first observer, ‘This mountain is it’. It is a jewel! This is the place where the most advanced and powerful observations from this Earth can be made.” [3]

Herring’s final report on Mauna Kea tests, published in March 1966, clearly demonstrated its superiority: ‘The general stability of both the seeing and meteorological conditions is insured by the unusual elevation of the mountain, which places the observatory well above the normal cloud level, the source of so much trouble at Haleakala’. Herring also found the summit to be wide enough to support many observatories, should the need be felt: ‘the mountain top will not only support a large complex of scientific installations, but it will be possible to place these so that no telescope will directly interfere with another’, he wrote, referring to the atmospheric turbulence caused by the massive buildings themselves. [4]

A month after Kuiper’s enthusiastic speech, the Australian physicist John Jefferies landed in Honolulu with his wife and three children. A specialist of solar physics, he was relocating from Boulder, Colorado to the University of Hawai’i (UH) to supervise the opening of the new solar observatory on Maui’s Haleakalā. Jefferies later recalled that Kuiper’s grandiose dreams for Mauna Kea ‘had nothing to do with my coming here, nothing at all. I didn’t even know about it’ [5]. Another mountain was his calling.

Yet from the moment Jefferies set foot on Oʻahu, it was impossible for him to ignore the hype around Mauna Kea. A few weeks after his arrival, Kuiper arranged an informal meeting with him. The Arizona-based astronomer had his views set on a second NASA grant, this time to build a full-size telescope, and the funders had made it clear they were more likely to fund the project if UH was on board. At first, Jefferies had no objection to underwriting Kuiper’s application. However, after learning that Harvard University was also thinking of bidding for the same grant to build its own telescope on Mauna Kea, he changed his mind. As Jefferies explained in a later interview,

> “So the University of Hawaii was in a position of hearing from these two outside groups that they had designs on a mountain which, I suppose, could reasonably have been regarded as under Hawaii’s jurisdiction, and yet no one was talking to the University of Hawaii.” [6]

To Jefferies, the state and the UH were two sides of the same coin. Encouraged by his new colleagues, he decided he would draft an independent proposal in the name of UH. It was a gamble: strictly speaking, the university had no astronomy department to speak of, as astronomical research was conducted from the university’s Institute of Geophysics; neither did it have in-house skill for building optical telescopes, and Jefferies himself acknowledged he was a theorist rather than an observer.

Moreover, the easier choice for him would have been to focus entirely on Haleakalā, a site with a fine access road, new facilities and a mild climate, rather than on Mauna Kea with its 1930s mid-level stone cabins, shifting track, rarefied atmosphere and regular snowstorms. Nobody even knew if human beings would be able to survive, let alone work for extended periods of time, in such an environment. However, Jefferies had a distinct advantage in the competition for the NASA grant: the close relationship between the University of Hawaiʻi and the state government.

The final proposal, which UH submitted to NASA in February 1965, guaranteed that the state would contribute the 2 million dollars necessary for a blacktopped summit access road, a power line, modern mid-altitude accommodation and a few scientific staff positions. Strategically, the proposal suggested two possible sites for a 2.14 metre (84-inch) telescope, Mauna Kea and Haleakalā, while postponing the final decision (Jefferies later acknowledged that it would have been politically tricky for him to choose a site at this stage, because of the rivalry between Maui and Hawai‘i Island businessmen; better let NASA choose).

The ground-breaking ceremony coincided with the autumnal equinox of 1967 . A journalist noticed that Mitsuo Akiyama was not at the ceremony, and asked him why: ‘I just guess I wasn't invited', the Hilo businessman said, which was certainly true considering Jefferies' constant wish to present Mauna Kea astronomy as his own creation. Akiyama suggested that Kuiper, who was not present either, was the one who deserved all the credit for the ‘discovery' of Mauna Kea: ‘he made the scientific discovery. He announced it to the world'.

References:

[1] John Jefferies, interview by Spencer Weart, 29 Jul. 1977, transcript, Niels Bohr Library & Archives, American Institute of Physics, College Park, MD USA.
[2] Alika K. Herring, ‘The Mauna Kea Site Survey', 7 Mar. 1966, 1, Mitsuo Akiyama Archival Collection.
[3] Gerard P. Kuiper, ‘Address Given at Mauna Kea Station Dedication', 20 Jul. 1964, Mitsuo Akiyama Archival Collection.
[4] Jefferies, ‘Astronomy in Hawai‘i'.
[5] Jefferies, interview by Weart.
[6] University of Hawaii, ‘Proposal to the National Aeronautics and Space Administration for the Construction of a 84-inch Telescope', Feb. 1965, Mitsuo Akiyama Archival Collection.

Common Rock Forming Minerals

Dark-Colored minerals			
Hardness	**Cleavage**	**Physical Properties**	**Name**
Hardness >5	Excellent or good	Dark gray, Blue-gray or black. May be iridescent. Cleavage in 2 planes at nearly right angles, Striations. Hardness-6	**Plagioclase Feldspar**
		Brown, gray, green or red. Cleavage in 2 planes at nearly right angles. Exsolution Lamellae. Hardness-6	**Potassium Feldspar**
		Opaque black. 2 cleavage planes at 60°and 120°. Hardness- 5.5	**Hornblende (Amphibole)**
	Poor or absent	Opaque red, gray, hexagonal prisms with striated flat ends. Hardness- 9	**Corrundum**
		Gray, brown or purple. Greasy luster. Massive or hexagonal prisms and pyramids. Transparent or translucent. Hardness- 7	**Quartz Black or brown- Smoky , Purple- Amethyst**
		Opaque red or brown. Waxy luster. Hardness- 7. Conchoidal Fracture	**Jasper**
		Opaque black. Waxy luster. Hardness- 7	**Flint**
		Transparent- translucent dark red to black. Hardness- 7	**Garnet**
Hardness < 5	Excellent or good	Colorless, purple, green, yellow, blue. Octahedral cleavage. Hardness- 4	**Flourite**
		Green. Splits along 1 excellent cleavage plane. Hardness- 2-3	**Chlorite**
		Black to dark brown. Splits along 1 excellent cleavage plane. Hardness- 2.5-3	**Biotite mica**
	Poor or absent	Opaque green, yellow or gray. Silky or greasy luster. Hardness- 2-5	**Serpentine**
		Opaque white, gray or green. Can be scratched with fingernail. Soapy feel. Hardness- 1	**Talc**
		Opaque earthy red to light brown. Hardness- 1.5-6	**Hematite**

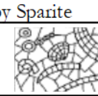
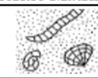
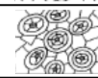
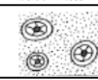
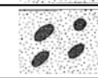
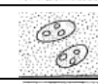
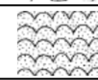
Light-colored minerals			
Hardness	**Cleavage**	**Physical Properties**	**Name**
Hardness >5	Excellent or good	White or gray, Cleavage in 2 planes at nearly right angles, Striations. Hardness-6	**Plagioclase Feldspar**
		Orange, brown, white, gray, green or pink. Cleavage in 2 planes at nearly right angles. Exsolution Lamellae. Hardness-6	**Potassium Feldspar**
		Pale brown, white or gray. Long slender prisms. Cleavage in 1 plane. Hardness- 6-7	**Sillimanite**
	Poor or absent	Opaque red, gray, white hexagonal prisms with striated flat ends. Hardness- 9	**Corrundum**
		Colorless, white, gray or other colors. Greasy luster. Massive or hexagonal prisms and pyramids. Transparent or translucent. Hardness- 7	**Quartz White-Milky, Yellow-Citrine, Pink- Rose**
		Opaque gray or white. Waxy luster. Hardness- 7. Conchoidal Fracture	**Chert**
		Colorless, white, yellow, light brown. Translucent opaque. Laminated or massive. Cryptocrystalline. Hardness- 7	**Chalcedony**
		Pale olive green. Conchoidal fracture. Transparent or translucent. Hardness- 7	**Olivine**
Hardness < 5	Excellent or good	Colorless, white, yellow, blue, green. Excellent cleavage in 3 planes. Breaks into rhombohedrons. Effervesces in HCl. Hardness- 3	**Calcite**
		Colorless, white, yellow, blue, green. Excellent cleavage in 3 planes. Breaks into rhombohedrons. Effervesces in HCl only if powdered. Hardness- 3.5-4	**Dolomite**
		White with tints of brown. Short tabular crystals or roses. Very heavy. Hardness- 3-3.5	**Barite**
		Colorless, white or gray. Massive or tabular crystals, blades or needles. Can be scratched by fingernail. Hardness- 2	**Gypsum**
		Colorless, white. Cubic crystals. Salty taste. Hardness- 2.5	**Halite**
		Colorless, purple, green, yellow, blue. Octahedral cleavage. Hardness- 4	**Flourite**
		Colorless, yellow, brown. Splits along 1 excellent cleavage plane. Hardness- 2-2.5	**Muscovite mica**
	Poor or absent	Yellow crystals or earthy masses. Hardness 1.5-2.5	**Sulfur**
		Opaque green, yellow or gray. Silky or greasy luster. Hardness- 2-5	**Sepentine**
		Opaque white, gray or green. Can be scratched with fingernail. Soapy feel. Hardness- 1	**Talc**
		Opaque earthy white to light brown. Hardness- 1-2	**Kaolinite**

Metallic			
	Streak	**Physical Properties**	**Name**
Hardness > 5	Dark Gray	Brass yellow	**Pyrite**
		Dark gray-black, attracted to magnet	**Magnetite**
	Brown	Silvery black to black tarnishes gray	**Chromite**
Harness < 5	Red-Red/Brown	Silvery gray, black, or brick red	**Hematite**
	Dark Gray	Brass yellow, tarnishes dark brown or purple	**Chalcopyrite**
		Iridescent blue, purple or copper red, tarnishes dark purple	**Bornite**
		Silvery gray, tarnishes dull gray Cleavage good to excellent	**Galena**
		Dark gray to black, can be scratched with fingernail	**Graphite**

Sedimentary Rocks: Carbonates

Folk Classification Scheme for Carbonate Rocks

Folk's classification scheme is based upon the composition (and type of allochems) within a limestone. Figures from Prothero and Schwab, 2004

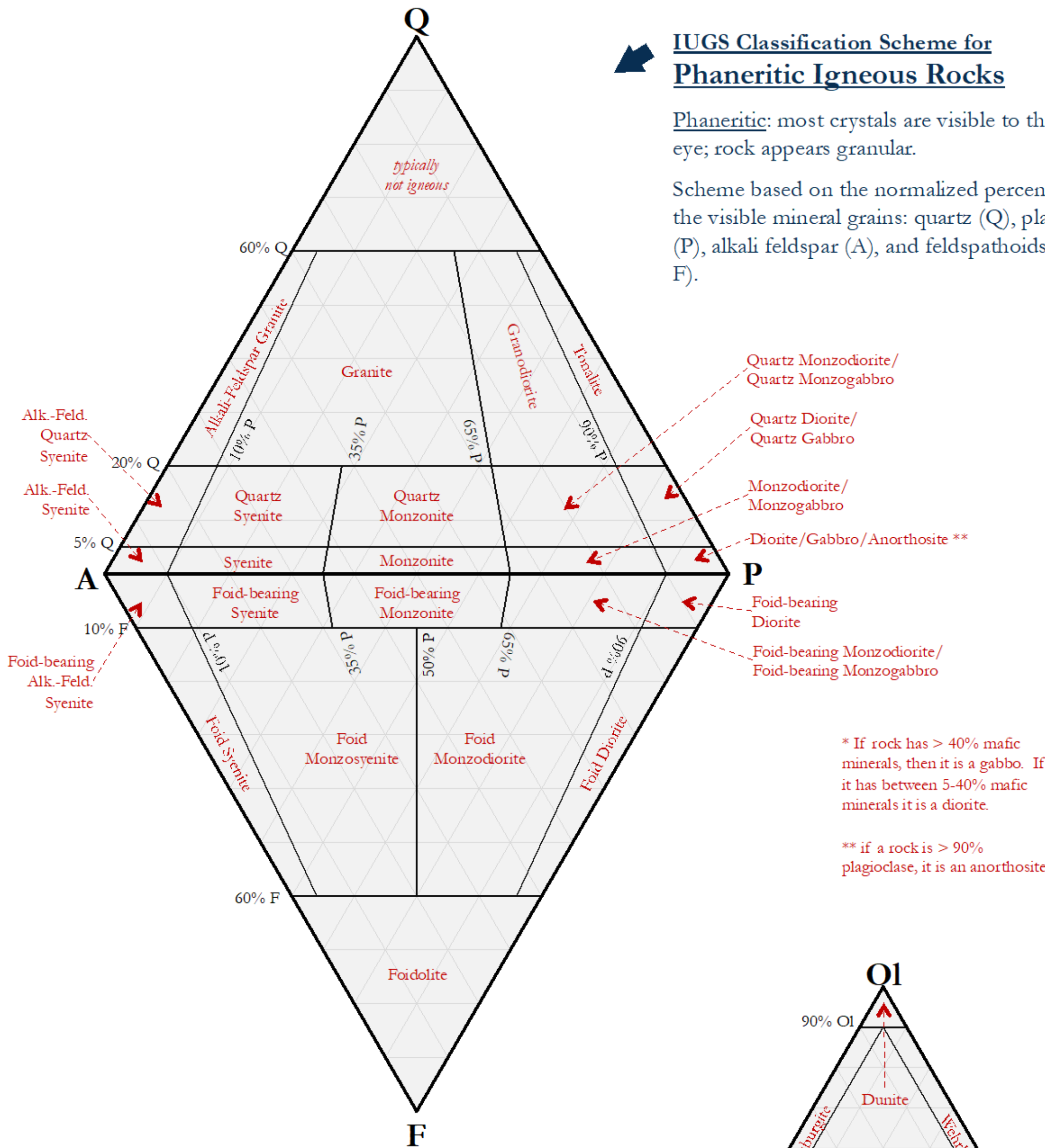
Principle Allochems in Limestone	Limestone Type: Cemented by Sparite		Limestone Type: Cemented by Micritic Matrix	
Skeletal Grains (Bioclasts)	Biosparite		Biomicrite	
Ooids	Oosparite		Oomicrite	
Peloids	Pelsparite		Pelmicrite	
Intraclasts	Intrasparite		Intramicrite	
Limestone formed in place	Biolithite		Terrestrial Limestone	

Dunham Classification Scheme for Carbonate Rocks

Dunham's classification scheme is based upon depositional textures within a limestone.

<table>
<tr><td colspan="6">Allochthonous Limestone
(original components not organically bound during deposition)</td><td colspan="3">Autochthonous Limestone
(original components organically bound during deposition; reef rocks)</td></tr>
<tr><td colspan="4">Of the allochems, less than 10% are larger than 2 mm</td><td colspan="2">Of the allochems, greater than 10% are larger than 2 mm</td><td colspan="3"></td></tr>
<tr><td colspan="3">Contains carbonate mud</td><td>No mud</td><td rowspan="3">Matrix supported</td><td rowspan="3">Grain supported</td><td rowspan="3">Organisms acted as baffles</td><td rowspan="3">Organisms are encrusting and binding</td><td rowspan="3">Organisms building a rigid framework</td></tr>
<tr><td colspan="2">Grain supported</td><td colspan="2" rowspan="2">Grain supported</td></tr>
<tr><td>Less than 10% grains</td><td>More than 10% grains</td></tr>
<tr><td>Mudstone</td><td>Wackestone</td><td>Packstone</td><td>Grainstone</td><td>Floatstone</td><td>Rudstone</td><td>Bafflestone</td><td>Bindstone</td><td>Framestone</td></tr>
</table>

Igneous Rocks



IUGS Classification Scheme for
Phaneritic Igneous Rocks

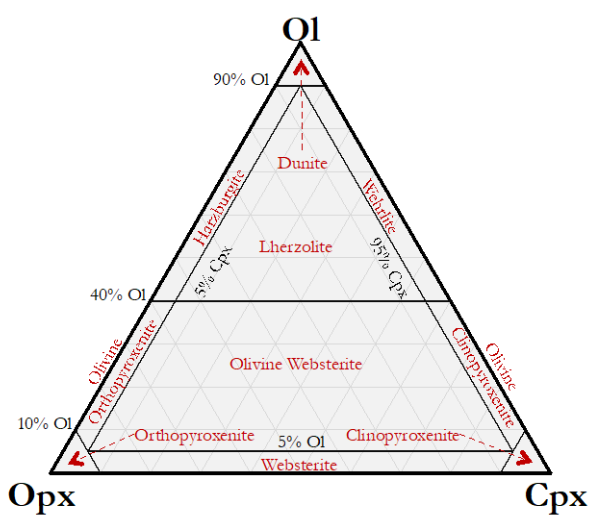
Phaneritic: most crystals are visible to the naked eye; rock appears granular.

Scheme based on the normalized percentages of the visible mineral grains: quartz (Q), plagioclase (P), alkali feldspar (A), and feldspathoids (foids, F).

IUGS Classification Scheme for
Phaneritic Ultramafic Igneous Rocks (1)

Ultramafic: more than 90% of the total minerals are mafic.

Scheme based on the normalized percentages of the visible minerals: olivine (Ol), orthopyroxene (Opx), and clinopyroxene (Cpx).

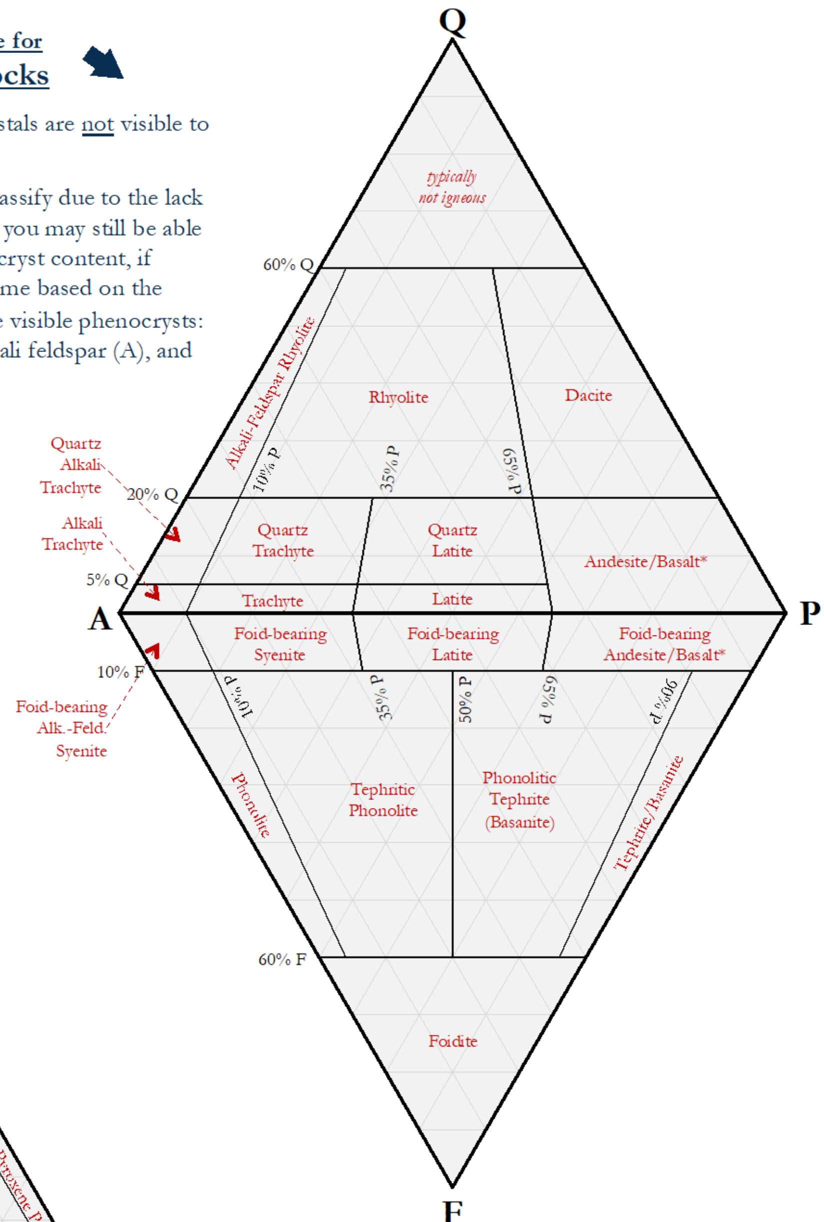


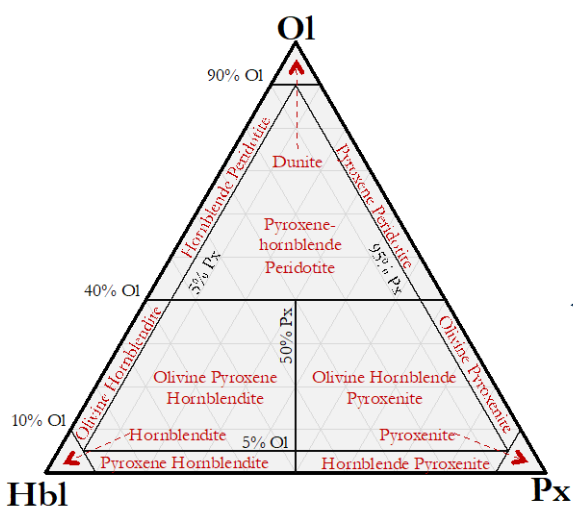
Igneous Rocks

IUGS Classification Scheme for
Aphanitic Igneous Rocks

Aphanitic: the majority of crystals are not visible to the naked eye.

Aphanetic rocks are hard to classify due to the lack of visible minerals. However, you may still be able identify them based on phenocryst content, if phenocrysts are present. Scheme based on the normalized percentages of the visible phenocrysts: quartz (Q), plagioclase (P), alkali feldspar (A), and feldspathoids (foids, F).





IUGS Classification Scheme for
Phaneritic Ultramafic Igneous Rocks (2)

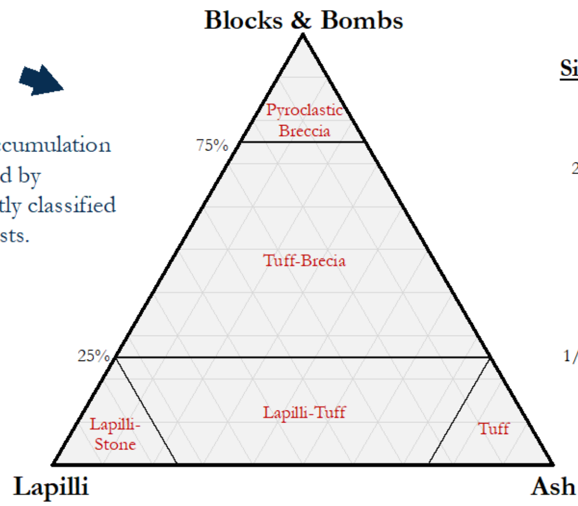
Ultramafic: more than 90% of the total minerals are mafic.

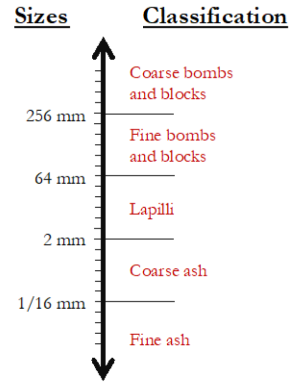
Scheme based on the normalized percentages of the visible minerals: olivine (Ol), hornblende (Hbl), and pyroxene (Px).

Igneous Rocks

Classification Scheme for Pyroclastic Igneous Rocks

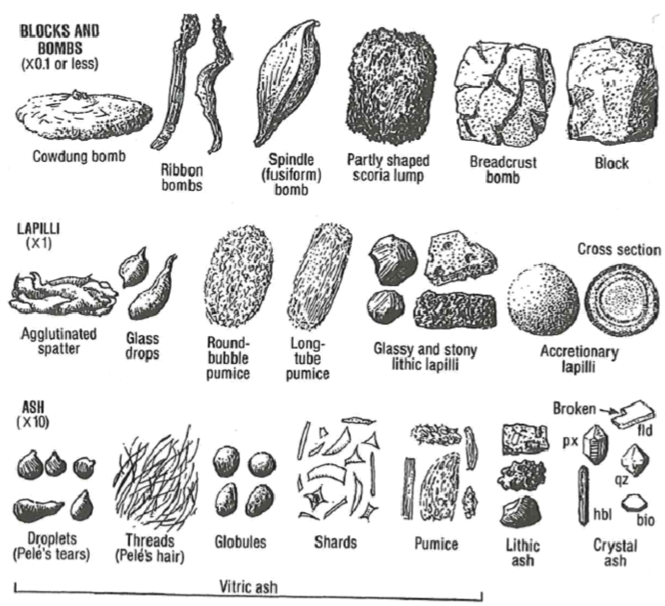
Pyroclastic rocks are formed via the accumulation of fragments of volcanic rock scattered by volcanic explosions. They are frequently classified based upon the size distribution of clasts.

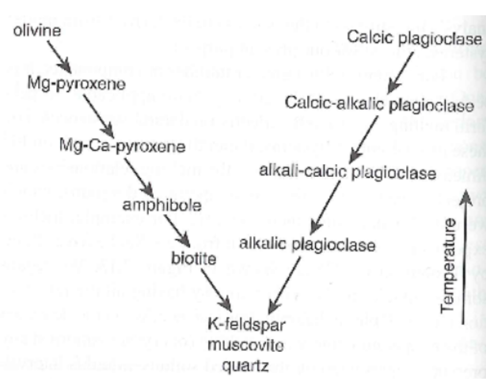




Types of Tephra (Pyroclasts)

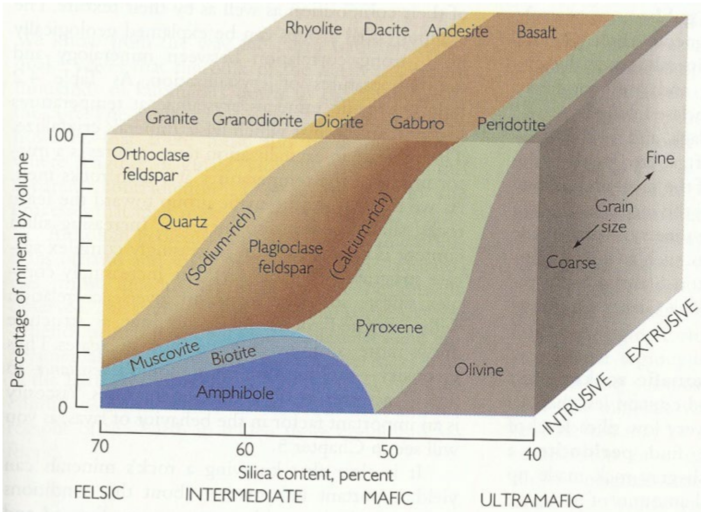
In each row, the viscosity of the lava increases to the right. From Compton, 1985.



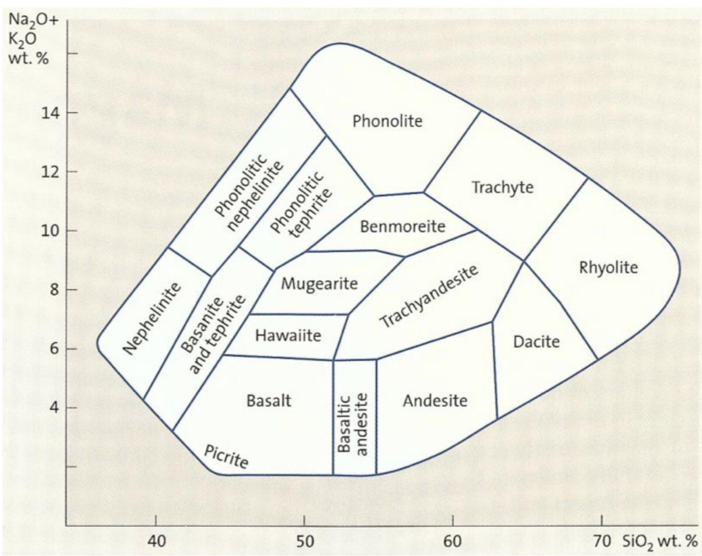


Bowen's Reaction Series

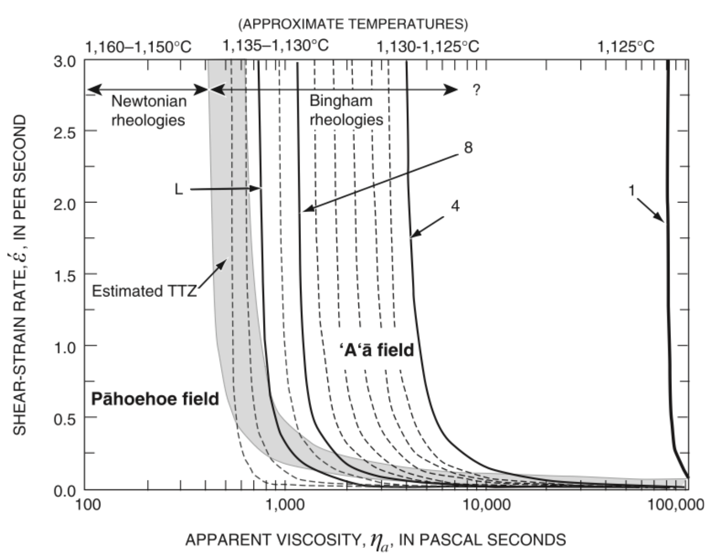
From Winter, 2010.



Mineral breakdown of igneous rocks of different silica content
(Press & Siever, 2nd edition)



Total alkali versus SiO_2 classifying extrusive volcanic rocks
(Schmincke 2004)

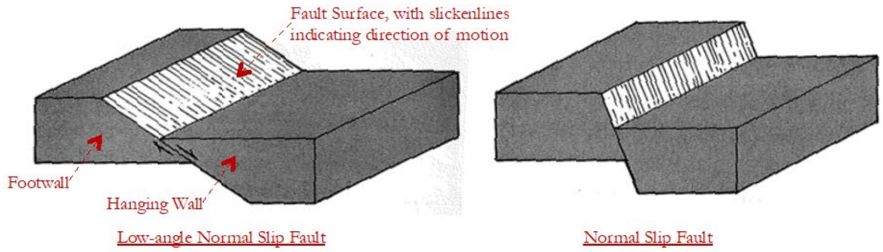


Conditions for forming Pahoehoe vs Aa flows
(Hon et al., USGS paper 1676)

Structural Geology: Normal Faults

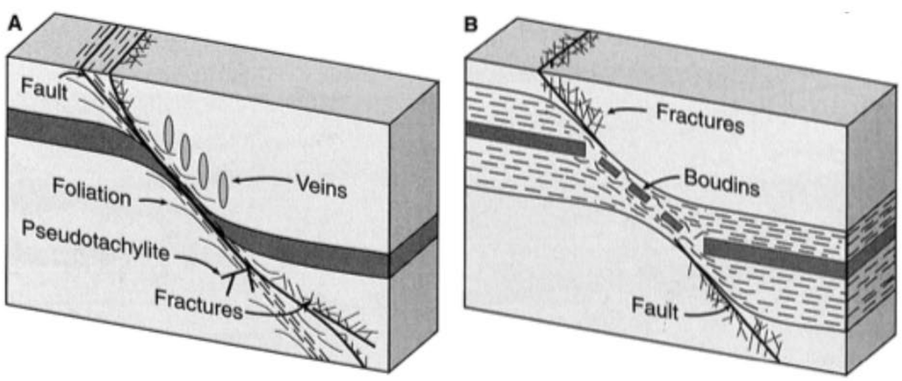
Normal Faults

In normal faults, the footwall goes up with respect to the hanging wall. Normal faults are indicative of extension. Figures from Davis & Reynolds, 1996.



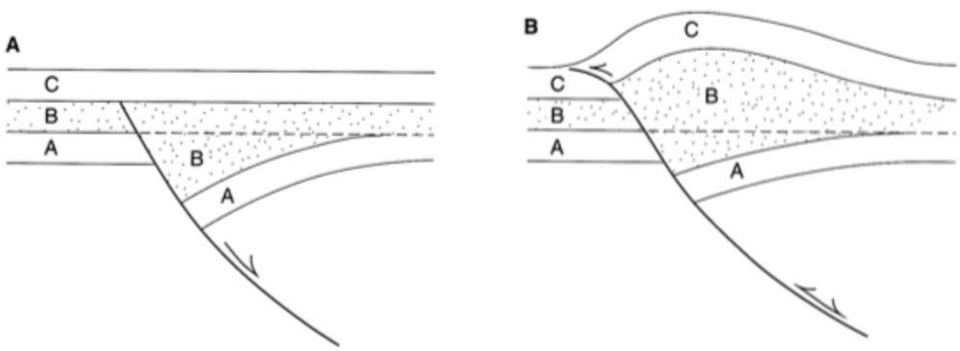
Effects of Brittle or Ductile Shear in Normal Faults

The block diagrams below illustrate the effects of changing the nature of deformation, between brittle deformation (which results in clear fault planes, fractures and fault rocks), ductile deformation (which causes deformation over a larger shear zone). Often, strata of different rheologies will behave differently, as is shown in the figure at right. The dashed layer was weak and deformed ductilely, while the middle grey layer was rigid and formed boudins. Figures from Davis & Reynolds, 1996.



Inversion Tectonics

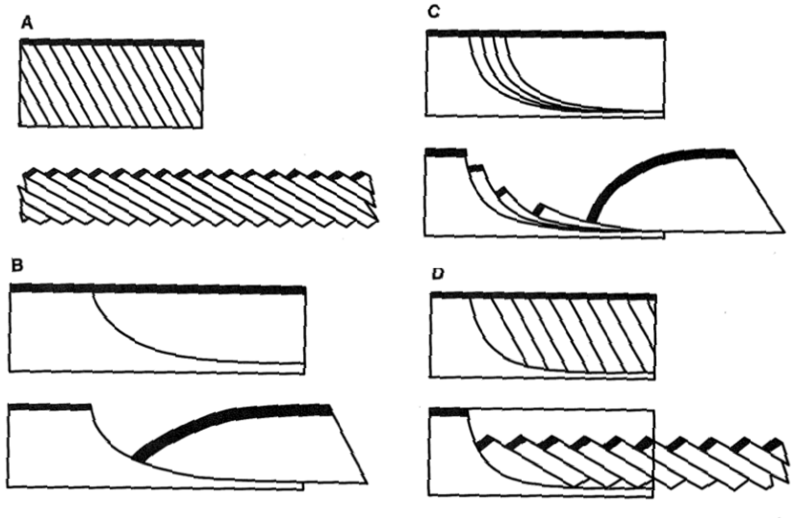
If the regional stresses change, previously inactive faults can reactivate, and change their sense of motion. In the figure at left, layer-A was formed prior to the formation of a normal fault. Layer-B and layer-C were deposited after the formation, and shut down of the fault. In the figure at the right, the fault has reactivated, though as a reverse fault. The resulting stratigraphic sequence is a combination of effects one would expect from both normal and reverse faults. Figures from Davis & Reynolds, 1996.

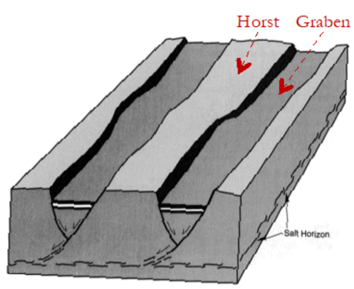


Structural Geology: Normal Faults

Normal Faults Geometries

Various normal fault geometries are possible. They all allow for lithospheric extension. (A) Domino style faulting. (B) Listric normal faulting with reverse drag. (C) Imbricate listric normal faulting. Note that listric faulting can cause extreme rotation of faulted blocks. (D) Listric normal faulting bounding a family of planar normal faults. Figures from Davis & Reynolds, 1996.



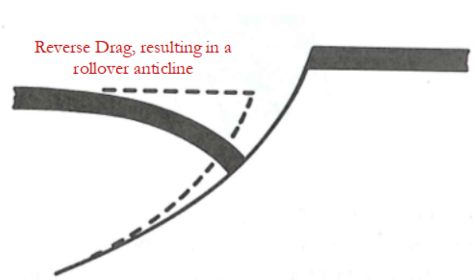


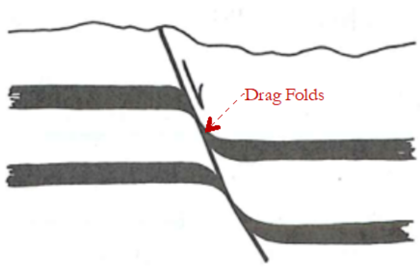
Horsts & Grabens

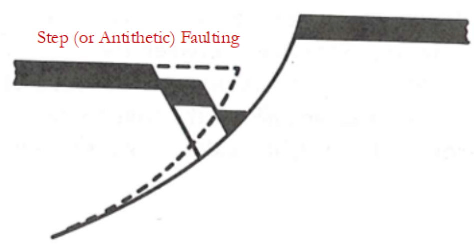
Classical formation describing fault-bounded uplifted (horsts) and down-dropped blocks (grabens). Figures from Davis & Reynolds, 1996.

Drag Folds, Reverse Drag, and Step Faulting

Faulting does not always produce clean displacement along the fault surface. Fault blocks are frequently folded or fractured, and the nature of these deformations are non-trivial. Figures from Davis & Reynolds, 1996.



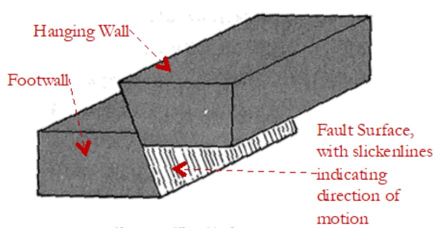




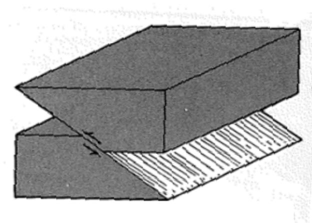
Structural Geology: Reverse & Thrust Faults

Reverse Faults

In reverse faults, the footwall goes down with respect to the hanging wall. Normal faults are indicative of compression. Thrust faults are reverse faults with fault dips <45 degrees. Figures from Davis & Reynolds, 1996.

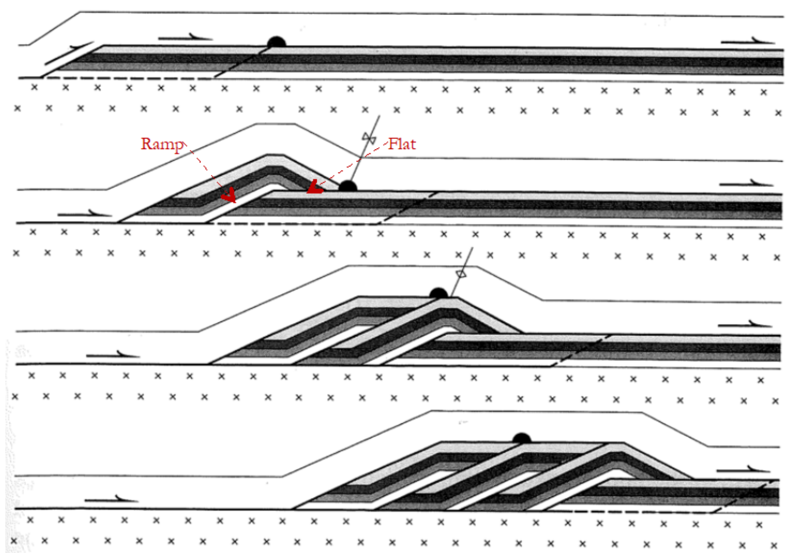


Reverse Slip Fault


Thrust Slip Fault

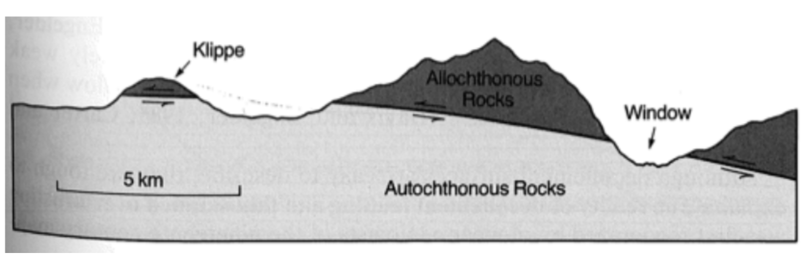
"Ramp-Flat" Geometry of Typical Thrust Fault Systems

In a regional thrust, faulted blocks are "thrust" on top of younger strata. The exact geometry of these thrust systems can vary significantly. Figures from Davis & Reynolds, 1996.



Klippe & Windows

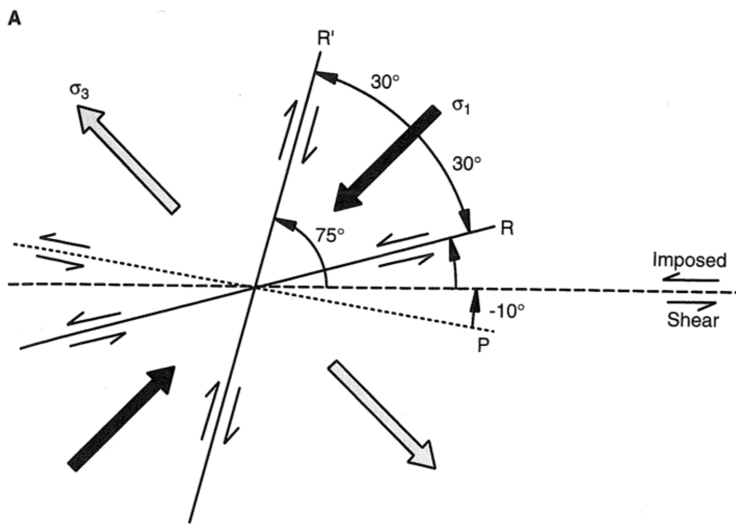
Thrust faults move large blocks of non-indigenous rock (referred to as "allochthonous" rock) over emplaced rock (referred to as "autochthonous" rock). If the overlying allochthonous rock is eroded, it can create windows into the lower underlying autochthonous rock. Erosion can also create islands of isolated allochthonous rock, called klippe. Figures from Davis & Reynolds, 1996.

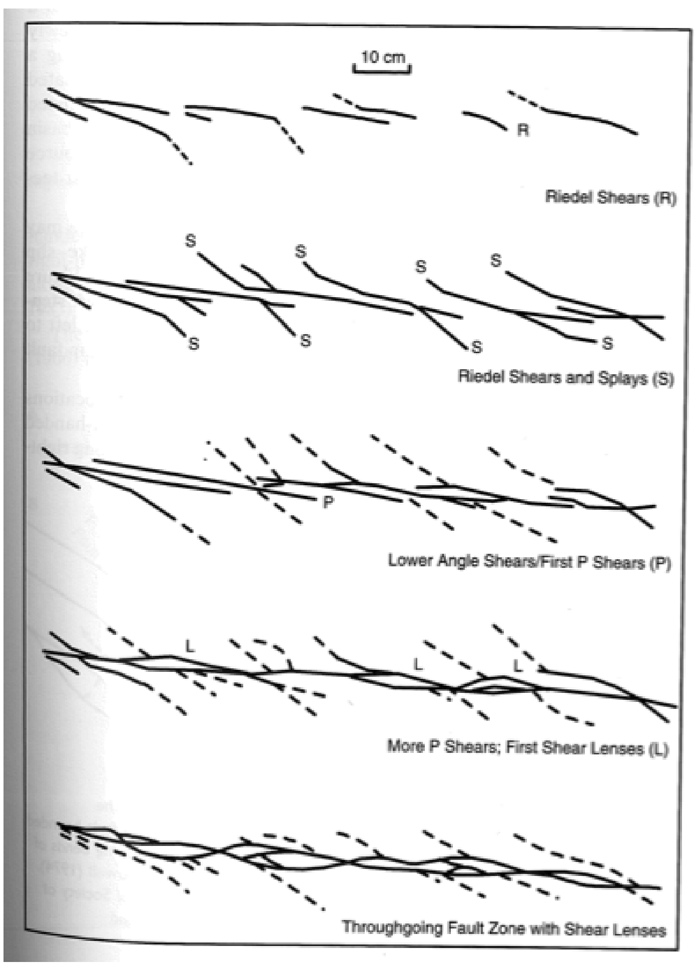


Structural Geology: Strike-Slip or Transform Faults

Riedel Shears

When under compression, rocks tend to form fail with faults forming 30° from the primary compressional stress. In a strike-slip fault, the primary compressional stress (σ_1) is 45° away from the plane of strike-slip shearing. The combination of these two facts results in fractures at interesting angles with respect to the motion of shear. These are called Riedel shears. The figure below shows a left-handed strike-slip zone. Figures from Davis & Reynolds, 1996.



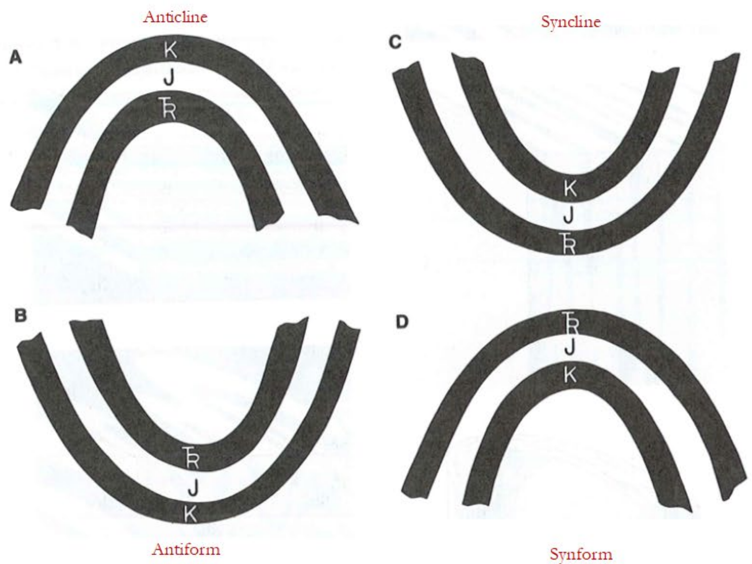


The figure at left illustrate the formation sequence of Riedel shears and other splays and shears in a right-handed strike-slip zone. Figures from Davis & Reynolds, 1996.

Structural Geology: Folds

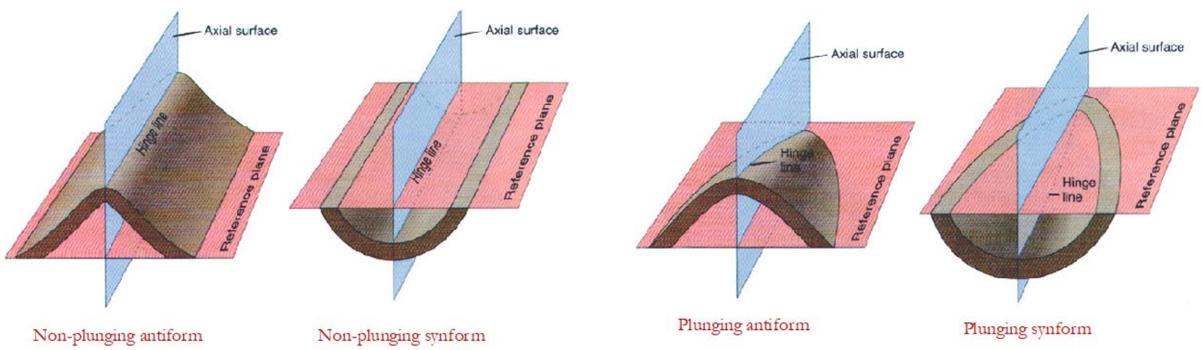
Anticlines & Antiforms, and Synclines & Synforms

Antiforms are concave-down folds, while Synforms are concave-up folds. Anticlines are antiforms were we <u>know</u> that the younger strata lie on top of older strata. Similarly, Synclines are antiforms where younger strata lie on top of older strata. Figures from Davis & Reynolds, 1996.



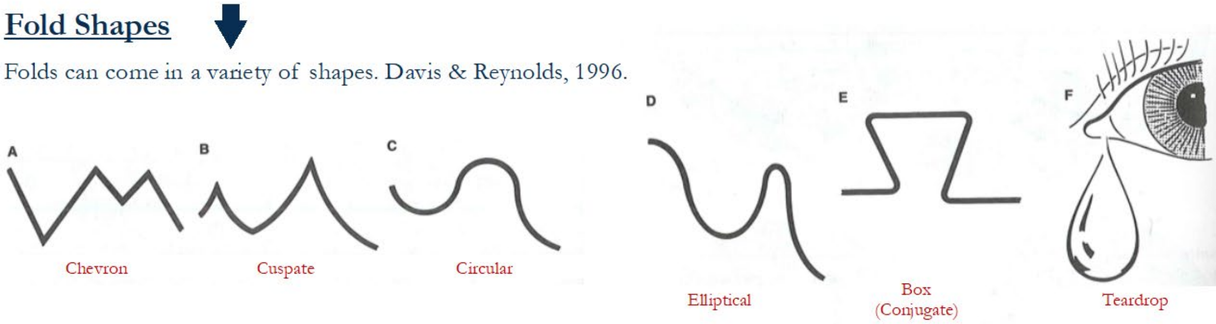
Plunging Folds

Folds (defined by hinge lines and axial surfaces) are not necessarily perpendicular to the Earth's surface. They can be dipping into or out of the surface. This can create interesting patterns of exposed surface rock, or even topography. Figures from Jones, 2001.



Fold Shapes

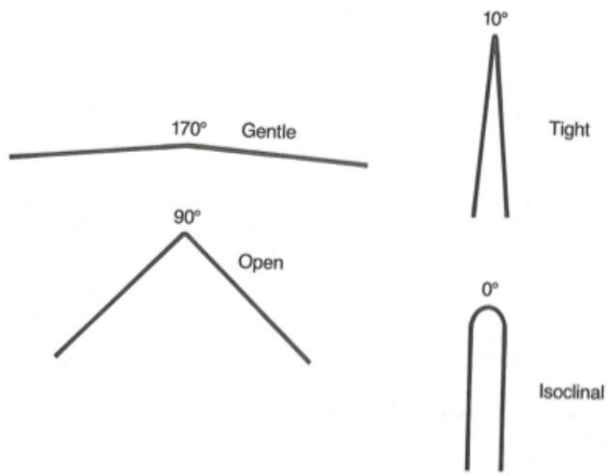
Folds can come in a variety of shapes. Davis & Reynolds, 1996.

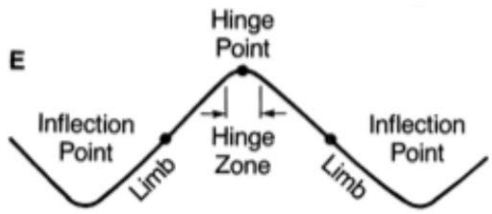


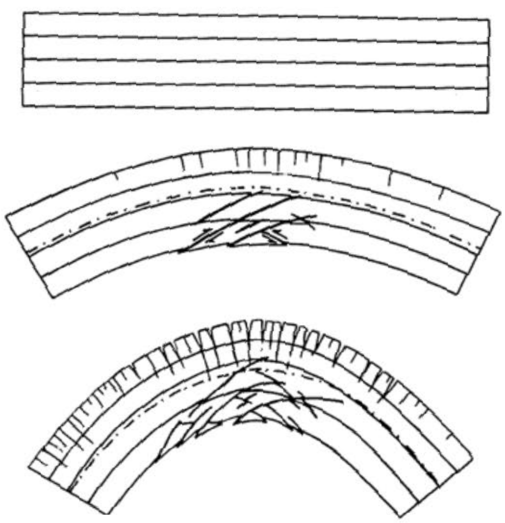
Structural Geology: Folds

Fold Tightness

Fold tightness is based upon the size of the inter-limb angle. Figures from Davis & Reynolds, 1996.





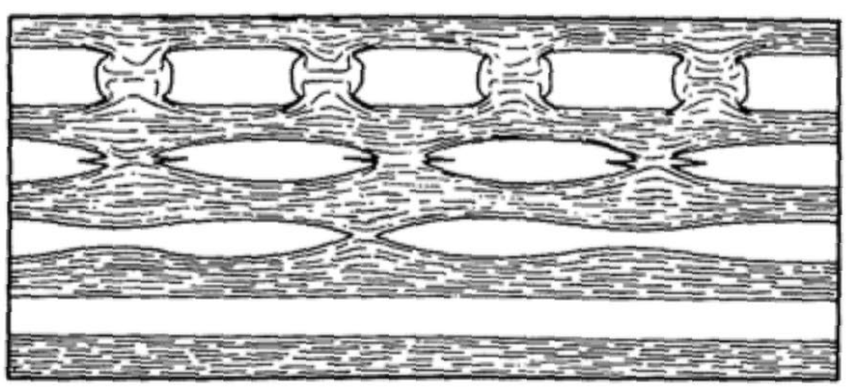


Minor Structures in Folds

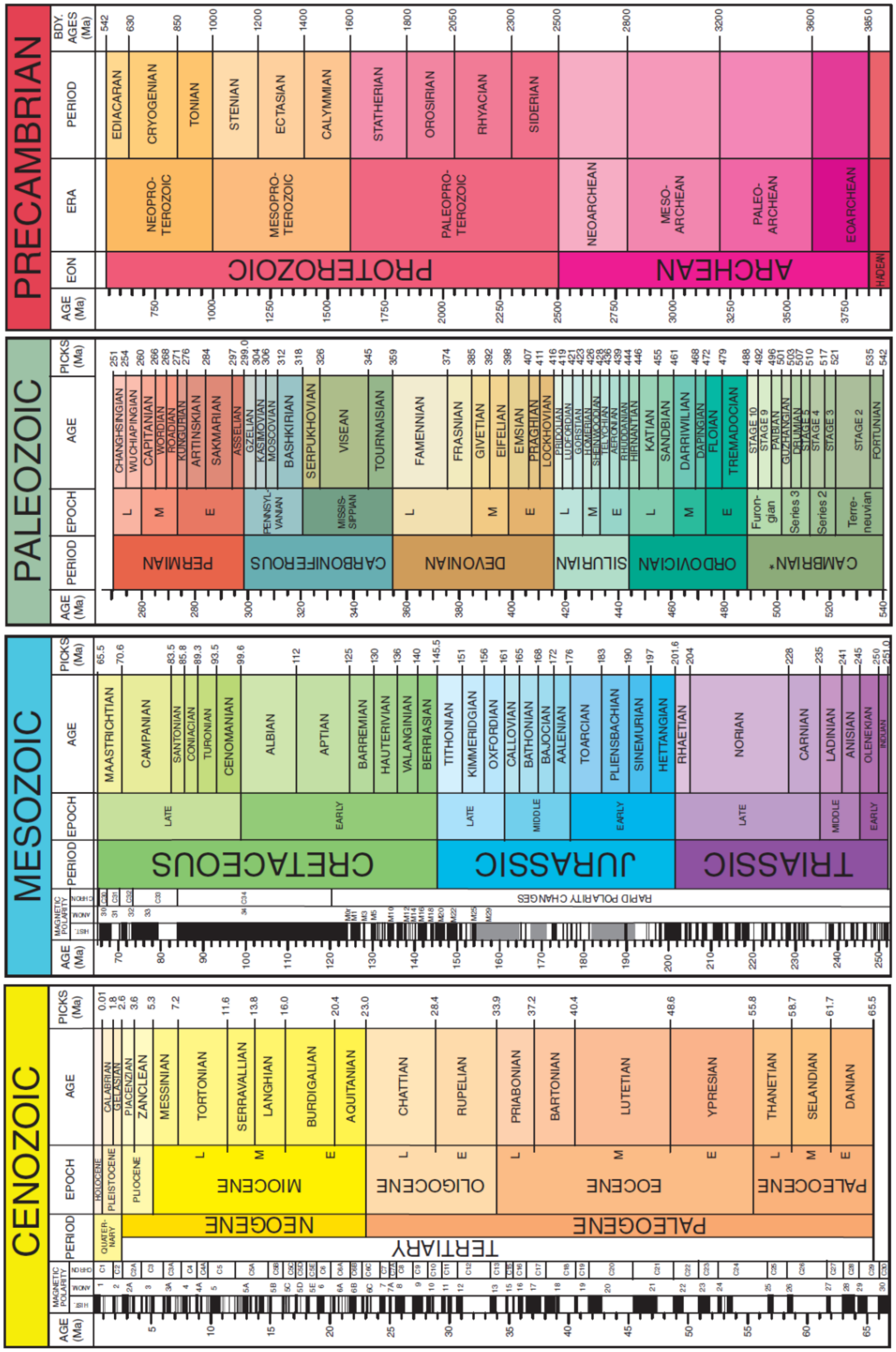
When folding layers of strata, layer-parallel stretching occurs in the outer arc of a folded layer, while layer-parallel shortening occurs in the inner arc. Figures from Davis & Reynolds, 1996.

Boudins

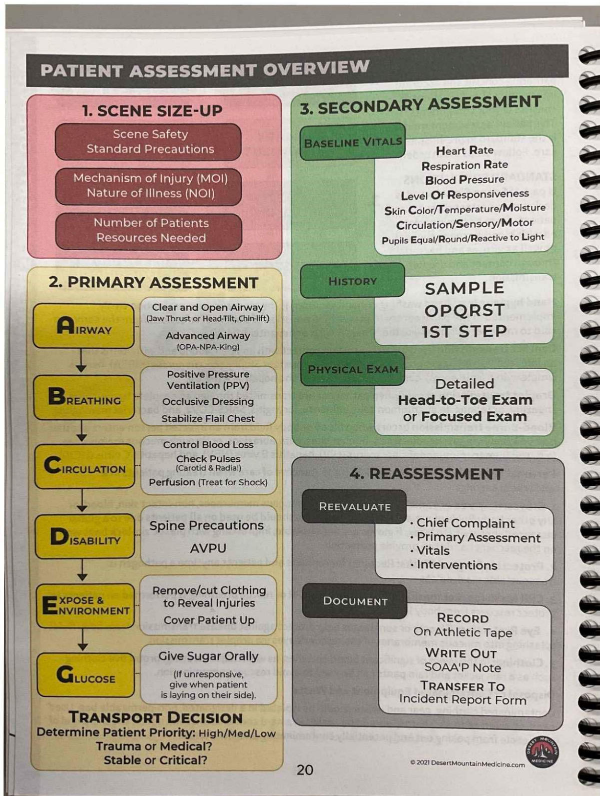
Layer-parallel stretching can pinch off layers of strata, depending on the ductility contrast between layers. This can result in pinch-and-swell structures or boudins (where the pinching completely pinches off portions of a given strata). Figures from Davis & Reynolds, 1996.



Geologic Timescale



2009 version, from the Geologic Society of A



PATIENT ASSESSMENT OVERVIEW

1. SCENE SIZE-UP

- Scene Safety / Standard Precautions
- Mechanism of Injury (MOI) / Nature of Illness (NOI)
- Number of Patients / Resources Needed

2. PRIMARY ASSESSMENT

- **Airway**: Clear and Open Airway (Jaw Thrust or Head-Tilt, Chin-lift); Advanced Airway (OPA-NPA-King)
- **Breathing**: Positive Pressure Ventilation (PPV); Occlusive Dressing; Stabilize Flail Chest
- **Circulation**: Control Blood Loss; Check Pulses (Carotid & Radial); Perfusion (Treat for Shock)
- **Disability**: Spine Precautions; AVPU
- **Expose & Environment**: Remove/cut Clothing to Reveal Injuries; Cover Patient Up
- **Glucose**: Give Sugar Orally (If unresponsive, give when patient is laying on their side).

TRANSPORT DECISION
Determine Patient Priority: High/Med/Low
Trauma or Medical?
Stable or Critical?

3. SECONDARY ASSESSMENT

- **Baseline Vitals**: Heart Rate; Respiration Rate; Blood Pressure; Level Of Responsiveness; Skin Color/Temperature/Moisture; Circulation/Sensory/Motor; Pupils Equal/Round/Reactive to Light
- **History**: SAMPLE; OPQRST; 1ST STEP
- **Physical Exam**: Detailed Head-to-Toe Exam or Focused Exam

4. REASSESSMENT

- **Reevaluate**: Chief Complaint; Primary Assessment; Vitals; Interventions
- **Document**: Record On Athletic Tape; Write Out SOAA'P Note; Transfer To Incident Report Form

20

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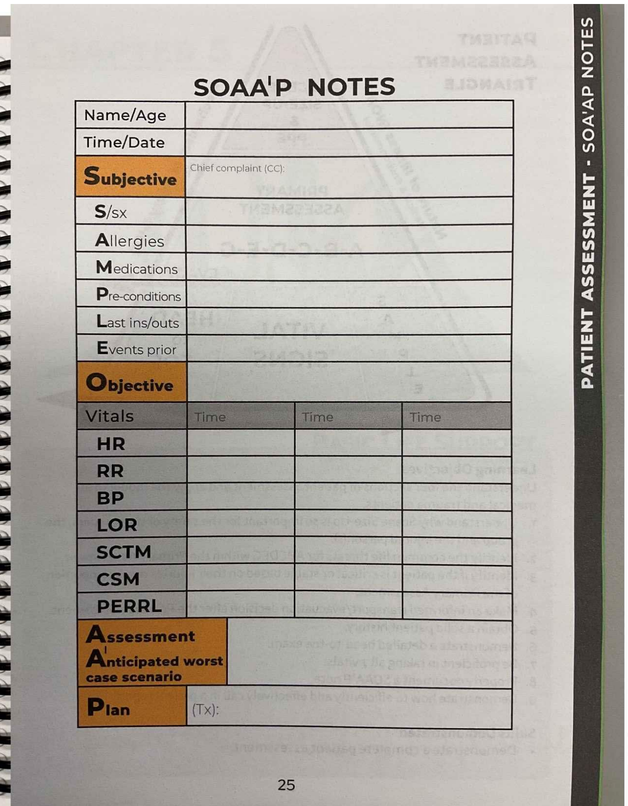
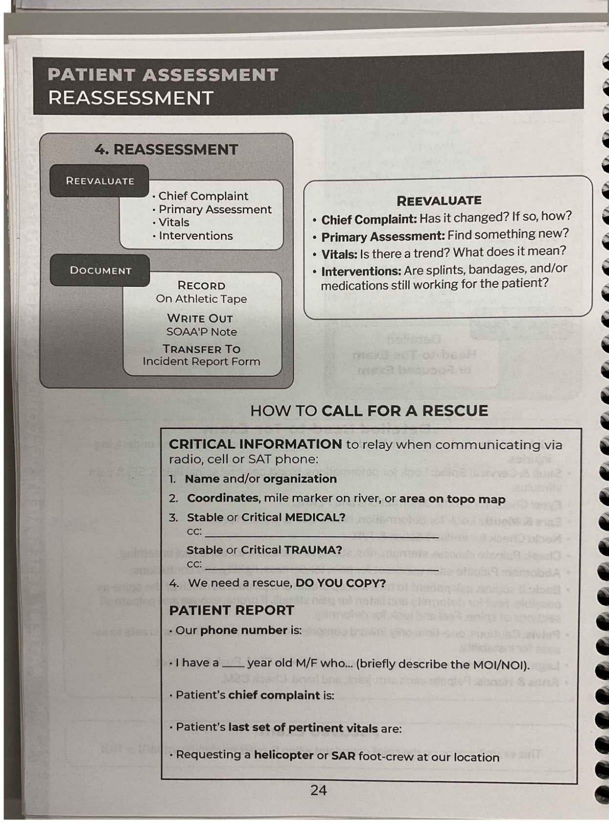


SOAA'P NOTES

Name/Age			
Time/Date			
Subjective	Chief complaint (CC):		
S/sx			
Allergies			
Medications			
Pre-conditions			
Last ins/outs			
Events prior			
Objective			
Vitals	Time	Time	Time
HR			
RR			
BP			
LOR			
SCTM			
CSM			
PERRL			
Assessment / Anticipated worst case scenario			
Plan	(Tx):		

PATIENT ASSESSMENT - SOA'AP NOTES

25



PATIENT ASSESSMENT REASSESSMENT

4. REASSESSMENT

- **Reevaluate**: Chief Complaint; Primary Assessment; Vitals; Interventions
- **Document**: Record On Athletic Tape; Write Out SOAA'P Note; Transfer To Incident Report Form

REEVALUATE
- **Chief Complaint:** Has it changed? If so, how?
- **Primary Assessment:** Find something new?
- **Vitals:** Is there a trend? What does it mean?
- **Interventions:** Are splints, bandages, and/or medications still working for the patient?

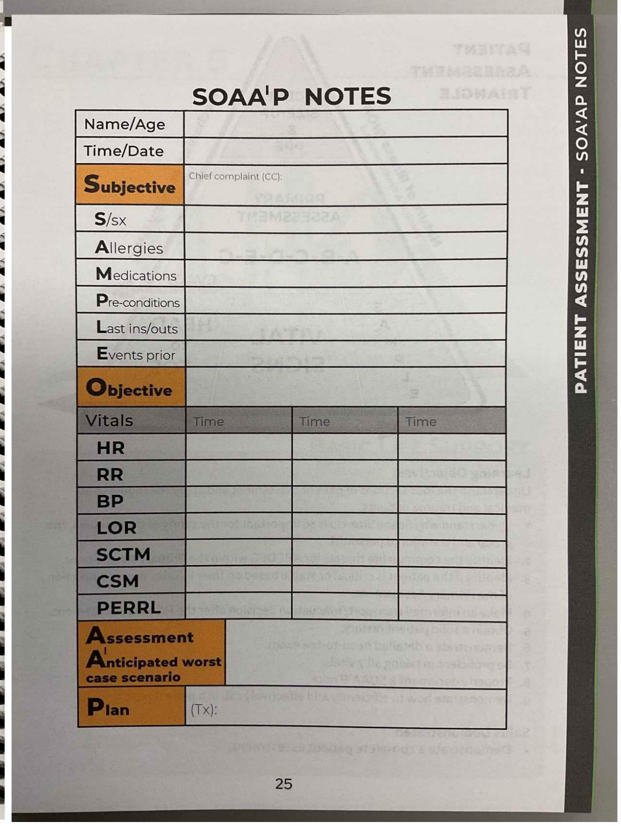
HOW TO **CALL FOR A RESCUE**

CRITICAL INFORMATION to relay when communicating via radio, cell or SAT phone:

1. **Name** and/or **organization**
2. **Coordinates,** mile marker on river, or **area on topo map**
3. **Stable** or **Critical MEDICAL?**
   CC: __________
   Stable or **Critical TRAUMA?**
   CC: __________
4. We need a rescue, **DO YOU COPY?**

PATIENT REPORT
- Our **phone number** is:
- I have a ___ year old M/F who... (briefly describe the MOI/NOI).
- Patient's **chief complaint** is:
- Patient's **last set of pertinent vitals** are:
- Requesting a **helicopter** or **SAR** foot-crew at our location

24



SOAA'P NOTES

Name/Age			
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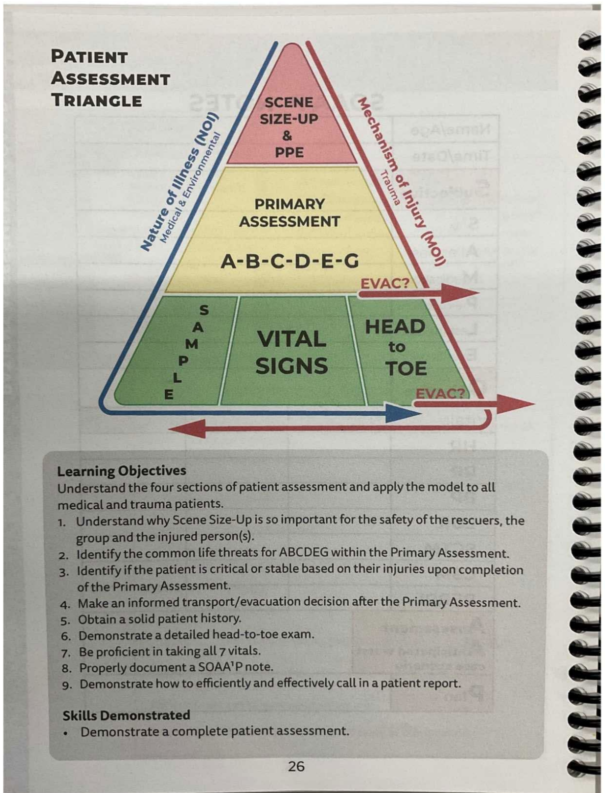
Medications			
Pre-conditions			
Last ins/outs			
Events prior			
Objective			
Vitals	Time	Time	Time
HR			
RR			
BP			
LOR			
SCTM			
CSM			
PERRL			
Assessment / Anticipated worst case scenario			
Plan	(Tx):		

PATIENT ASSESSMENT - SOA'AP NOTES

25



Patient Assessment Triangle

Learning Objectives

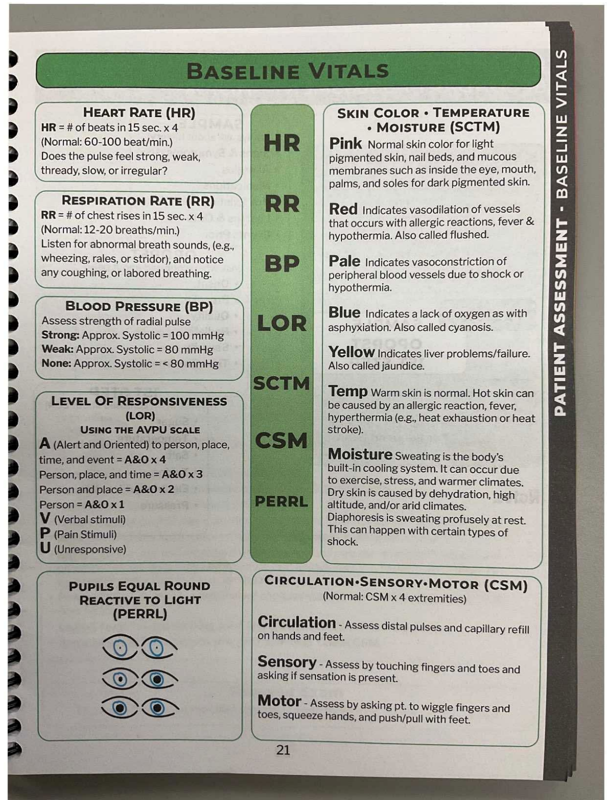
Understand the four sections of patient assessment and apply the model to all medical and trauma patients.

1. Understand why Scene Size-Up is so important for the safety of the rescuers, the group and the injured person(s).
2. Identify the common life threats for ABCDEG within the Primary Assessment.
3. Identify if the patient is critical or stable based on their injuries upon completion of the Primary Assessment.
4. Make an informed transport/evacuation decision after the Primary Assessment.
5. Obtain a solid patient history.
6. Demonstrate a detailed head-to-toe exam.
7. Be proficient in taking all 7 vitals.
8. Properly document a SOAA[1]P note.
9. Demonstrate how to efficiently and effectively call in a patient report.

Skills Demonstrated

- Demonstrate a complete patient assessment.

26



Baseline Vitals

Heart Rate (HR)
HR = # of beats in 15 sec. x 4
(Normal: 60-100 beat/min.)
Does the pulse feel strong, weak, thready, slow, or irregular?

Respiration Rate (RR)
RR = # of chest rises in 15 sec. x 4
(Normal: 12-20 breaths/min.)
Listen for abnormal breath sounds, (e.g., wheezing, rales, or stridor), and notice any coughing, or labored breathing.

Blood Pressure (BP)
Assess strength of radial pulse
Strong: Approx. Systolic = 100 mmHg
Weak: Approx. Systolic = 80 mmHg
None: Approx. Systolic = < 80 mmHg

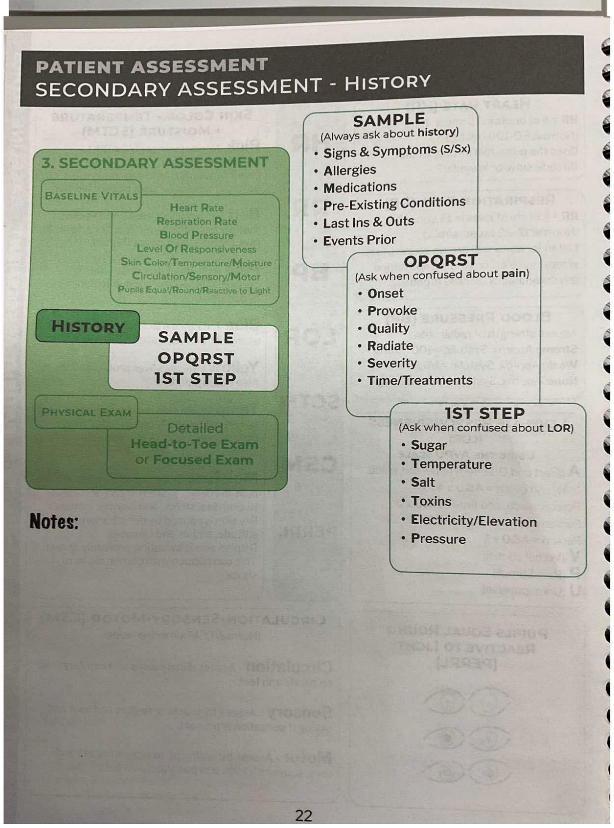
Level Of Responsiveness (LOR)
Using the AVPU scale
A (Alert and Oriented) to person, place, time, and event = **A&O x 4**
Person, place, and time = **A&O x 3**
Person and place = **A&O x 2**
Person = **A&O x 1**
V (Verbal stimuli)
P (Pain Stimuli)
U (Unresponsive)

Pupils Equal Round Reactive to Light (PERRL)

Skin Color • Temperature • Moisture (SCTM)
Pink Normal skin color for light pigmented skin, nail beds, and mucous membranes such as inside the eye, mouth, palms, and soles for dark pigmented skin.
Red Indicates vasodilation of vessels that occurs with allergic reactions, fever & hypothermia. Also called flushed.
Pale Indicates vasoconstriction of peripheral blood vessels due to shock or hypothermia.
Blue Indicates a lack of oxygen as with asphyxiation. Also called cyanosis.
Yellow Indicates liver problems/failure. Also called jaundice.
Temp Warm skin is normal. Hot skin can be caused by an allergic reaction, fever, hyperthermia (e.g., heat exhaustion or heat stroke).
Moisture Sweating is the body's built-in cooling system. It can occur due to exercise, stress, and warmer climates. Dry skin is caused by dehydration, high altitude, and/or arid climates. Diaphoresis is sweating profusely at rest. This can happen with certain types of shock.

Circulation•Sensory•Motor (CSM)
(Normal: CSM x 4 extremities)
Circulation - Assess distal pulses and capillary refill on hands and feet.
Sensory - Assess by touching fingers and toes and asking if sensation is present.
Motor - Assess by asking pt. to wiggle fingers and toes, squeeze hands, and push/pull with feet.

21



Patient Assessment
Secondary Assessment - History

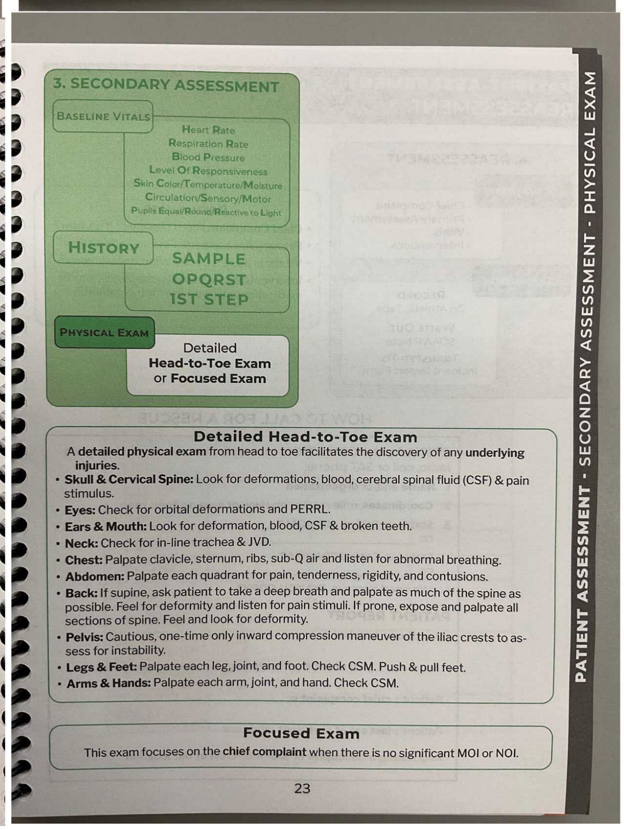
SAMPLE
(Always ask about **history**)
- Signs & Symptoms (S/Sx)
- Allergies
- Medications
- Pre-Existing Conditions
- Last Ins & Outs
- Events Prior

OPQRST
(Ask when confused about **pain**)
- Onset
- Provoke
- Quality
- Radiate
- Severity
- Time/Treatments

1ST STEP
(Ask when confused about **LOR**)
- Sugar
- Temperature
- Salt
- Toxins
- Electricity/Elevation
- Pressure

Notes:

22



Detailed Head-to-Toe Exam

A **detailed physical exam** from head to toe facilitates the discovery of any **underlying injuries.**

- **Skull & Cervical Spine:** Look for deformations, blood, cerebral spinal fluid (CSF) & pain stimulus.
- **Eyes:** Check for orbital deformations and PERRL.
- **Ears & Mouth:** Look for deformation, blood, CSF & broken teeth.
- **Neck:** Check for in-line trachea & JVD.
- **Chest:** Palpate clavicle, sternum, ribs, sub-Q air and listen for abnormal breathing.
- **Abdomen:** Palpate each quadrant for pain, tenderness, rigidity, and contusions.
- **Back:** If supine, ask patient to take a deep breath and palpate as much of the spine as possible. Feel for deformity and listen for pain stimuli. If prone, expose and palpate all sections of spine. Feel and look for deformity.
- **Pelvis:** Cautious, one-time only inward compression maneuver of the iliac crests to assess for instability.
- **Legs & Feet:** Palpate each leg, joint, and foot. Check CSM. Push & pull feet.
- **Arms & Hands:** Palpate each arm, joint, and hand. Check CSM.

Focused Exam

This exam focuses on the **chief complaint** when there is no significant MOI or NOI.

23