Volcano Seismology

Brief summary of what we are going to see ahead…

1. We try to locate the source of magma and source of the volcanic earthquakes and tremors.
2. We try to understand the mechanism of magma injection in conduit and its pathway up to the earth surface.
3. We will study about the acoustic property of magmatic and hydrothermal fluid- by using fluid crack model.
4. Experimental modeling of gas expansion in volcanic conduit.

- So that we understand its hazardous impact and predict its eruption.

Why seismic waves for imaging volcanoes?

We have many methods which could be used to do imaging and monitoring of volcanoes but seismology has some advantages over other methods like-

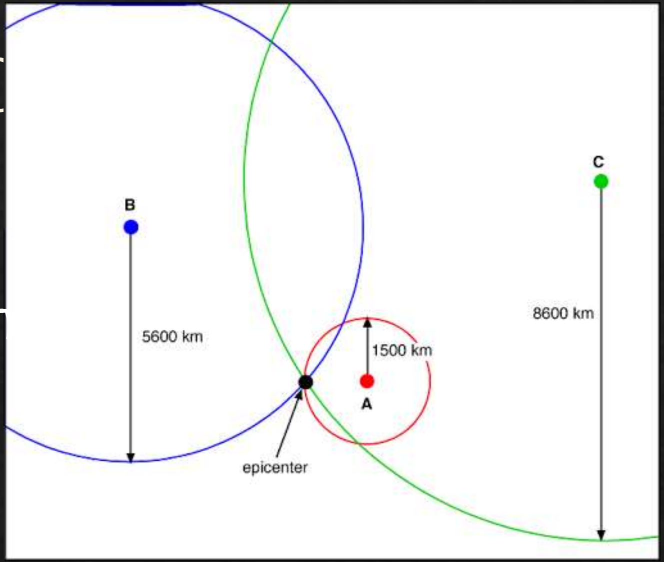
- Among all the other methods, seismic imaging provides us good resolution of data and precise estimates.

- It is hard to send long cables to deep down the earth so *electric resistivity* method has shallow depth of investigation, but seismology does not has any such limitations of depth.

- In *thermal imaging* from satellites or from ground, large amounts of ash and dust does not allow to record reliable data, but seismic instruments records most reliable data in any type of eruption or in any weather

Finding seismic sources of volcano

Can you think of a method analogous to triangulation method to find volcano's seismic source?



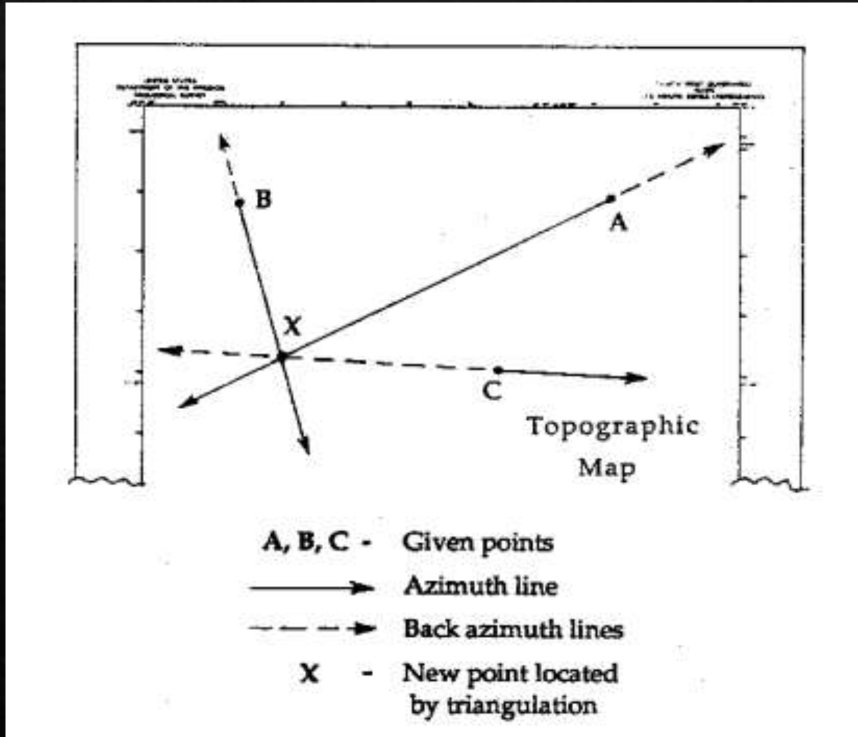
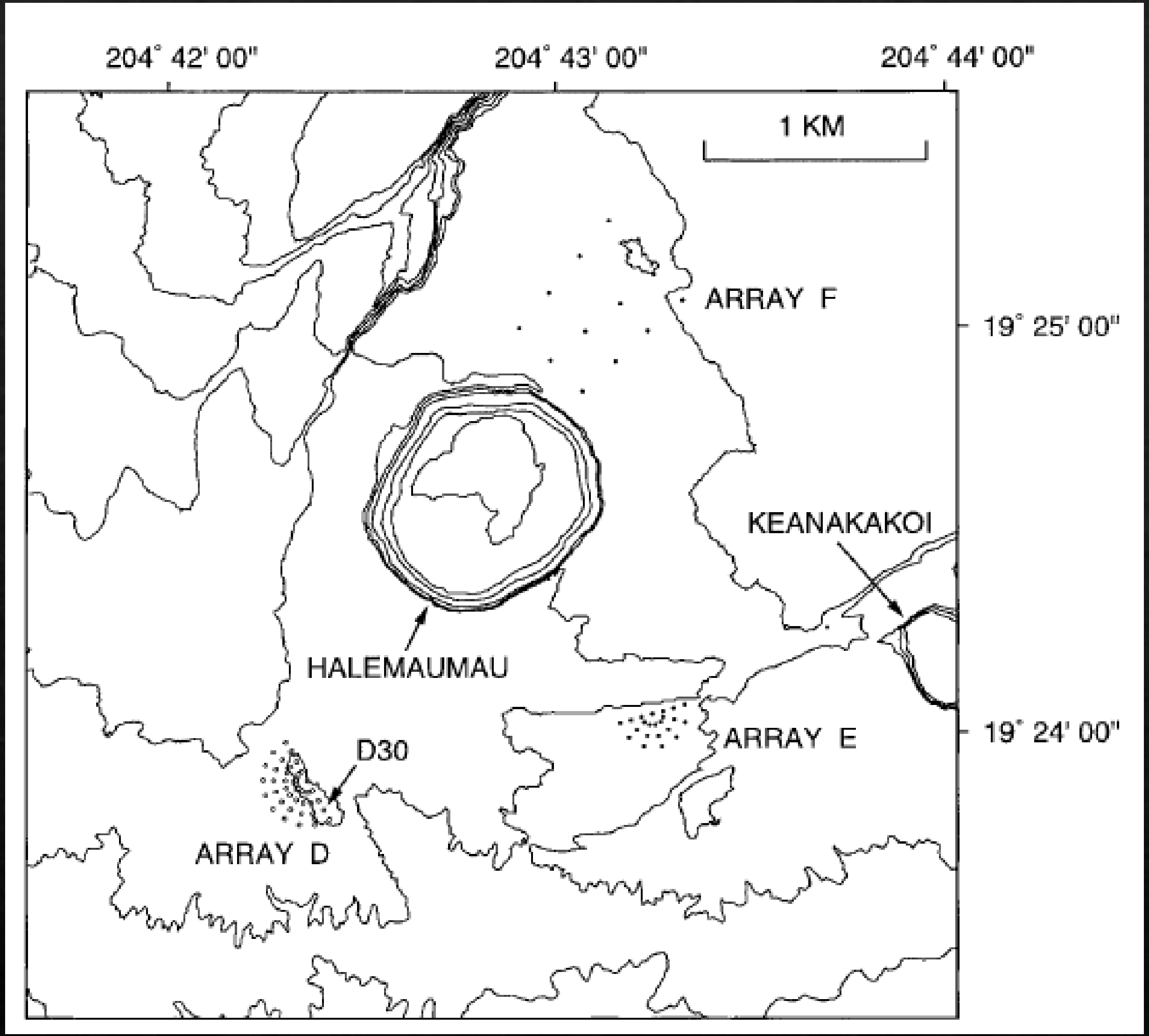


Figure 3. A typical triangulation diagram.

As in earthquake seismology we use triangulation method to estimate the epicenter of earthquake, similarly we use a method of drawing back-azimuths from seismometers to 'roughly' locate the position of source of magma.

Let's see it with an example of Kilauea caldera...



Array D- 41 sensors in semi-circle
Array E- 33 sensors in semicircle
Array F- 12 sensors in polygon shape

Why this specific shape of sensor arrays ???

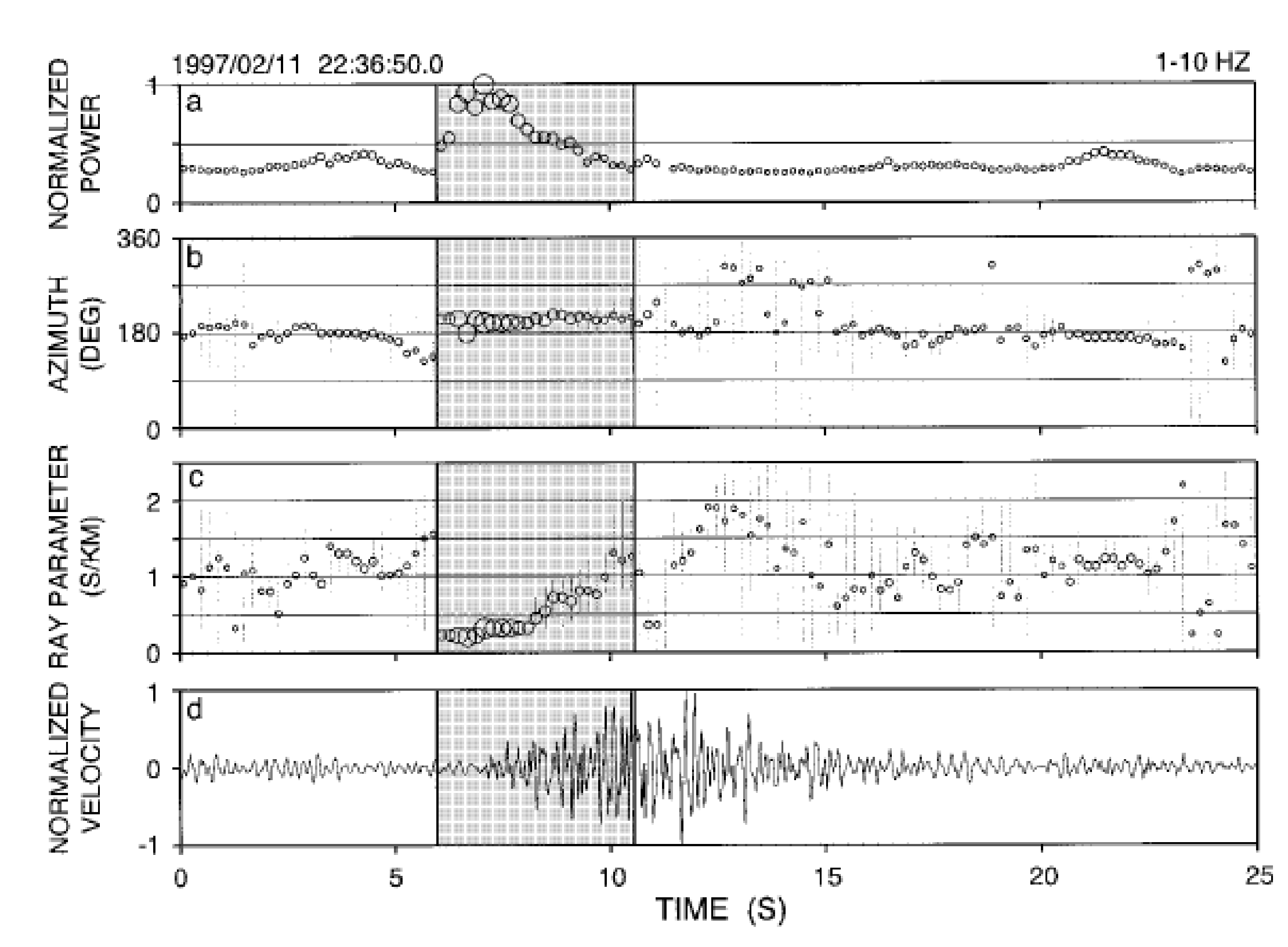
= This shapes are chosen according to place's topography so to record maximum data.

Map of the southern extent of the Kilauea caldera region showing locations of pit craters, main topographic features, and seismic antennas deployed during the 1997 Japan–U. S. experiment.

- This Long Period data was taken with the Small Aperture Seismic Array.
- This data in fig below was taken from array D.
- It shows the temporal distributions of power, azimuth, and ray parameter.

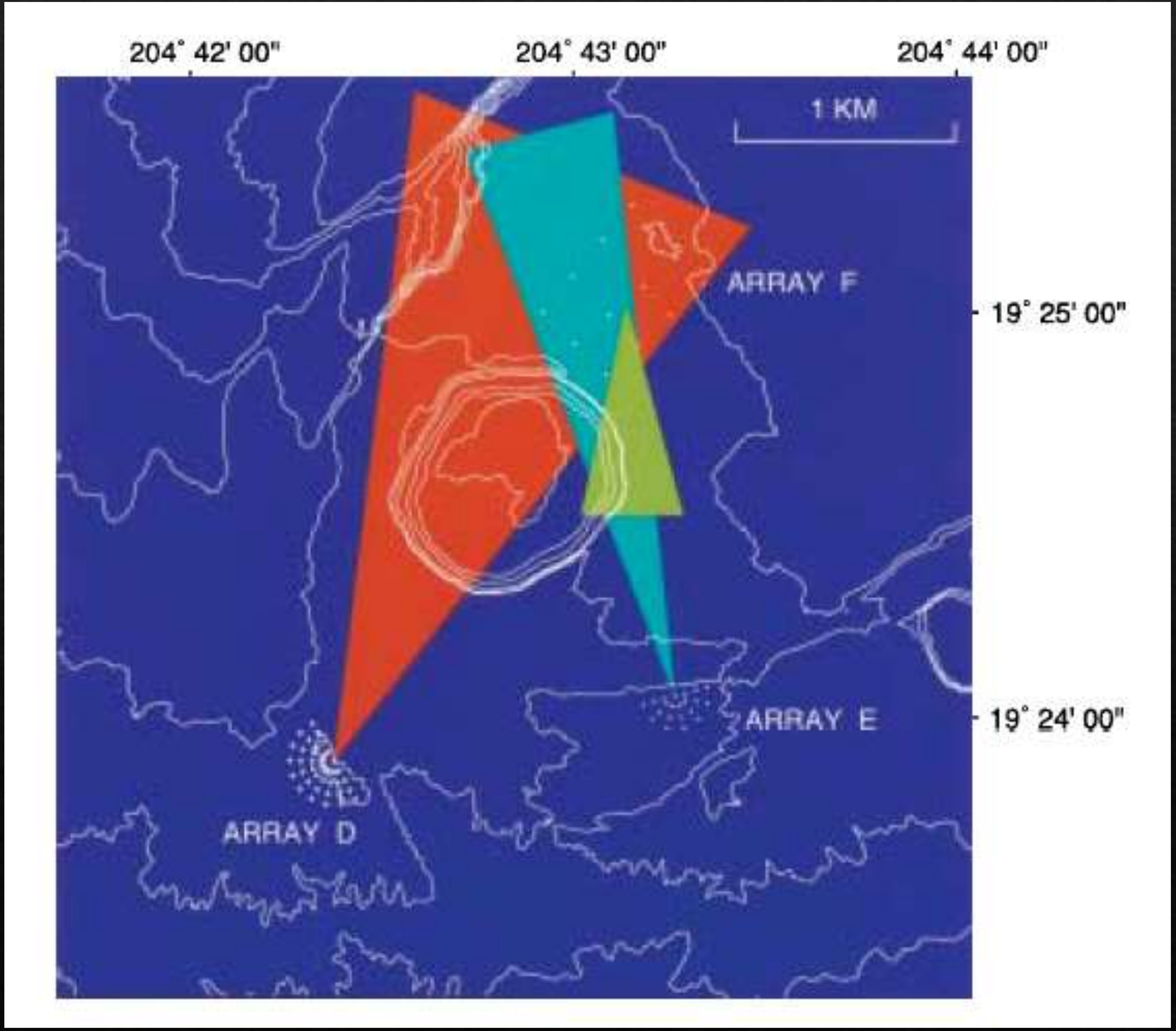
Using the time interval of shaded region, we recorded the azimuths, and then find out their corresponding back-azimuths.

Azimuths for this same time interval from all three arrays were recorded and plotted on the topographical map of Kilauea caldera. It formed a triangular shape as shown in next figure.

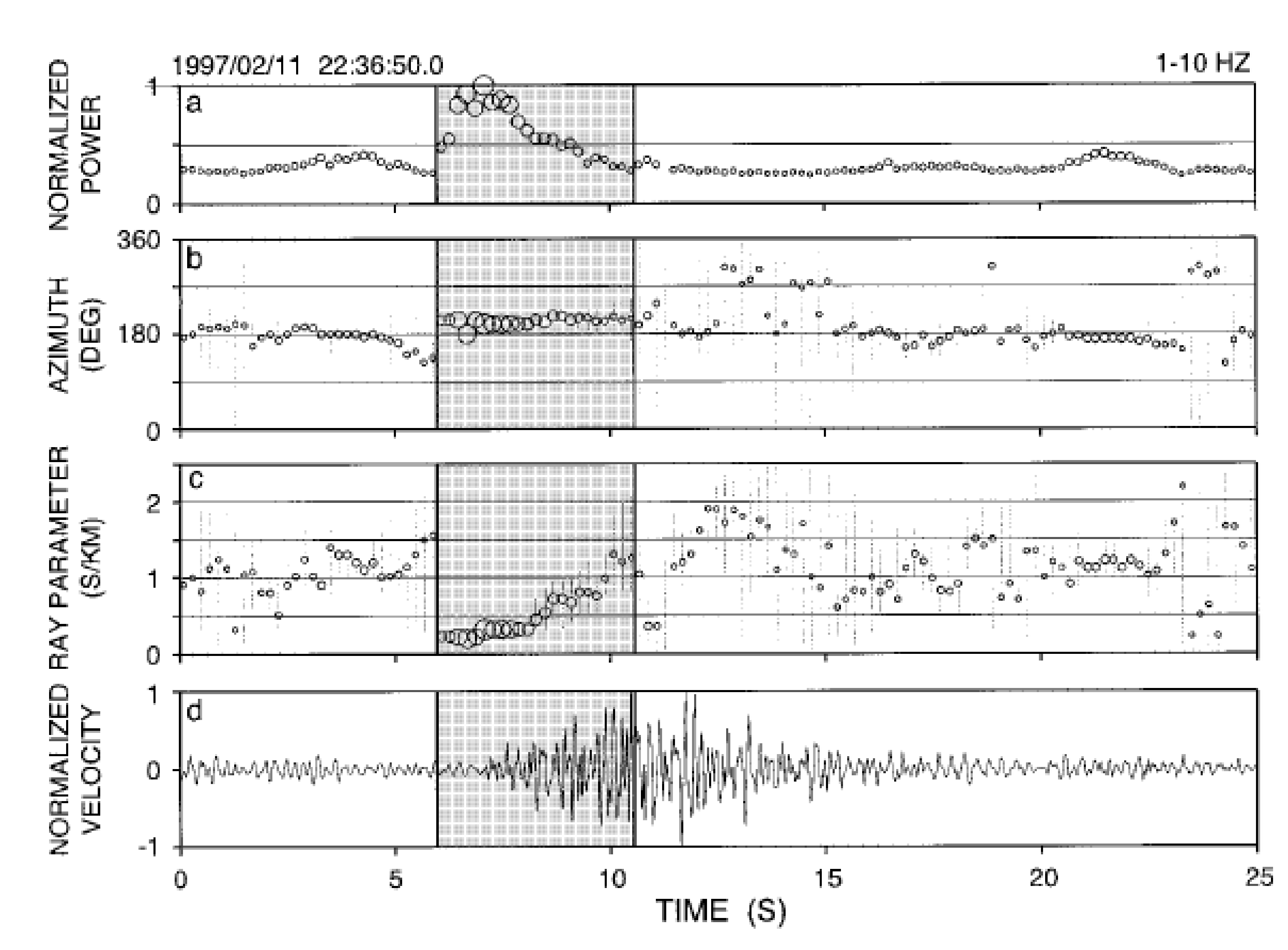


The back-azimuths for 5 sec interval formed wedges as in figure.

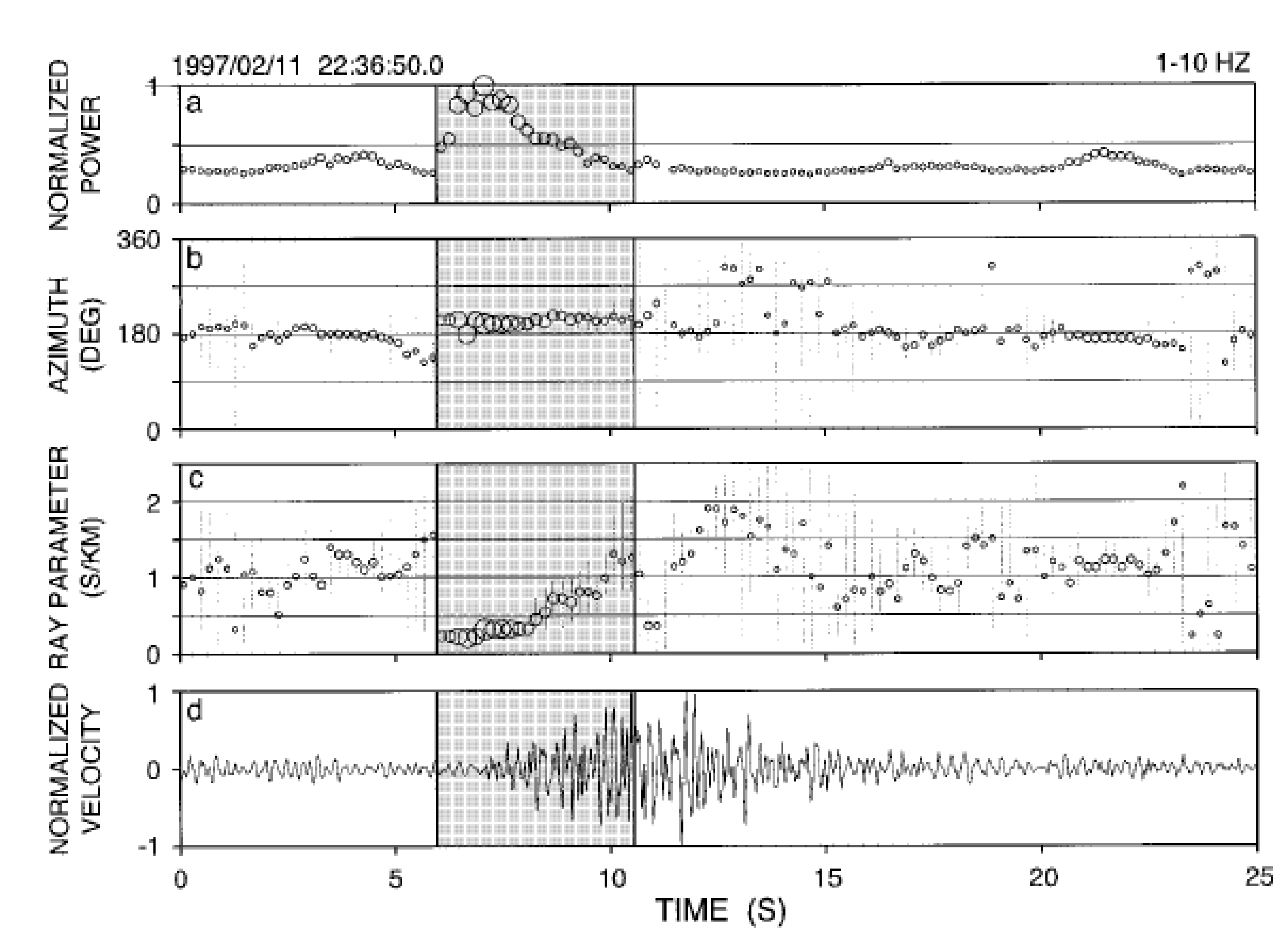
The intersection of these 3 wedges gives us the rough idea of the source location.



This shaded region five seconds time interval from 6th – 11th sec was used to plot azimuths. But why do we use this particular time slot and not some other set of time? THINK!



The direction of back-azimuths should give us most precise estimate of source direction, so from the data shown beside, we have to take such values of azimuths which can give us the direction from where the maximum energy comes within short time interval.



To estimate the directional properties, we take time interval characterized by enhanced power and most stable azimuths.

Another methods to better estimate of source region- by modeling the wavefield in the 3-D velocity structure and 3-D topography.

The back-azimuth method gives us the rough estimate of source region, but to have much precise estimate we use modeling method.

We used here spatio-temporal data received from sensors of previously discussed Kilauea caldera and do two types of modeling - (1) 3-D topography and (2) 3-D velocity structure.

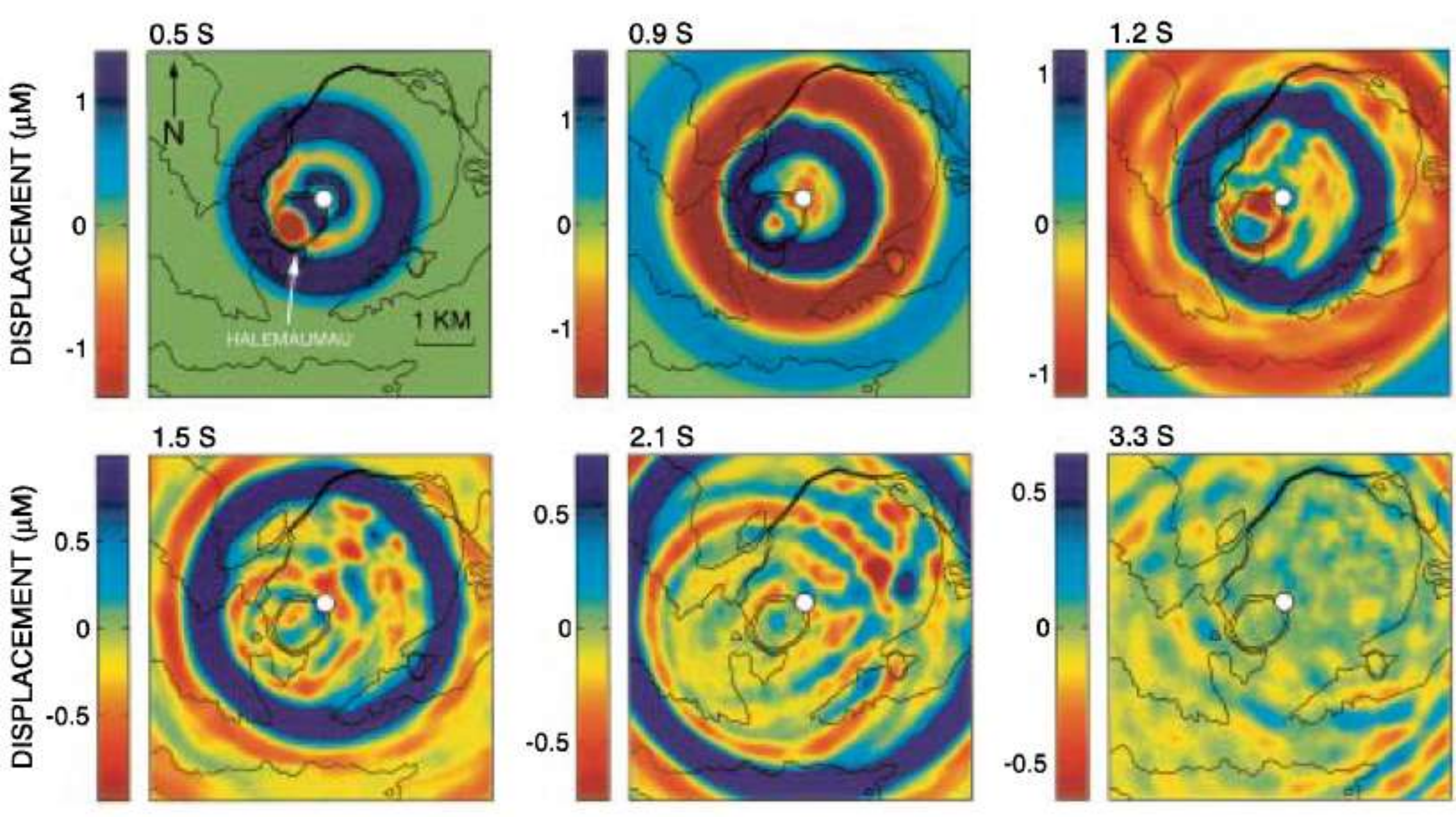
- 3-D topography modeling – assumes homogenous medium - gives details about how topography affects wave propagation
- 3-D velocity structure- assumes heterogeneous medium - gives more precise estimate than topography method.

3-D topography modeling

- This waves displacement also helps us to understand effects of topography on wave propagation.
- Here the medium is assumed to be homogenous and changes in velocity is not taken into account.

- The red anomaly in 0.5s is the diffraction of waves by halemaumau pit crater.
- Diffraction anomaly is also seen in 0.9s .
- Waves backscattered from cliffs marking the northwest caldera boundary appear as a linear band of orange oriented parallel to the topographic contours north of Halemaumau at t ¼ 1.2 s.

This figure represents the vertical component of ground displacement . The origin of the waves is the seismic source location (marked as white circle in the figure).

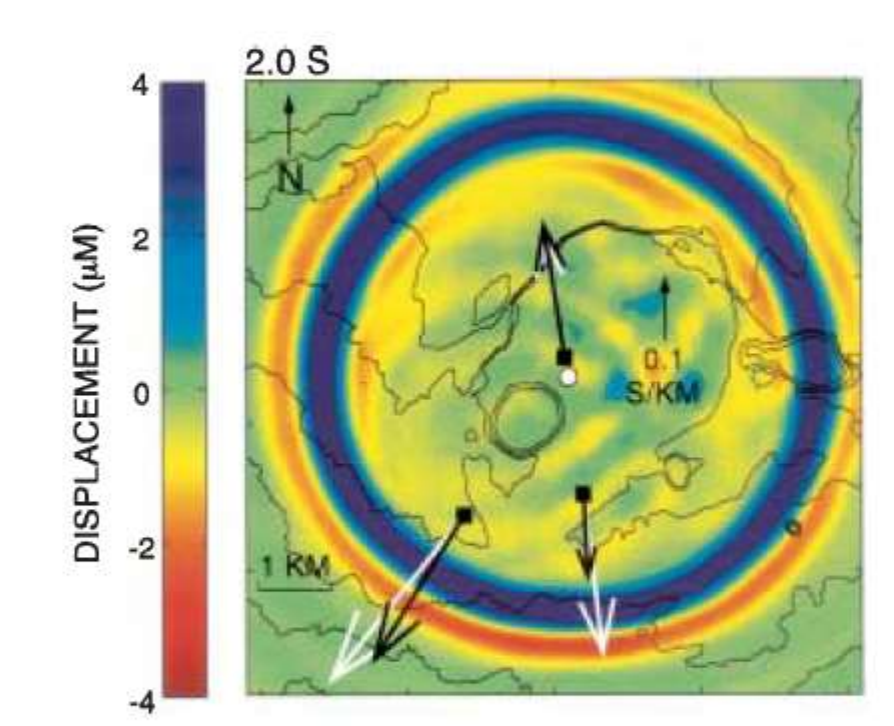


3-D modeling of velocity structure- give better estimate of source location.

Heterogeneous medium is taken. Changes in velocity of wave as it propagates is taken in account in this modeling.

Slowness vector is different in both cases-
- White arrow- topography only
- Black arrow- both topography and velocity structure

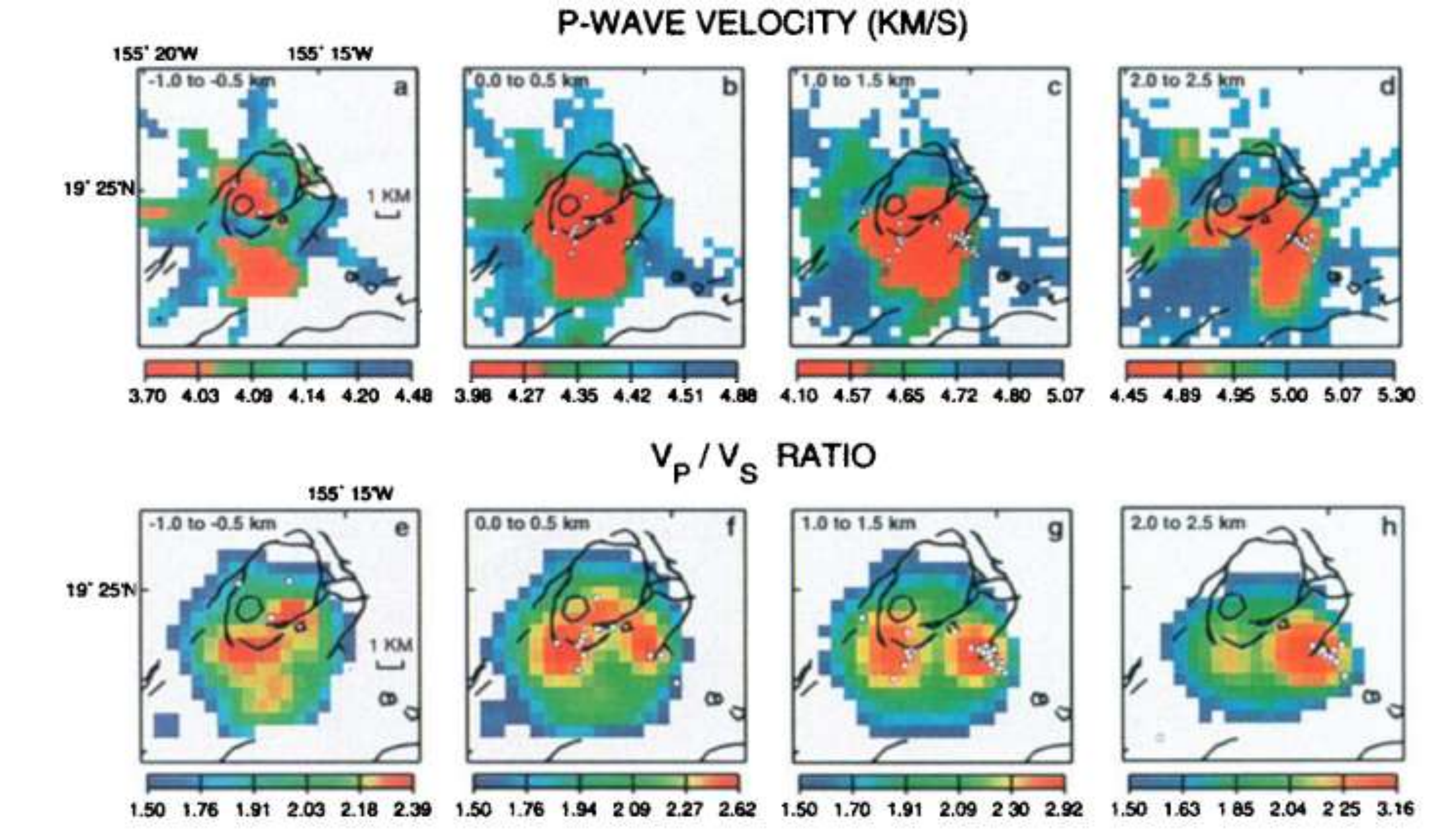
This difference in slowness vector shows us that it is mandatory to consider both factors, topography and velocity structure, to obtain precise results for source location estimates.



Locating the magma beneath volcano

- Here we image 3-D velocity structure of volcanic edifice by tomographic inversion of P-wave and S-wave arrival times.
  - A low velocity anomaly in P-wave is seen beneath Kilauea.
  - Vp/Vs ratio has anomaly at same region as the low P-wave anomaly, but it has two separate regions.
  - Same region shows a decrease in P- wave velocity, but simultaneously the Vp/Vs ratio increased in anomaly, showing that shear wave velocity has greater decrement.
  - And we know that S-wave velocity decreases drastically in liquid medium (in lava).

Map views of the P-wave velocity (a-d) and Vv/Vs ratio (e-h) models at four depths. Black lines indicate ring fractures, faults, and pit crater in Kilauea.



Vp/Vs ratio in HR tomography of volcano

Recall- velocity of shear wave is nearly zero in liquid medium.

- We prepare Vp/Vs model by using travel time inversion data.
- Studying that model we try to identify the position of magma source.
- The sudden increase in Vp/Vs ratio hints of the presence of magma.
- Anomalies observed in Vp or sudden decrease in Vs can also tell us about the presence of magma.

Only the details of Velocity of S or P wave can also provide the hint of presence of magma, then what are the advantages of using Vp/Vs ratio?

- Calculating Vp/Vs ratio is easier than calculating Vp and Vs separately, as we won't need to know the density of every point in magma.
- Moreover, Vp/Vs ratio can be used to predict rock type.

$$v_{\mathrm{P}} = \sqrt{\frac{\lambda + 2\mu}{\rho}}$$

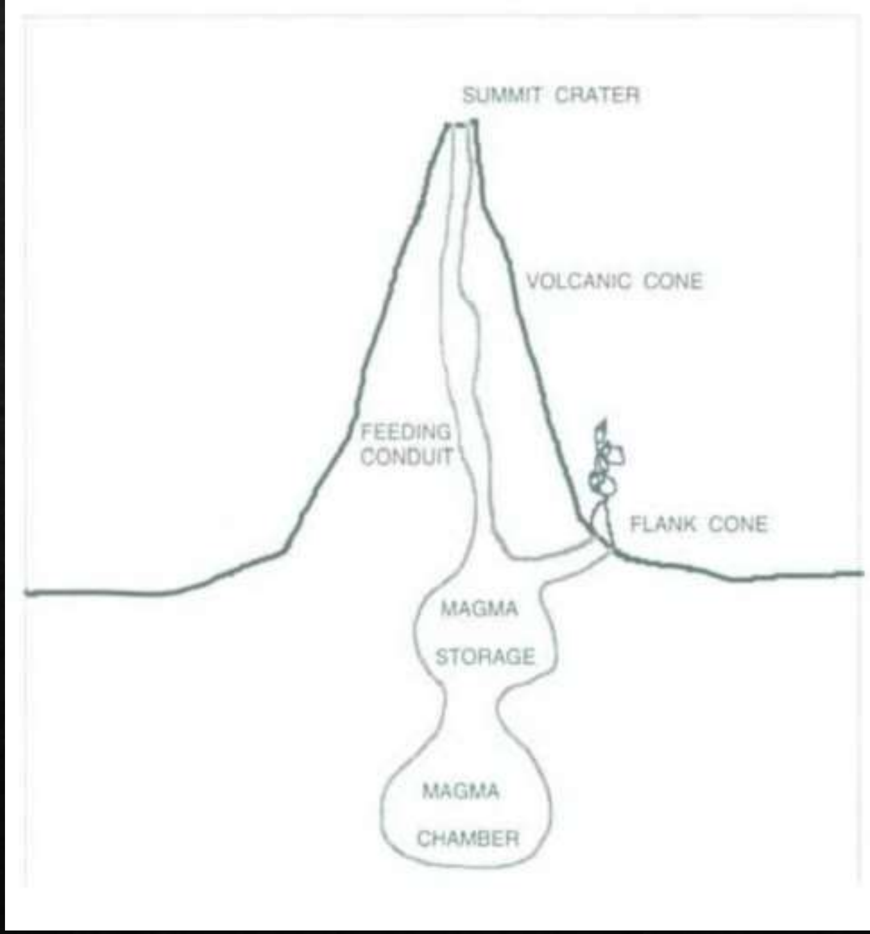
$$v_{\mathrm{S}} = \sqrt{\frac{\mu}{\rho}}.$$

Magma migration to earth surface

o When magma rises from its storage zone, it begins to move along system of tectonic fracture and volcanic conduit in the form of dyke or sill.

o Some magma rises directly straight upwards in dykes, in some volcanic systems magma flow into horizontal sills, while in some cases it rides upward at some angle and forms flank crater on surface.

What property or what factor determines the pathway of magma?

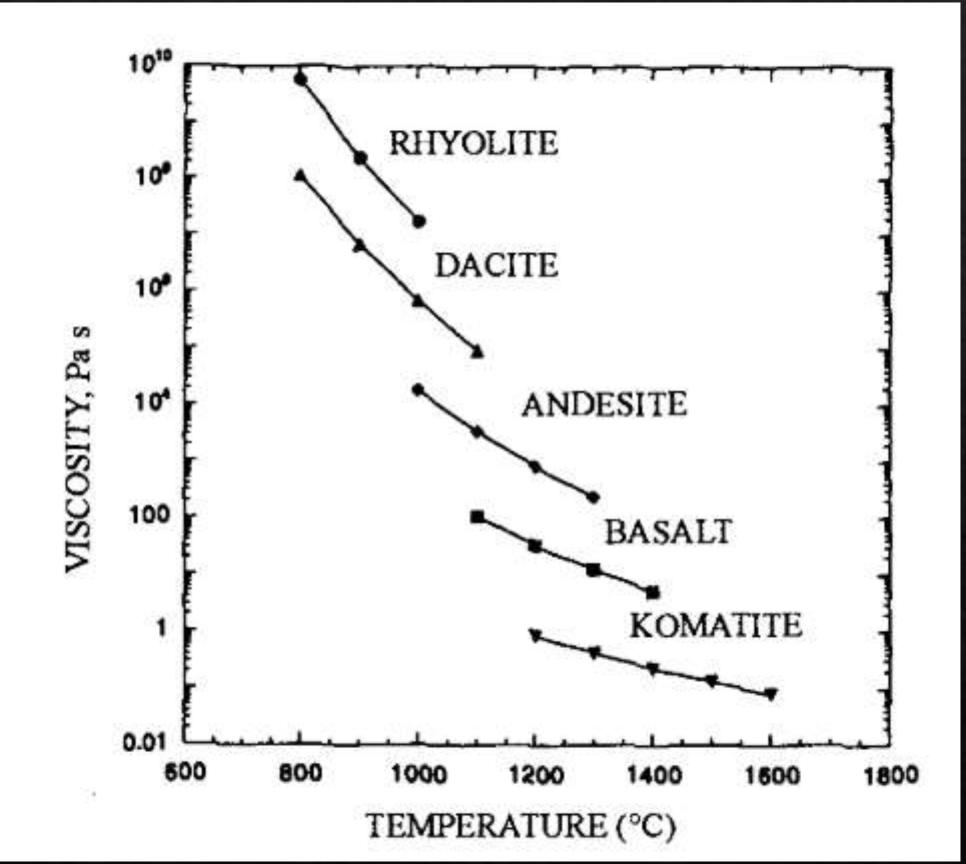


VISCOSITY – viscosity of magma determines the pathway of magma up to the surface.

- Less viscous magma (basaltic magma)- prefer to go along with faults and their strike.

- Intermediate viscosity (andesitic-basaltic)- may prefer to go along with faults and their strike or it may cut through them.

- High viscosity magma (dacitic)- slowly cut the stratified structure and form obelisks.



3 Types of volcano and their seismic data

Depending on type of lava, we have 3 types of volcanic eruptions-

1. Pelean - dacitic and andesitic lava- (HIGH)central eruption, pyroclastic flow, lava dome

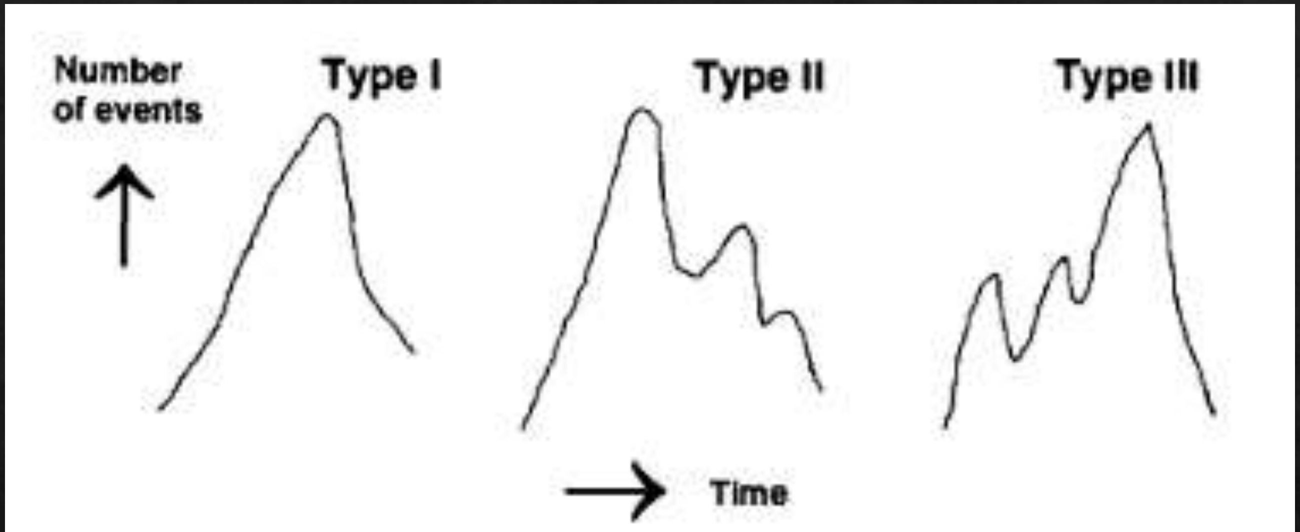
1. Strombolian - andesitic basaltic lava- (INTERMIDEATE)- strong eruption without pyroclastic flow, lava flow, dark eruption clouds

1. Hawaiian – basaltic lava- (LOW)- central, fissure and flank eruptions, lava flow.

Volcanic eruptions are characterized by earthquake swarms rather than one single major event. The general properties (spatial or temporal distributions) of these swarms helps us in differentiating volcanoes. Though not all but most of the volcanoes of similar viscosity follow a particular trend in seismic events.

On observing all patterns of temporal distributions of many volcanoes, temporal distribution was classified into three types-

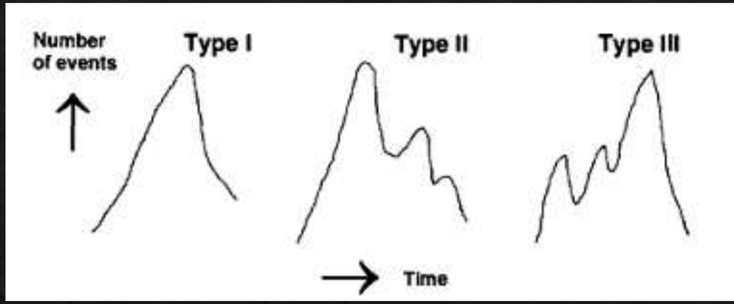
Type I – One peak [Very Rare]
Type- II – Multipeak with highest peak at the start of events [Found mainly in Basaltic and Dacitic]
Type III – Multipeak with highest peak at the end of sequence [Found mainly in Andesitic and sometimes in Dacitic]



- ❑For basaltic volcano majority of eruptions occur after the end of seismic sequence,
- ❑ For andesitic and Dacitic volcano majority of eruptions occur during the maximum number of volcano-tectonic earthquake.

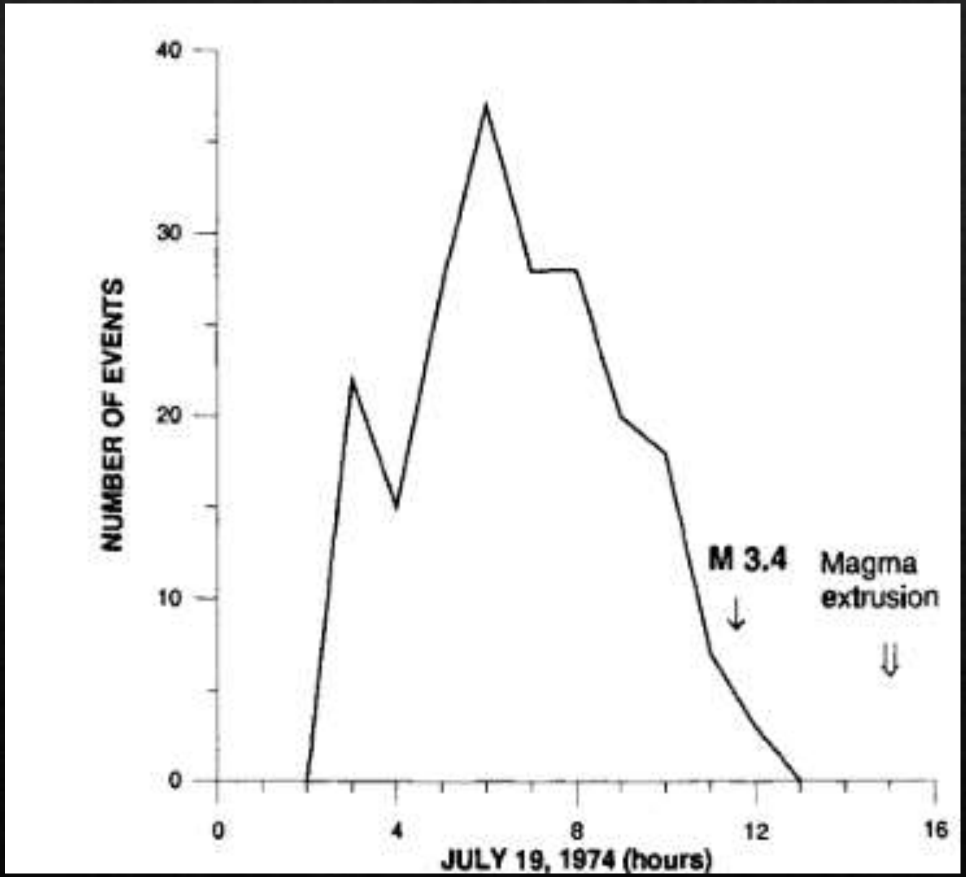
What do you think is the possible reason for these multipeaks?

Multipeak temporal variation in seismic events is the result of migration of seismic foci (or seismic clusters). As just before eruption seismic activities begin to concentrate at shallower depths.

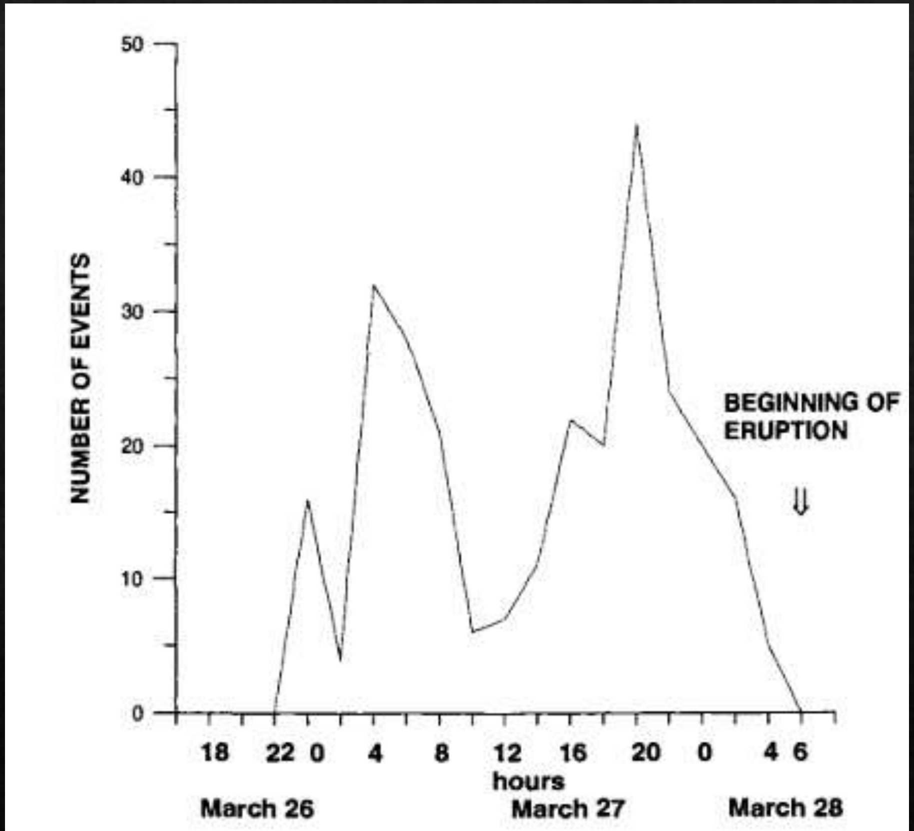


- *We will see a few examples of temporal distribution of earthquake swarms, i.e. , no of events vs time graphs of a few volcanic eruptions.*

Temporal distribution of events for Basaltic magma (Low viscosity)

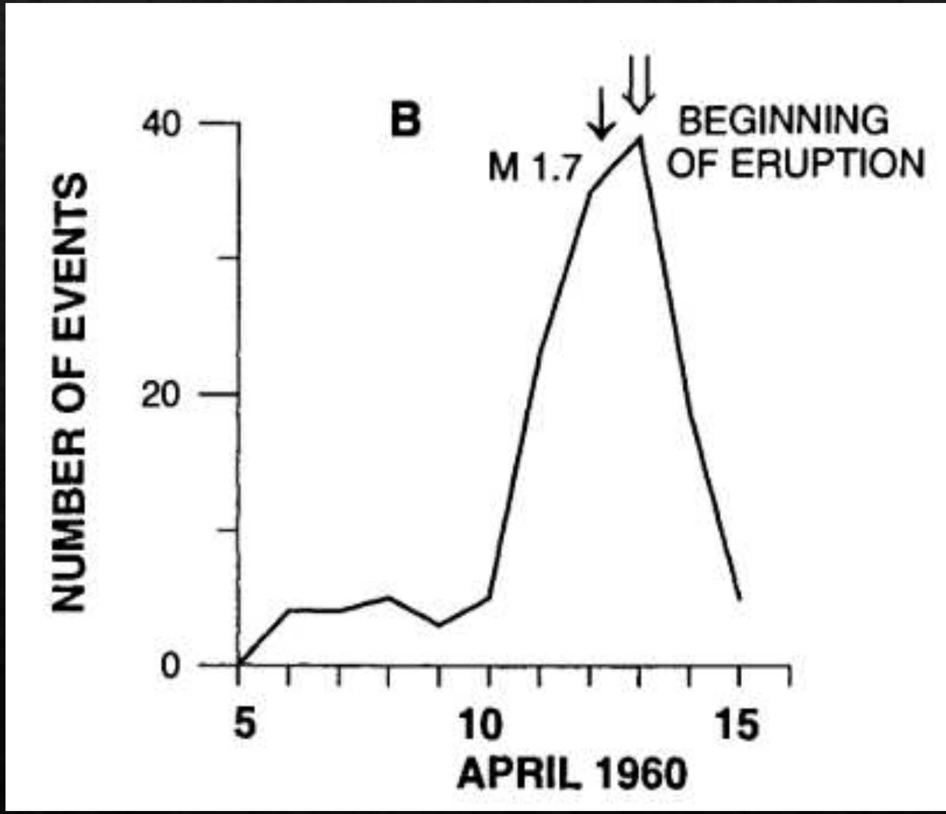


Kilauea volcano

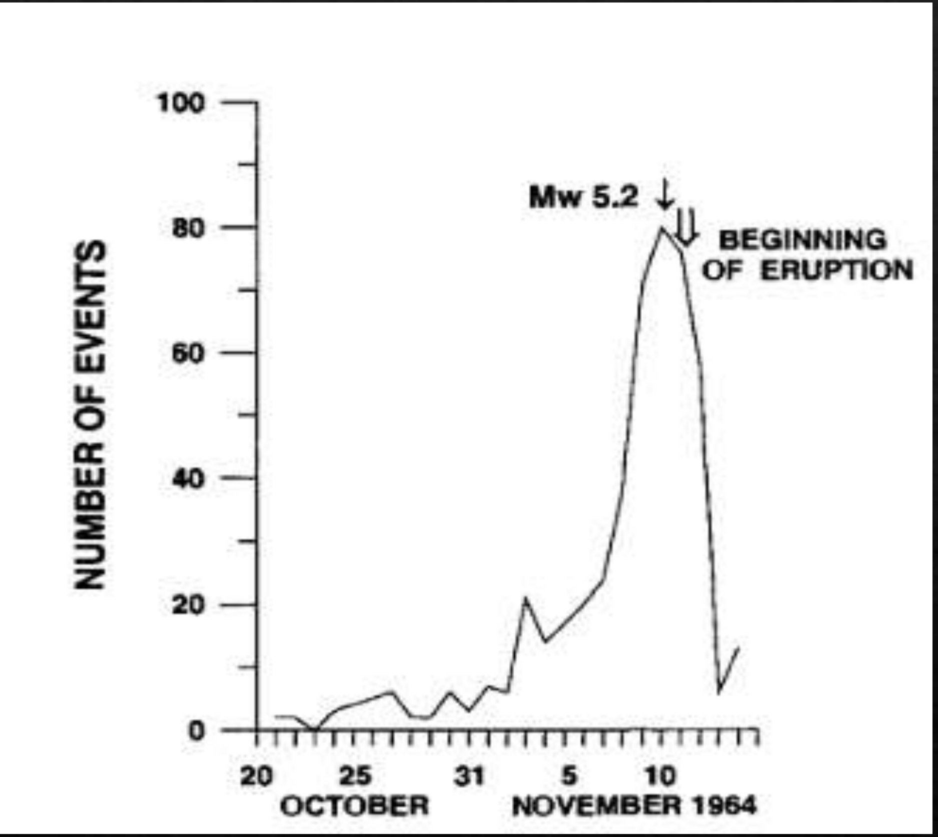


Mt. Etna , Sicily

Temporal distribution of events for Andesitic magma (Intermediate viscosity)

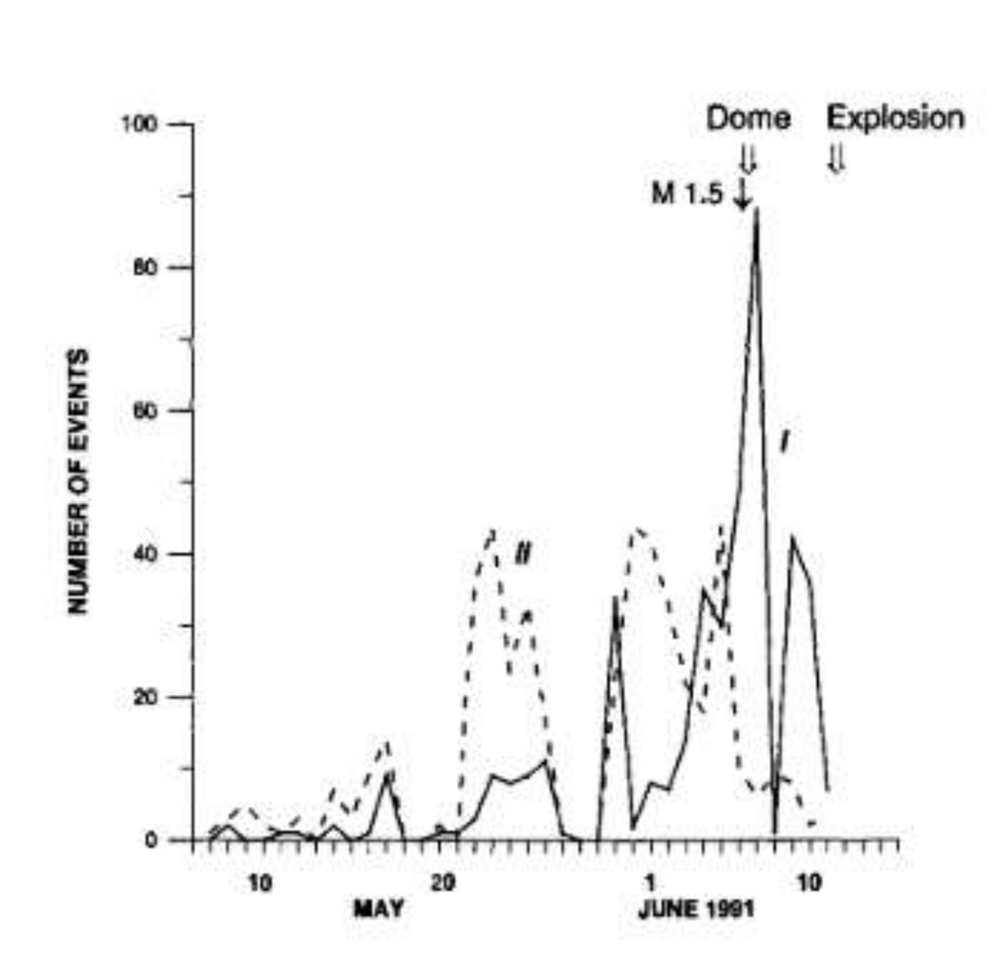


Bezymianny Volcano, Russia

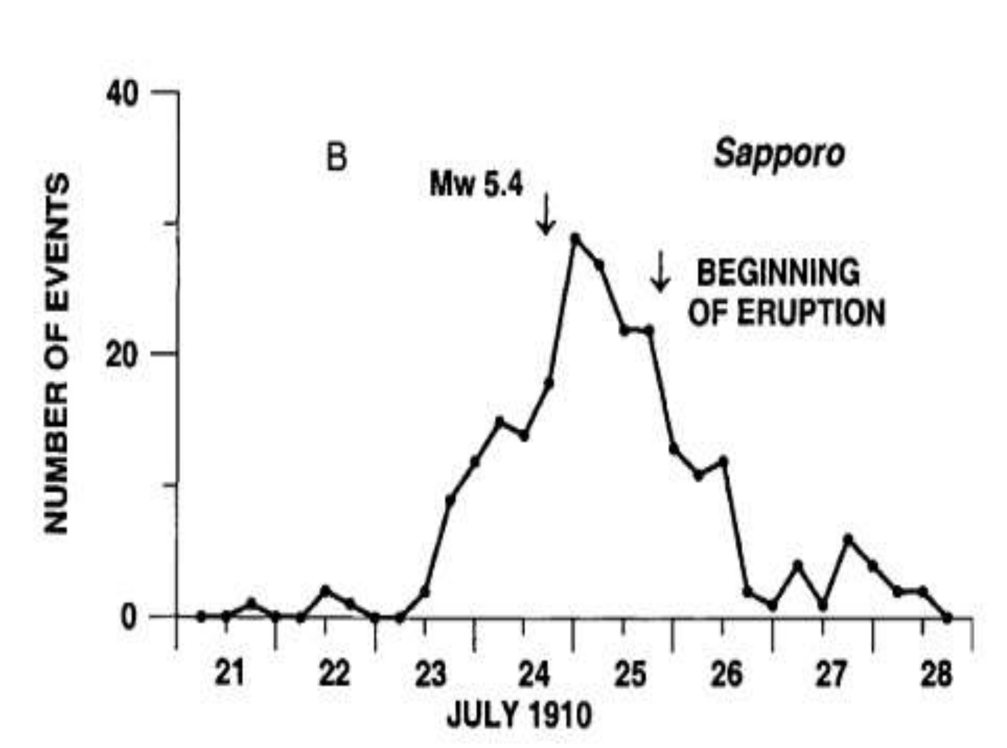


Sheveluch Volcano, Russia

Temporal distribution of events for Dacitic magma (HIGH VISCOSITY)



Usu volcano, Hokkaido



Pinatubo volcano

Identifying viscosity changes before eruption

- We know that magma viscosity determines type of eruption. Most of volcanoes have been already classified according to there viscosity. But sometimes viscosity may be different from previous eruptions during a particular eruption.

- Now if we could identify if there is going to be some change in predetermined viscosity type then it could be of great use in predicting eruption hazards and warning people ahead to evacuate places nearby volcano.

May 2018 rift intrusion and eruption of Kilauea Volcano, Hawaii displayed exceptional chemical and thermal variability in erupted lavas, leading to unpredictable effusion rates and explosivity. But monitoring its fault plane solution (FPS) we could pre-estimate the chances of more viscous eruption than it use to be.

- Fault plane solution or FPS- indicate a fault's orientation and sense of movement.

The key idea is – rotation of FPS by 90 degree indicates the presence of high viscous magma.

As it was observed in lower east rift zone (LERZ) that FPS rotated by 90 degree (the red peach balls show rotated FPS), it was predicted that viscosity of magma beneath is high in contrast to it being low (basaltic) usually.

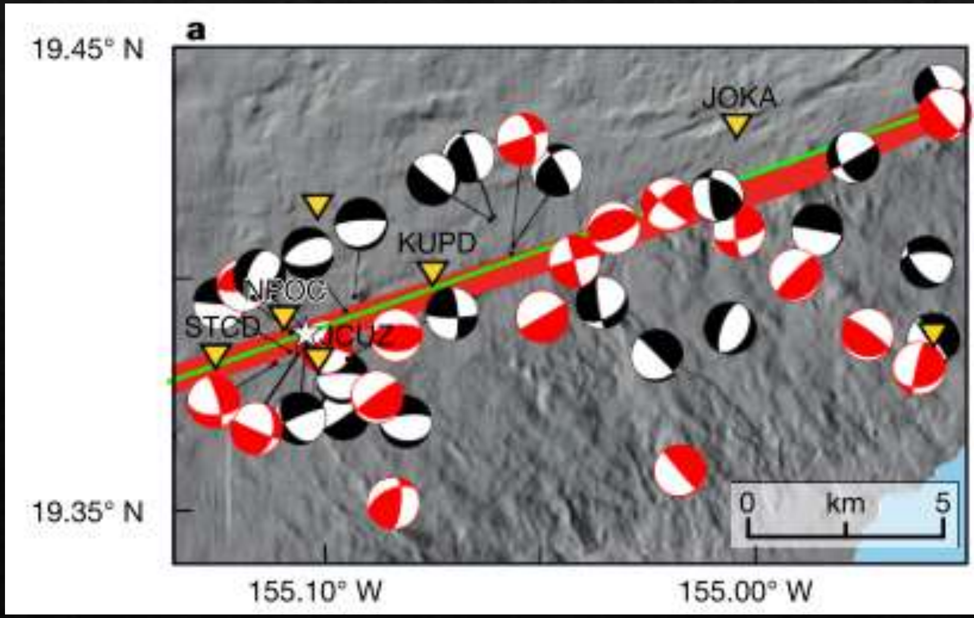
From where does this high viscous magma came?

Some of the magma was stagnant beneath PuuOo vent .

Overtime this magma partially crystallized and formed a semi-rigid barrier that impeded further transport downrift.

In May 2018, the increase in summit magma pressure increased the pressure beneath the PuuOo vent to which caused failure of the semi-rigid magma barrier.

This triggered the downrift transport of magma through a system that contained stagnant pocket of higher viscous magma.



Lower east rift zone

Viscosity threshold for FPS rotation

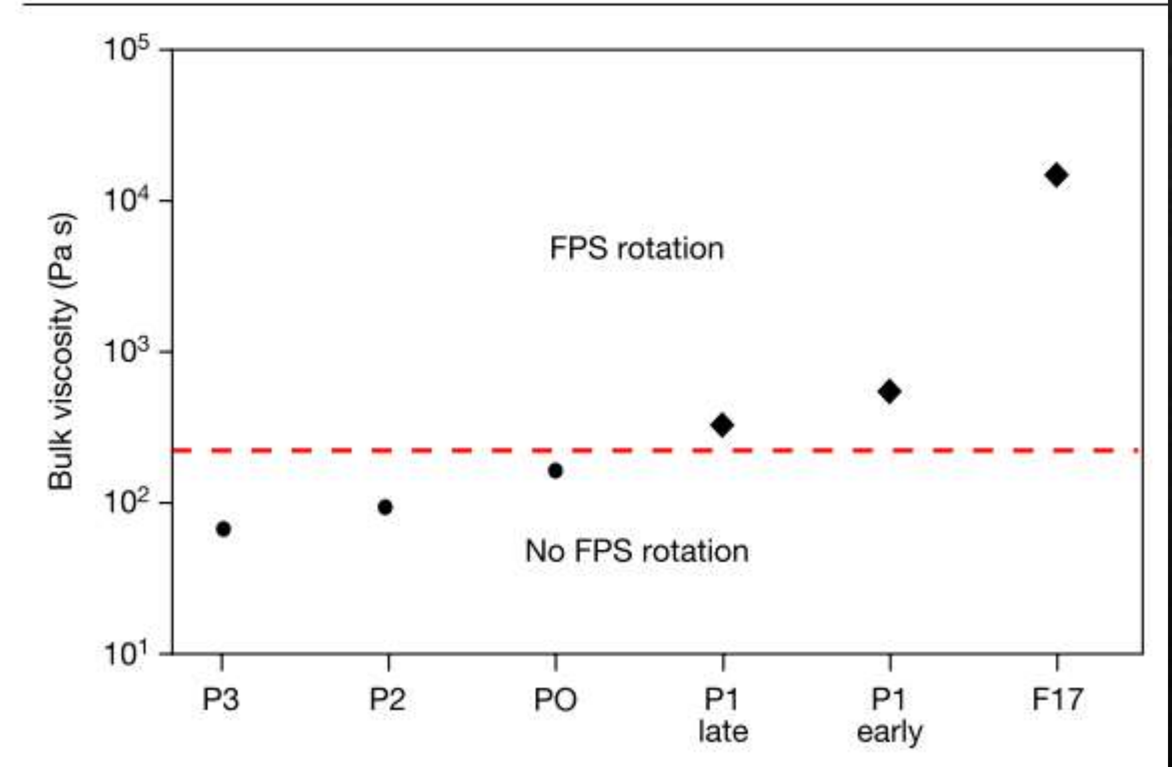


Fig. 4 | Bulk viscosity of Kīlauea 2018 and Pu‘u ‘Ō‘ō (PO) eruptive products.

Lower-viscosity (<~102 Pa s) magmas are not associated with periods of FPS rotation (circles), whereas higher-viscosity (>~102.5 Pa s) magmas are associated with periods of FPS rotation (diamonds). The red dashed line indicates the threshold bulk viscosity for FPS rotation.

How is high viscosity doing this?
For FPS rotation, is it just fault rotating in real or it can rotate by stress field rotation only?

- Rotations of the axis of local maximum compression (FPS P-axis orientations) by approximately 90° have been observed in double-couple FPS for volcano-tectonic earthquakes prior to and during eruptions and have been ***linked to stresses produced in the walls of an inflating or pressurizing dike.***

- Such stress-field rotations of around 90° have been documented only in cases where the erupted magma is highly and/or partially crystalline and thus may reflect that ***the stress is normal to the flow direction during magma emplacement***.

- ***Dynamic normal stresses may result from a volume increase during flow of highly crystalline*** magma under a velocity gradient, via a nonlinear process known as shear dilatancy.

- Therefore, comparison of local stress-field response at a single volcano between episodes of low- and high-viscosity magma transport is necessary to prove the hypothesized link between magma viscosity and stress-field rotation.