Fluvial seismology

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Many active Earth surface processes, such as landslides or sediment transport in flooding rivers can be challenging, costly and potentially dangerous to monitor.

Thanks to seismology !

Rivers, landslides , sediment transport etc. all transfer energy to the ground in the form of elastic or seismic waves. Traditionally considered "noise" by earthquake seismologists, these seismic signals contain valuable information about the processes that generated them and the ground through which they travel. By decoding these signals, we can use this information to characterize and study these processes.

Major Cause of fluvial seismicity

1. Landslides
2. Storms
3. Heavy Rainfall
4. Glacier melting

Main types of seismic sources

1. Debris flow
2. Bedload Transport
3. Fluid traction
4. Air water interaction

Type of information we decode from "Noise"

1. To identify the specific sources of seismic signals (e.g., waterfalls, landslides, etc.).
2. Characterizing the signals of water turbulence and sediment transport.
3. Characterize seismic wave attenuation properties in river .

Now we study some case study to understand Fluvial seismic source characteristic.

Analysis of seismic noise induced by rivers

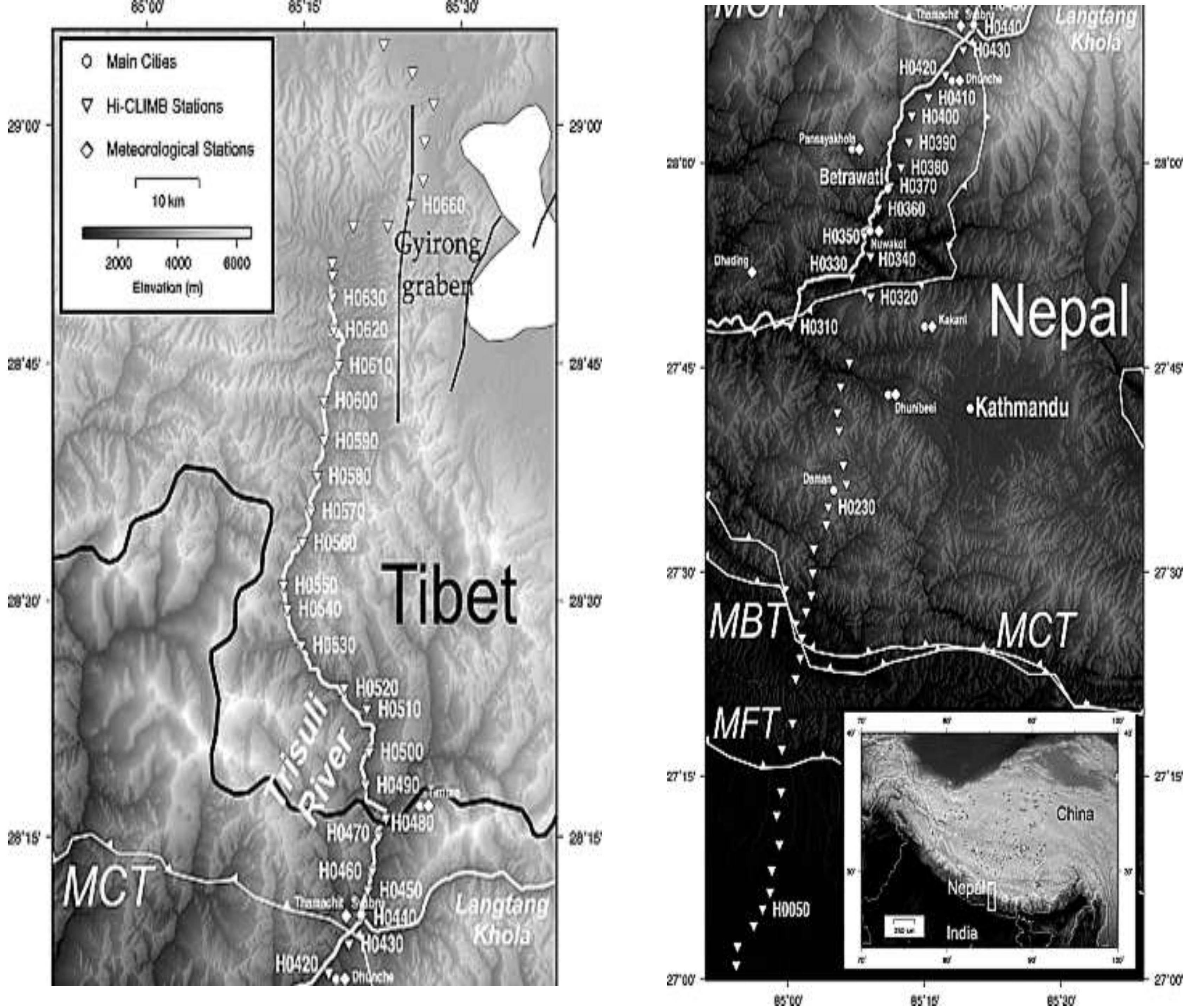
A. Burtin et al. 2008

Aim of the analysis:
To found out the potential of using background seismic noise to quantify in continuous river bed load and monitor its spatial variations.

Data acquisition:

The data was used from (Hi-CLIMB), a project designed to image the lithospheric structures across the Himalayan collision zone. During this 3-year experiment, **115 broadband seismometers** were deployed from southern Nepal to the Bang-gong suture in central Tibet along the Trisuli River.
Burtin used the data for the year 2003.

Location map shown ahead.



85°00'
85°15'
85°30'
29°00'
28°45'
28°30'
28°15'
28°00'
27°45'
27°30'
27°15'
27°00'
Main Cities
Hi-CLIMB Stations
Meteorological Stations
10 km
2000
4000
6000
Elevation (m)
H0660
Gyirong graben
H0630
H0620
H0610
H0600
H0590
H0580
H0570
H0560
H0550
H0540
Tibet
H0530
H0520
H0510
Trisuli River
H0500
H0490
H0480
H0470
H0460
H0450
MCT
Langtang Khola
H0440
H0430
H0420
Dhunche
H0410
H0400
Pansayakhola
H0390
H0380
Betrawati
H0370
H0360
H0350
Nuwakot
Dhading
H0330
H0340
H0320
Nepal
H0310
Kakani
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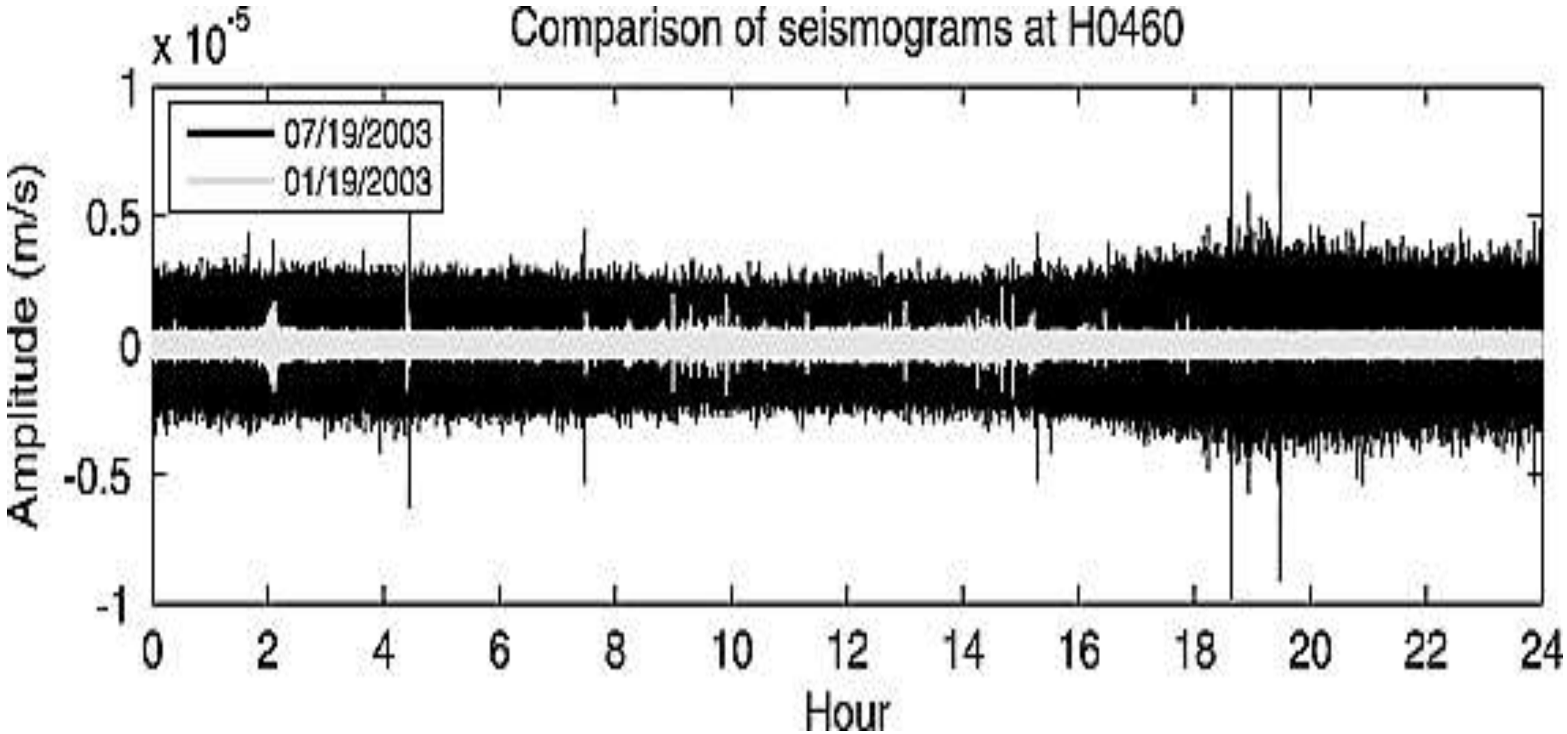
Kathmandu
Daman
H0230
MBT
MCT
MFT
China
Nepal
India
H0050

Observation 1

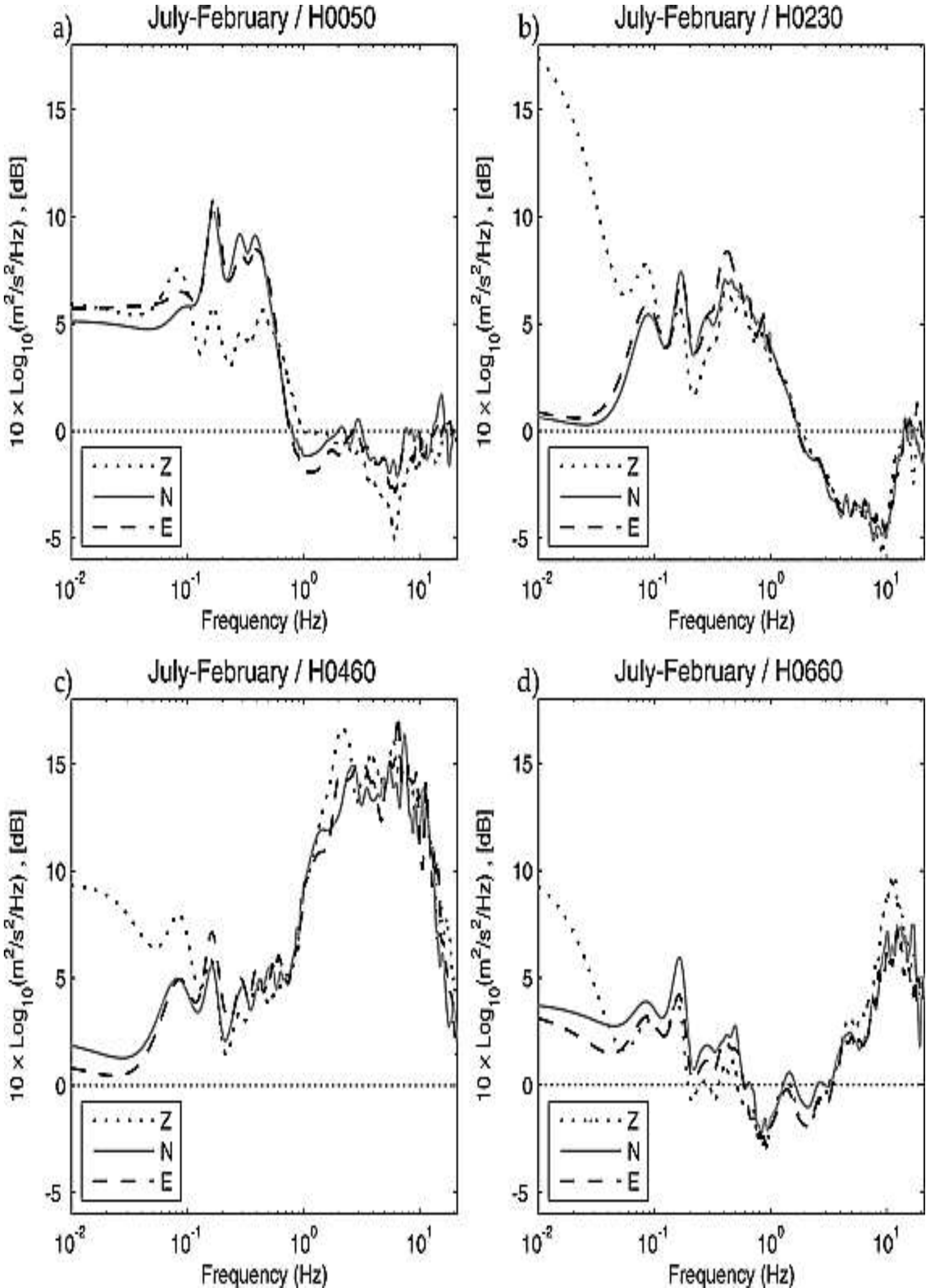


Comparison of two 1-d-long vertical seismograms recorded at station H0460. A full day of January (19 January 2003) and July (19 July 2003) are represented in white and black, respectively.

- During summer, high-frequency noise is one order larger than during winter.
- Daily variation of the noise during summer is also noticed, with larger noise amplitude at night than during the day.

Observation 2

Seasonal Fluctuations



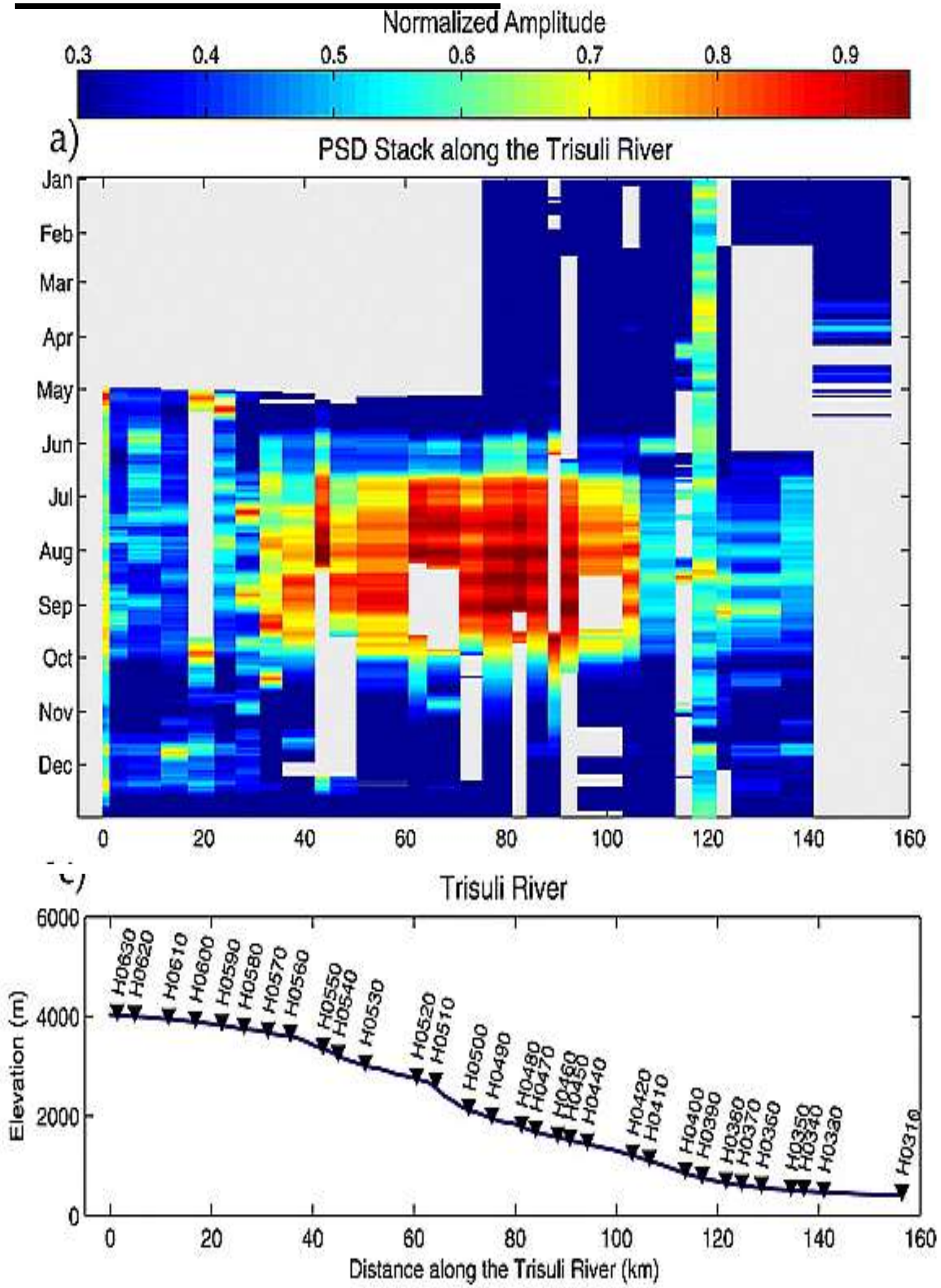
In the microseism band (0.1–1 Hz), stations H0050, H0230, and H0460 record larger energy amplitudes in July by about 5 to 10 dB .
Possible explanation: The **enhancement of oceanic swell in Gulf of Bengal.**

H0460 : (<u>nearest to trisuli river</u>) The noise ***<u>amplitudes on the seismograms from station H0460 are then 6 times larger at high frequency during the monsoon period than during the dry season</u>***. A similar observation was made at most stations located along the Trisuli River.

Possible explanation: ??

Seasonal fluctuation of seismic noise: obtained by subtracting the average July PSD to the average February PSD for 2003 at stations (a) H0050, (b) H0230, (c) H0460, and (d) H0660.

Observation 3



- Strong increase of the high- frequency energy (>1 Hz), from stations **H0410 to H0560 from June to September**.
- For these stations, the level of noise shows a first increase at the end of May lasting until mid-June.
- Then, the energy reveals a second increase and reaches an almost constant level until the end of September with intermittent peaks that are well correlated between stations.
- The time period of energy enhancement coincides with the summer monsoon period in Nepal.

Mean vertical PSDs at Hi-CLIMB stations along the Trisuli River.
Location of the Hi-CLIMB stations (downward black triangles) projected on the elevation profile of the Trisuli river.

What do you think could be the possible explanation for this type of seismicity?

a) More amp during July at seismometer near river?

b) Monsoon started from mid June but seismicity increase from may , why?

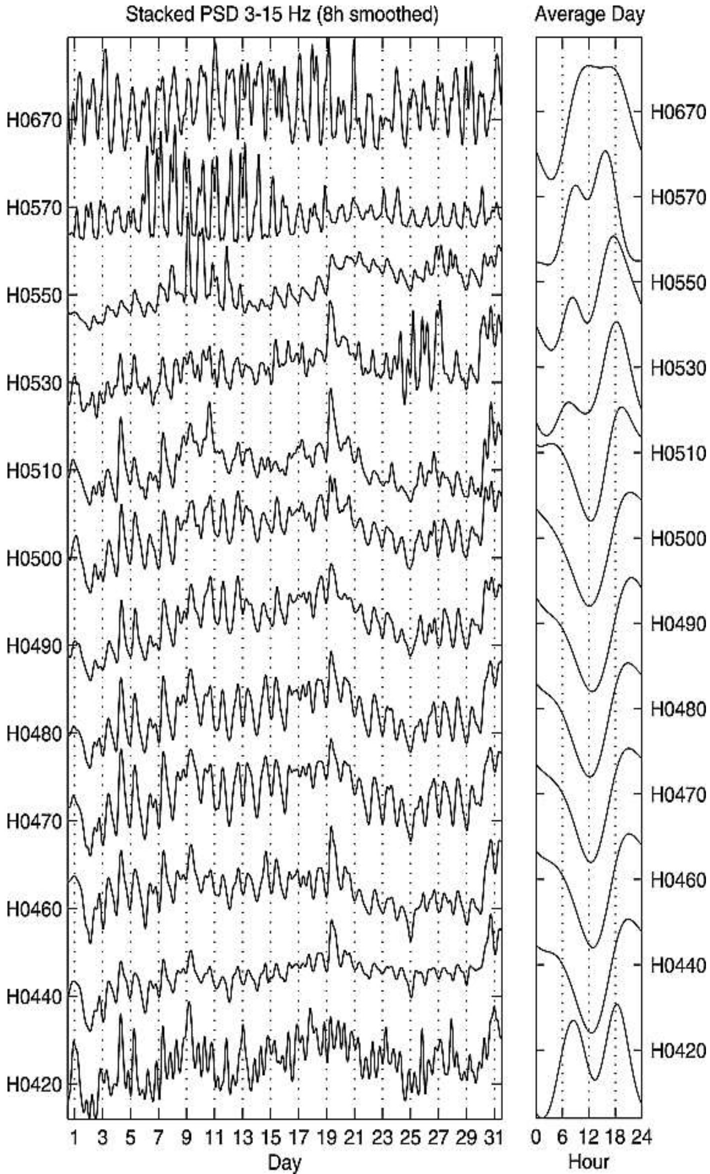
c) High PSD at seismic stations along Trisuli river?

d) High seismicity during night than day?

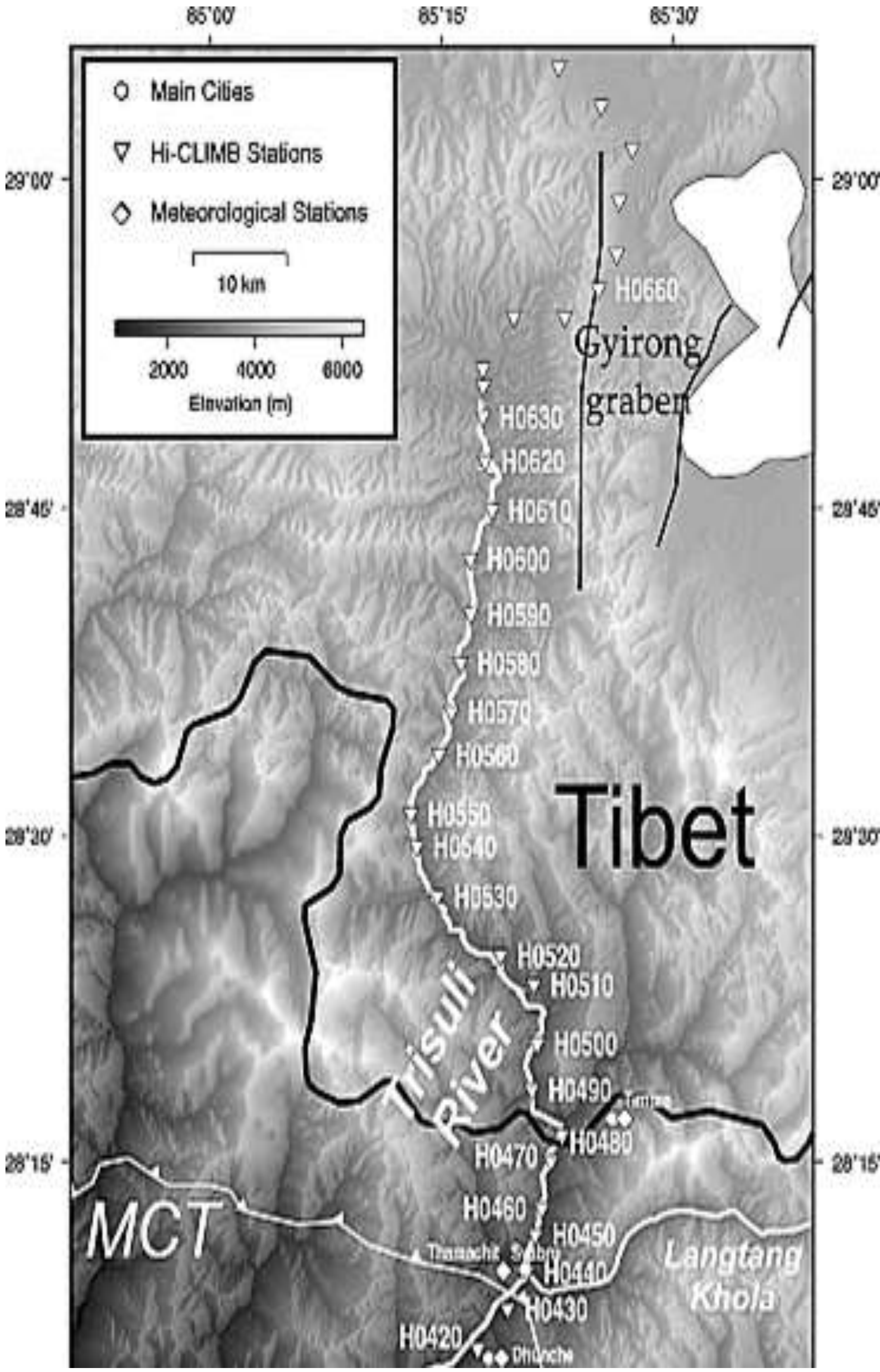
- Anthropogenic source ??
- Glacial melt (seasonal fluctuation) ??
- Precipitation ??
- Water level of river ??
- Bed-load transport ??
- Any other idea??

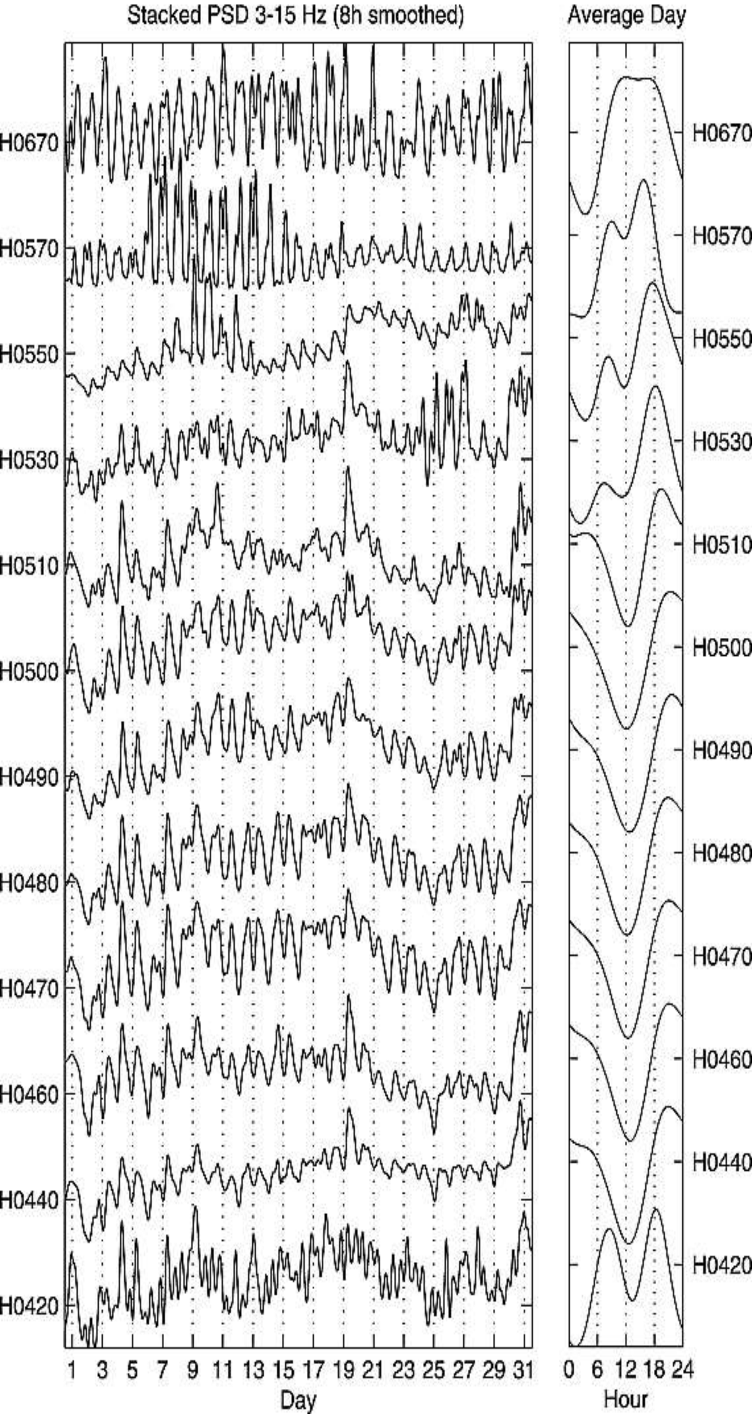
Let's see which one or more may be the possible reason...

Possibility of Anthropogenic source



(a) PSDs stacked over a frequency band of 3–15 Hz for July 2003.





- This 24-h cycle has a minimum amplitude reached at 01 pm and a maximum amplitude late in the evening.
- <u>This suggests that the source responsible for this seismic noise is anticorrelated with the possible sources of anthropogenic noise, which has a minimum at night.</u>

(a) PSDs stacked over a frequency band of 3–15 Hz for July 2003 and for a set of Hi-CLIMB stations from north to south, top to bottom, respectively. (b) Corresponding mean daily noise level variations calculated by summing 24-h-long segments of the curves

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- Glacial melt (seasonal fluctuation) ??
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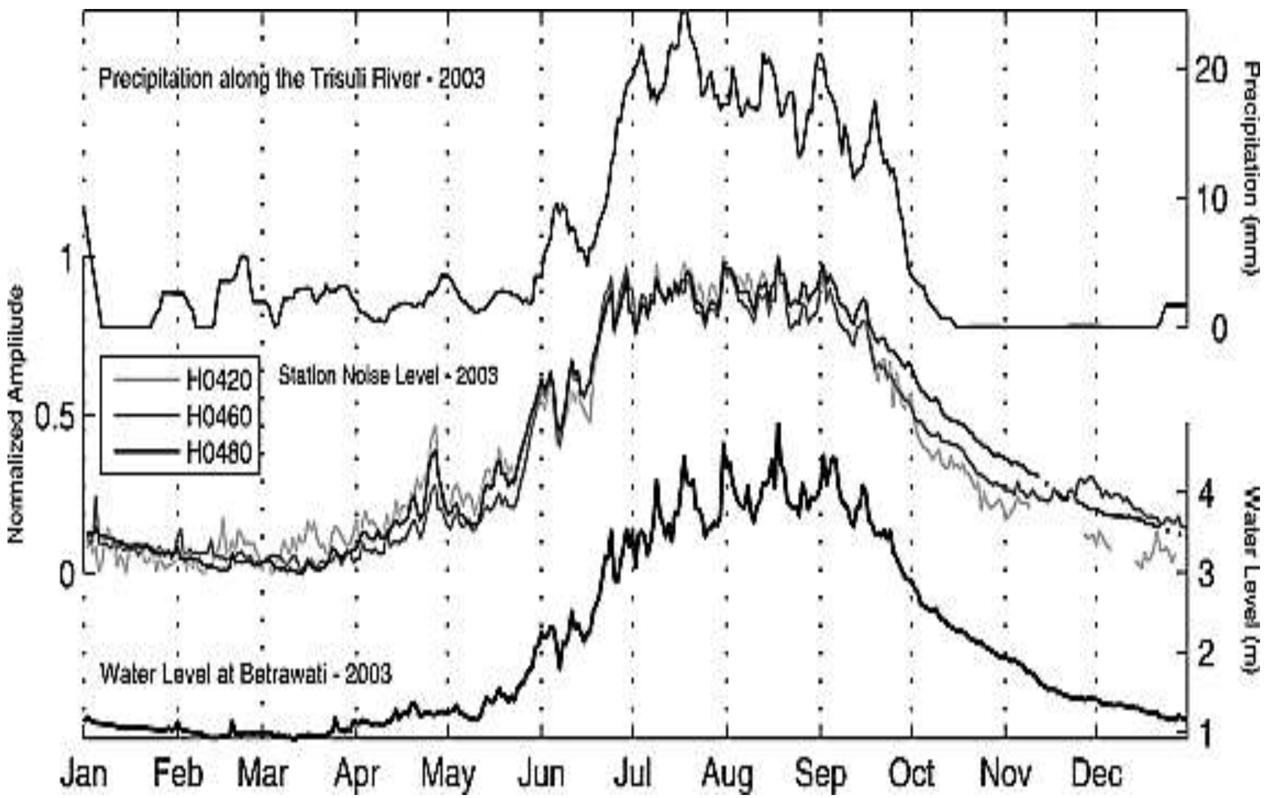
Comparison of local meteorological and hydrological data with the noise level curves



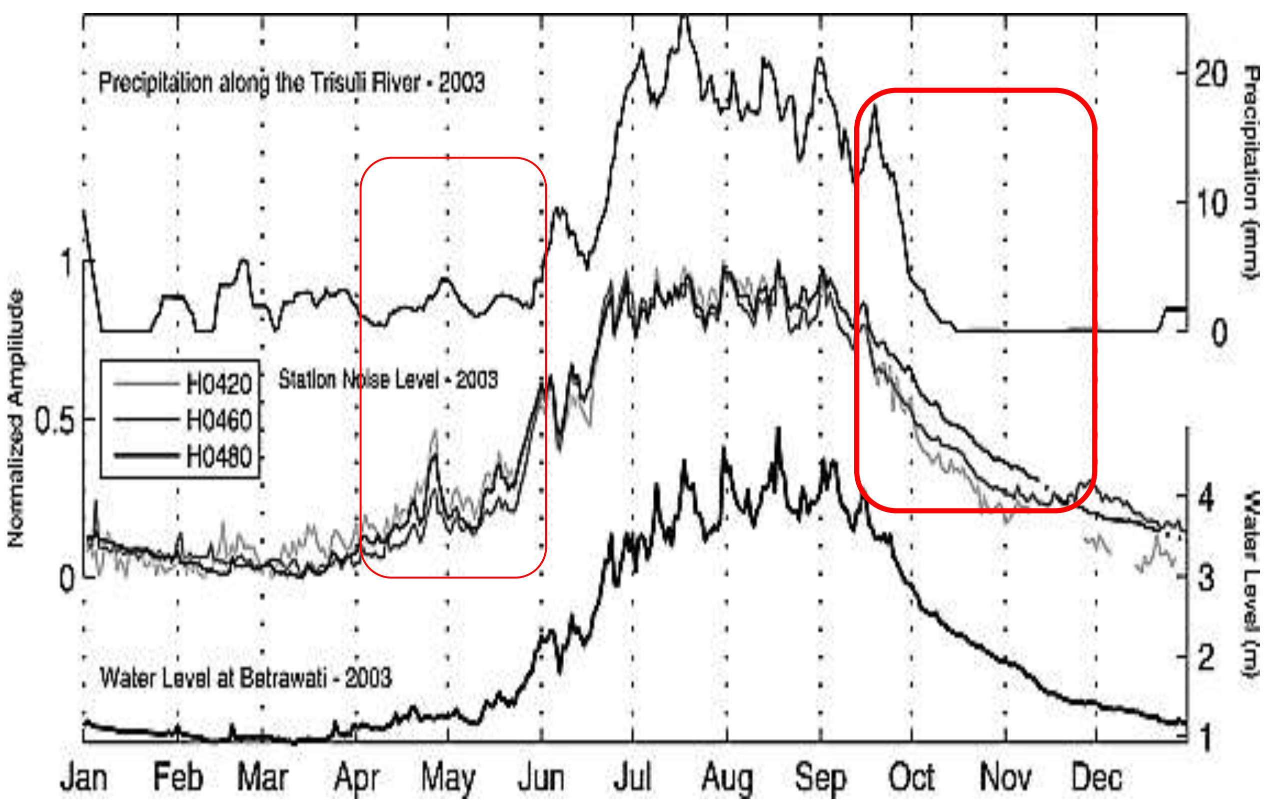
Top curve is the 10-d centered moving average of the daily precipitation rate in mm for year 2003 at 8 meteorological stations from the Department of Hydrology and Meteorology of Nepal (DHM) located along the valley of the Trisuli River.

Middle curves are the high-frequency noise level (averaged over the three components and the frequency band 3–15 Hz for year 2003) at stations H0420, H0460, and H0480.

Bottom curve is the Trisuli water level in meters measured at the town of Betrawati near station H0370 during year 2003.

From January to May the precipitation in the region are rare and weak meanwhile the noise level is low. However, the noise level time series does not correlate with the rare local rainfall.

In June at the onset of the monsoon season, the precipitation rate increases and remains at the highest levels of the year until the end of September. In June, seismic noise at the observed stations increases rapidly, reaching an amplitude threshold for the following three months.



At the end of September, the precipitation rates depict a sudden decrease whereas the recession of ambient noise is gentler.

- Peaks of noise level during the monsoon period are not well in phase with peaks of precipitation.
- Correlation coefficient between noise amplitude at H0460 with precipitation is 0.61.

What do you think could be the possible explanation for this type of seismicity?

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- Glacial melt (seasonal fluctuation) ??
- Precipitation
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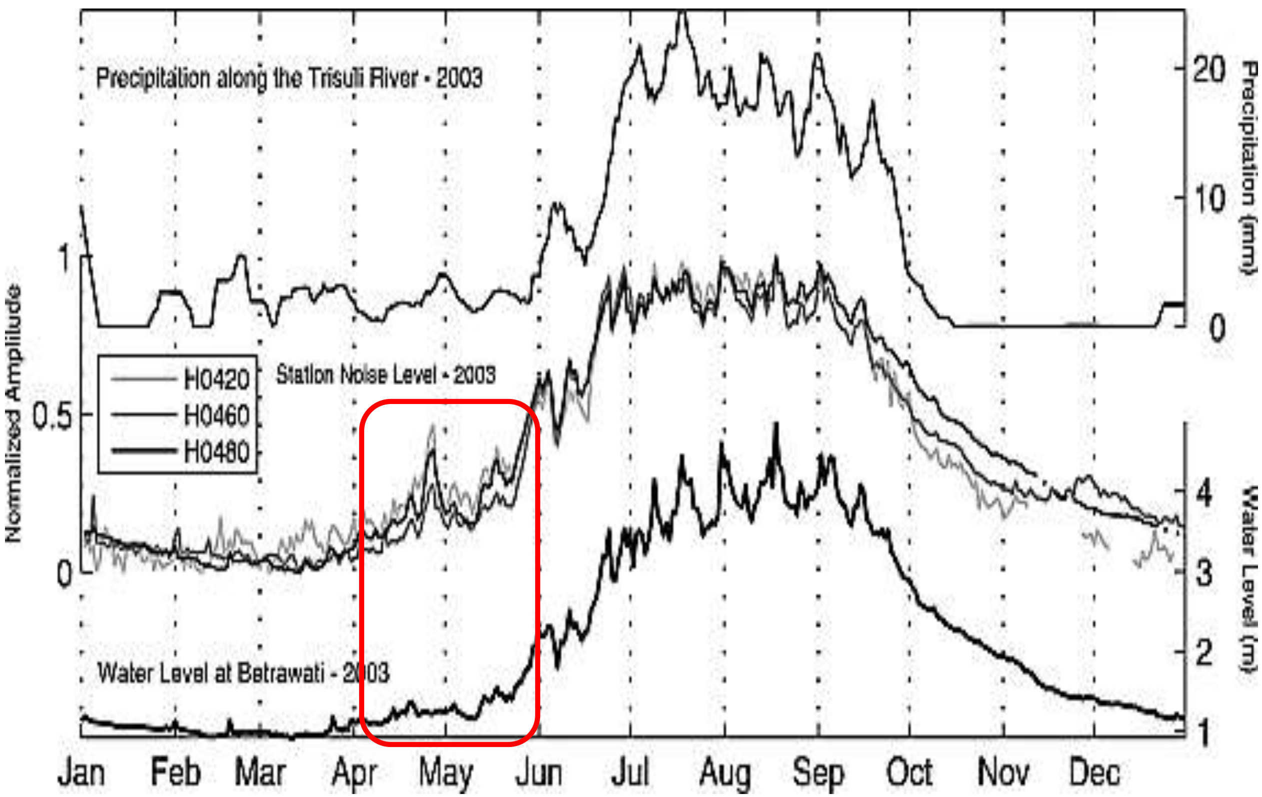
- Bed-load transport ??
- Any other idea??

Water discharge through Trisuli river was continuously monitored and we find-

1. Gentle increase of discharge from April to May.
2. Rapid augmentation in June <u>due to the fast melting of snow and ice in glaciers in response to increased air temperature</u>.
3. In July and August, discharge rates reach the largest values.
4. September to October- period of rapid discharge recession.
5. Whereas from November to March the discharge decreases only slightly.



- During the monsoon period, the time series of both data sets is well correlated.
- The correlation coefficient between H0460 seismic noise and water level is 0.86, whereas it is only 0.61 with precipitation.

What do you think could be the possible explanation for this type of seismicity?

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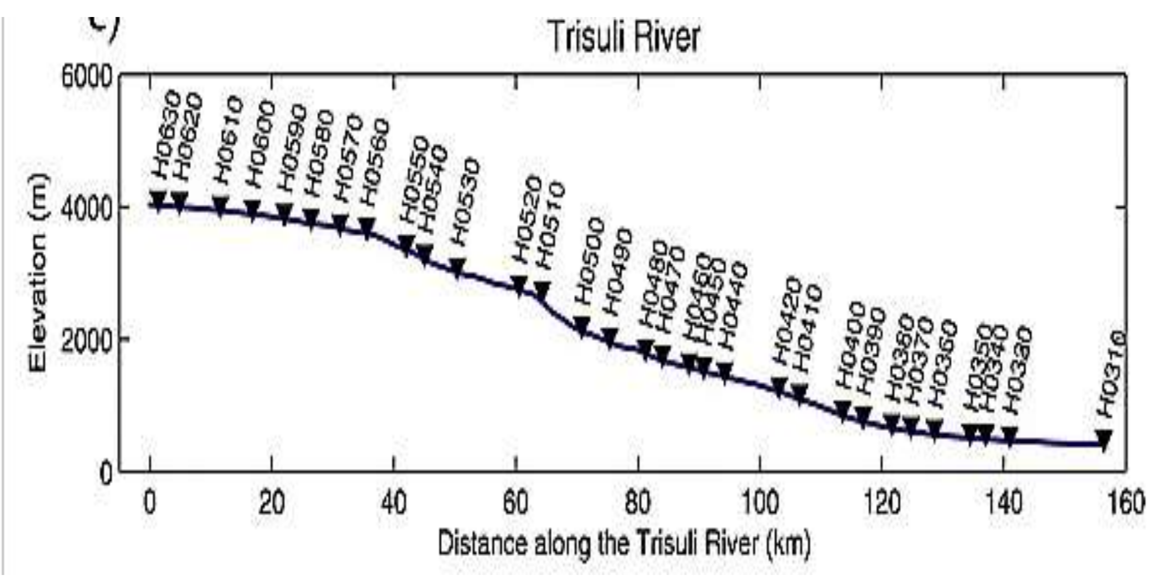
- Bed-load transport ??
- Any other idea??

1. River is going narrow on upstream while in downstream area river is wider.

→ Hydraulic radius increases in upstream → **Fluvial stress increases**

2. We see that slope gradient is steep in between H0510 TO H0410 than northern and southern.

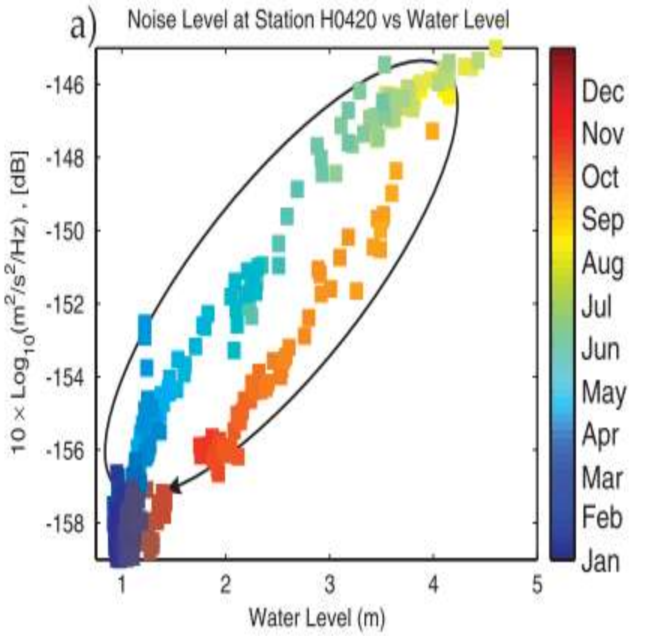
→ Slope increases → **Fluvial stress increases**



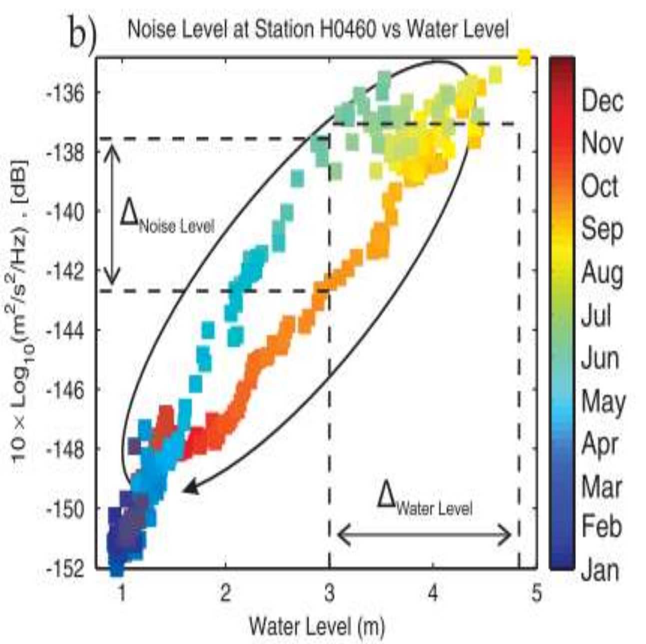
$$\tau = \rho g S R,$$

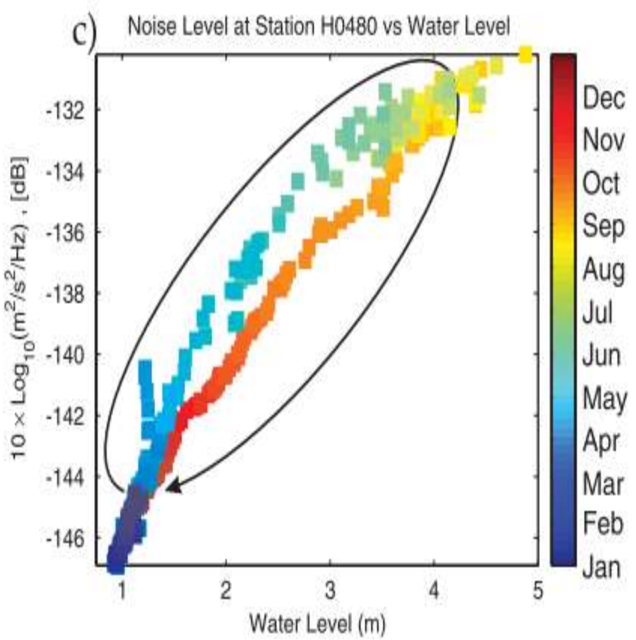
<u>Increase in fluvial stress leads to bedload transport .</u>

Characteristic of bedload transport signature



- For equivalent water level the amplitude of noise recorded at the beginning of the monsoon (June to July) is larger than the one recorded at the end of the rain season (September to October).
- part of the available bed load at the beginning of the rainfall season have been used or removed at the end of the monsoon, which leads to a decrease in the river-generated seismic noise, since only the largest boulders remain available to produce noise
- From July to August, despite a constant increase in water level (from 3.25 to 5 m), the amplitude of the noise remains almost constant (<2 dB).





Mean daily noise level amplitudes at station (a) H0420, (b) H0460, and (c) H0480 compared to the daily water level of the Trisuli River measured at Betrawati during year 2003. Each square represents 1 d, and its color indicates month of the year. The observed hysteresis progression is indicated by the black arrow curve.

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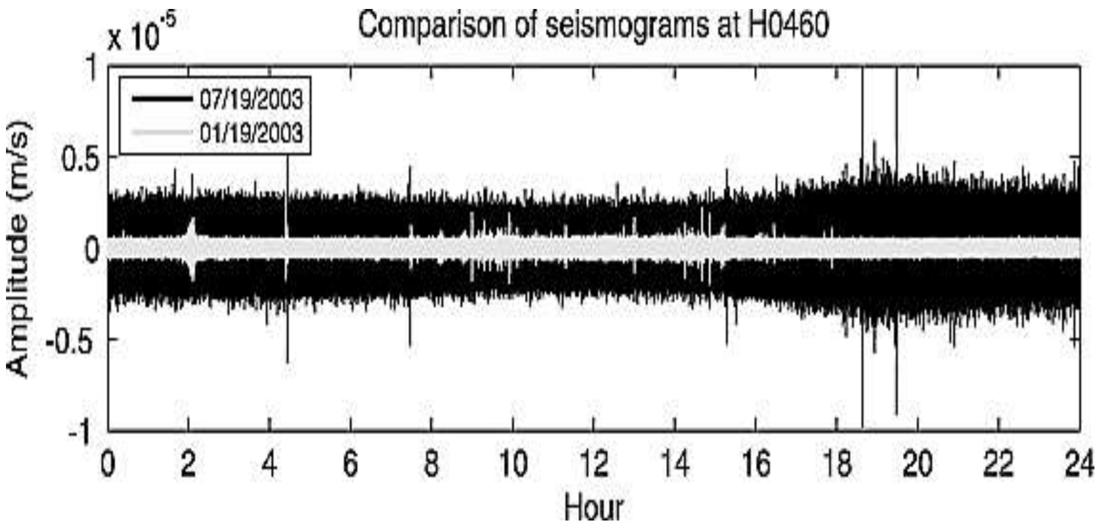
- Glacial melt (seasonal fluctuation)
- Precipitation
- Water level of river
- Bed-load transport
- Any other idea ??

Explanation for High seismicity at night



- Daily variation of discharge measurements seem to be well correlated with our observations of noise levels at seismic stations close to the Trisuli River.

- Ueno et al. [2001] show a remarkably periodic diurnal cycle during the summer monsoon. The total amount of precipitation from **04 pm to 06 am corresponds to 88% of the daily total amount.**

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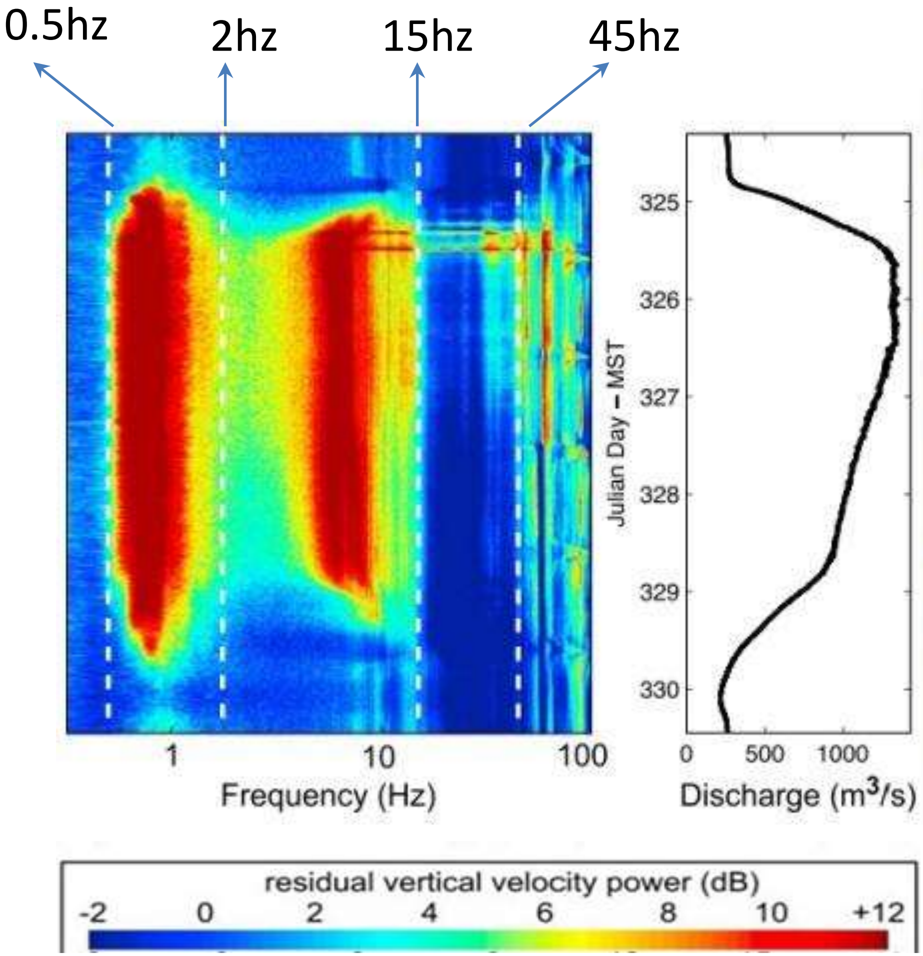
- ~~Anthropogenic source~~
- Glacial melt (seasonal fluctuation)
- Precipitation
- Water level of river
- Bed-load transport
- Any other idea – Regional characteristic (precipitation more at night).

Schmandt et al. 2013

Control Flood Experiment- Grand Canyon

- *Field site* - Eastern grand canyon .
- *Locatio*n of seismometer - 32 and 38m from the channel edge during peak discharge and minimum discharge respectively.
- *Instruments* - Three component ground velocity was measured by an L-22 seismometer with a corner frequency of 2 Hz and flat response to >>100 Hz.

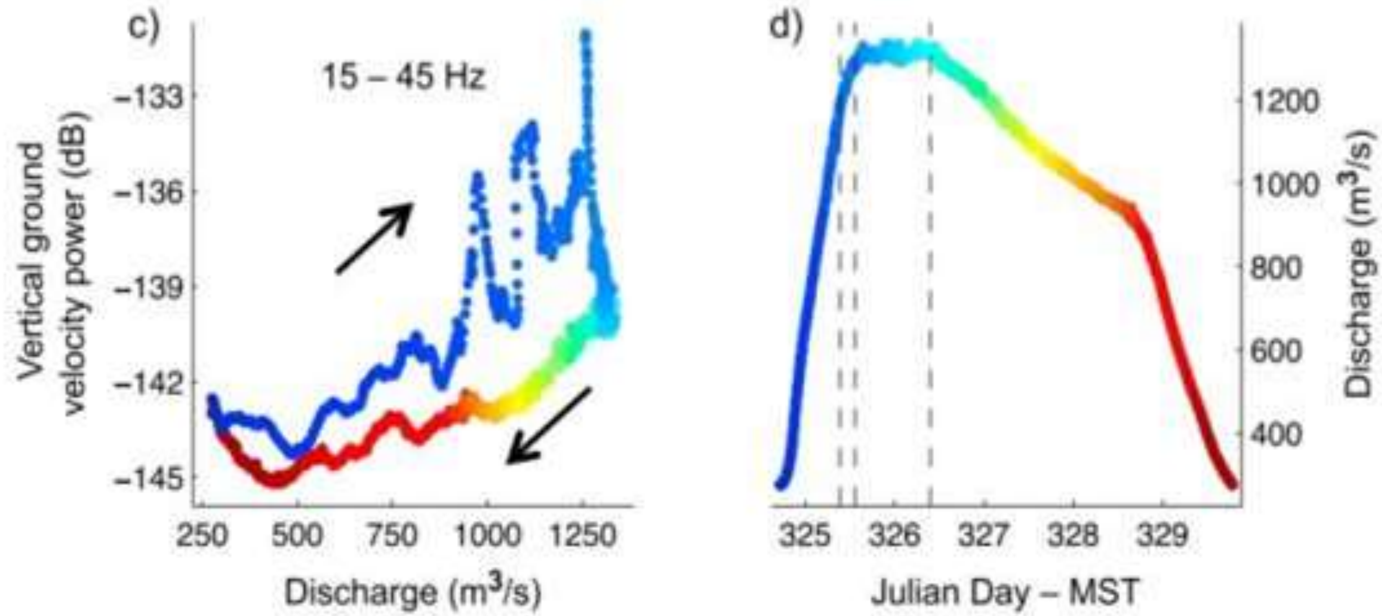
Spectral analysis



- The lowest frequency band excited by the CFE is 0.5–2 Hz, with a maximum increase of 17 dB at 0.73 Hz.
- A second local maximum of 14 dB increase occurs at 6.25 Hz.
- Frequencies from about 10–45 Hz show bursts of elevated power during near the end of the CFE's rising limb.
- Two peaks in the residual seismic spectrum remain prominent throughout the duration of the CFE, while frequencies between about 15–45 Hz are strongly excited during the rising limb but not the descending limb.

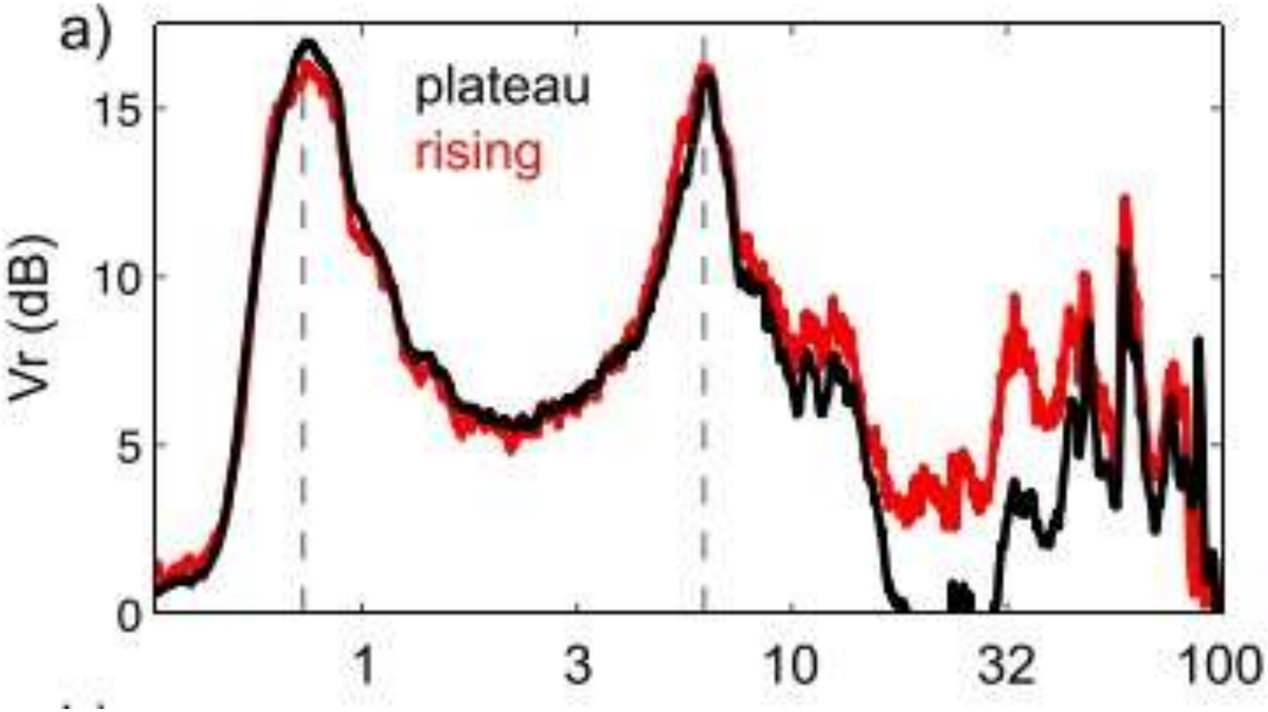
Observed signature of fluvial seismic sources

1.



- We consider the 15–45 Hz power variations to be dominantly driven by **<u>bed-load transports</u>**.
- This attribution is suggested by strong **<u>clockwise hysteresis</u>**.
- We also see in rising limb three episodes with 4–5dB power increases .
- we predict in this model the episodes with 4–5 dB power increases would correspond to <u>transient increases in bed-load flux by a factor of 2.5–3.2</u>, and the 9 dB drop in power at the end of the rising limb would correspond to an abrupt eightfold decrease in bed-load flux.

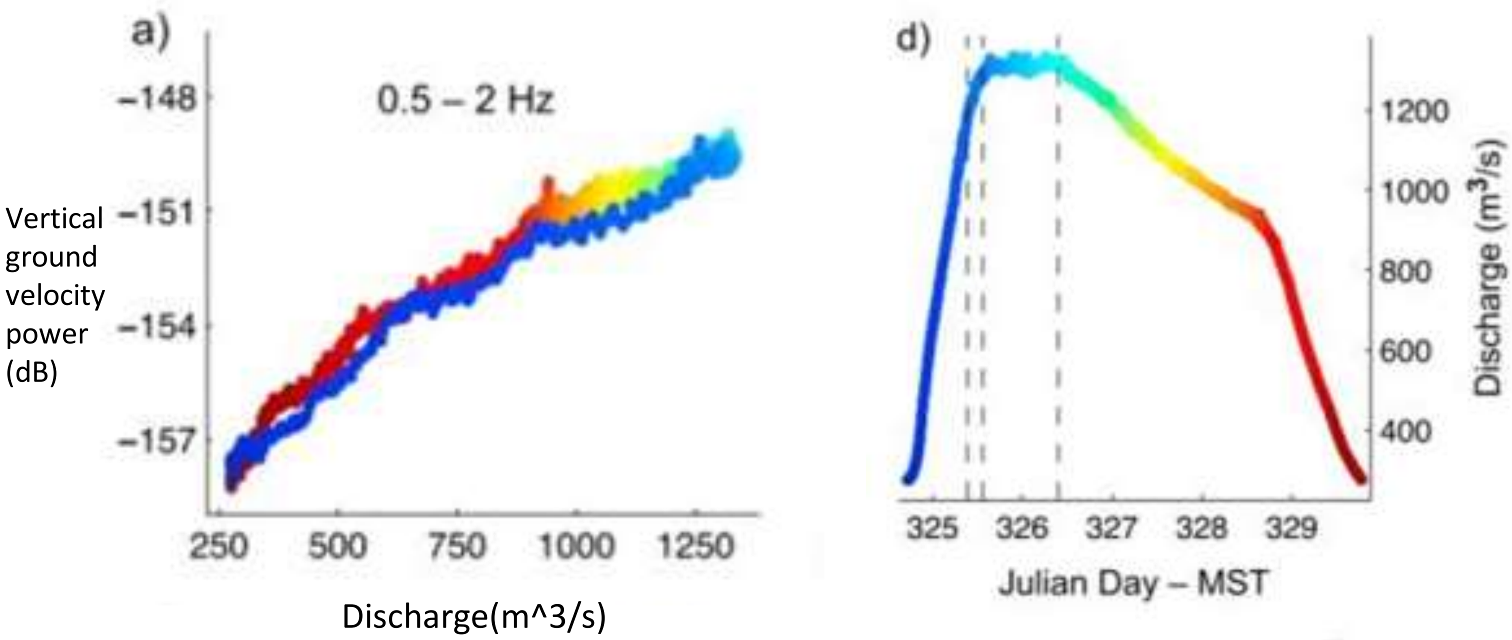
Seismic signal of bedload transport



Frequency(hz)

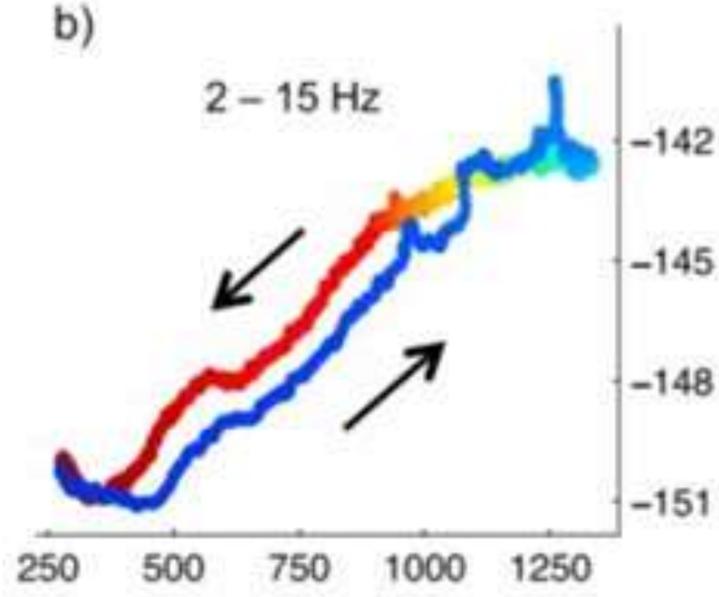
- We consider 15-45 hz power variation dominated by bedload transport .
- In that range the power of seismic signal during rising limb is clearly distinguish with plateau.

Seismicity Due To Fluid Traction



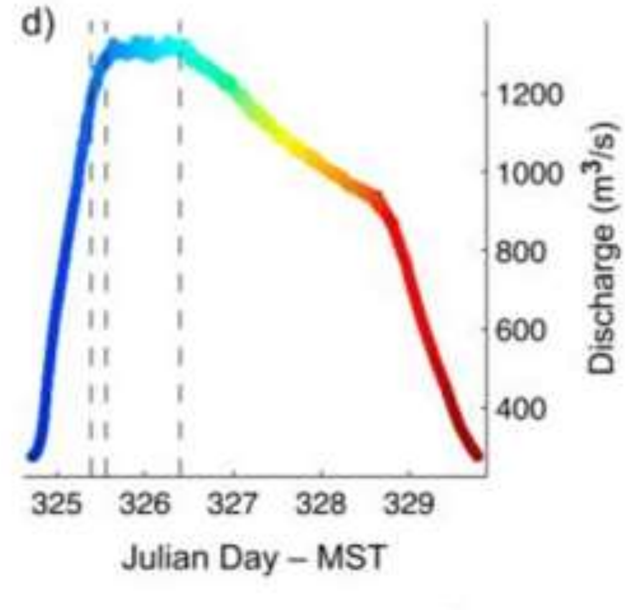
- Smooth power variations with discharge and lack of hysteresis are consistent with a fluid flow source.

Seismic Response Due to Air- Water Interaction



Vertical ground velocity power (dB)

Discharge(m^3/s)

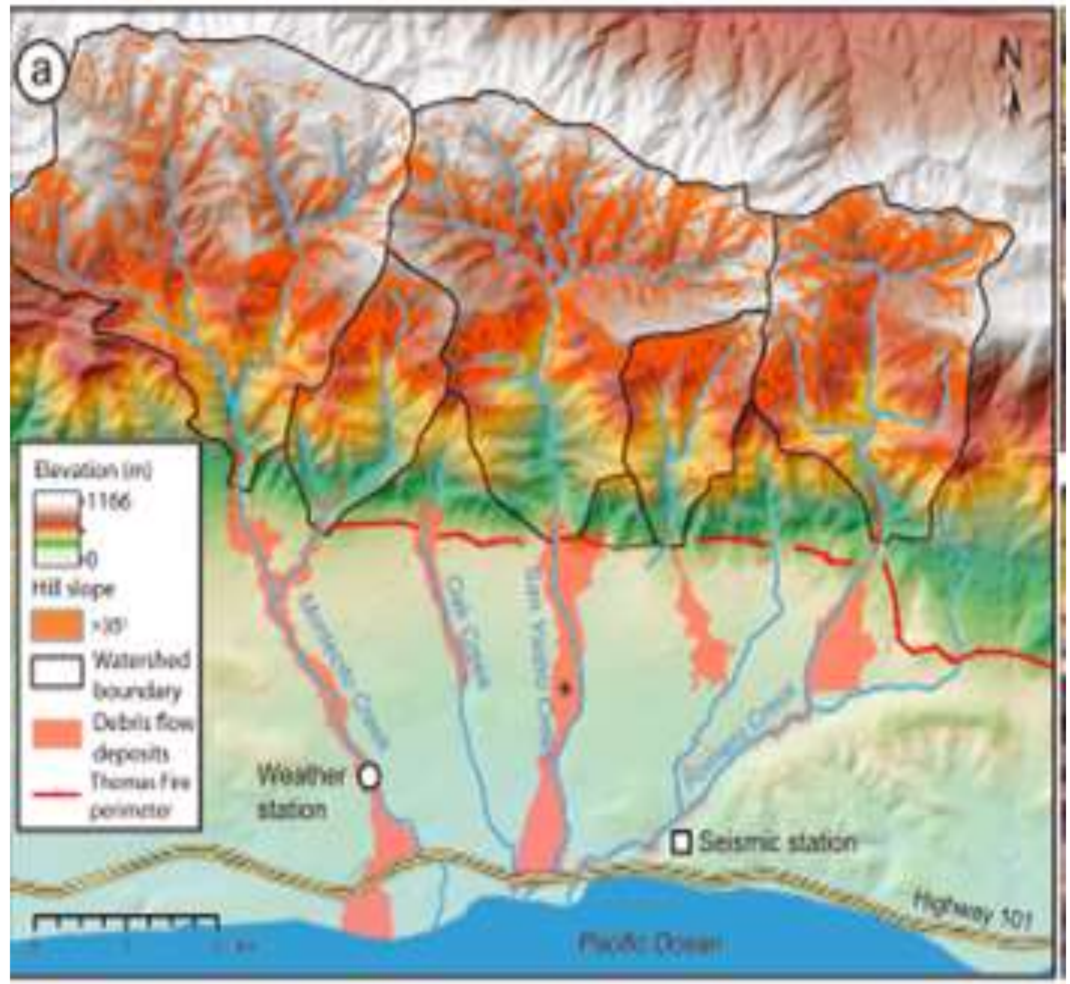


- Seismic power in the 2–15 Hz band exhibits **counter-clockwise hysteresis**.
- If waves at the fluid-air interface are primarily responsible for power in this band, the difference at intermediate discharge levels could represent a modest change in the water wave pattern owing to bed-load movement during peak discharge.

- Case study – Debris Flow At Montecito, California

Lai et al. 2018

- Seismic station used in this analysis is located within ~250 m of Romero Creek and ~1.5 km of the zone of major damage near San Ysidro Creek.

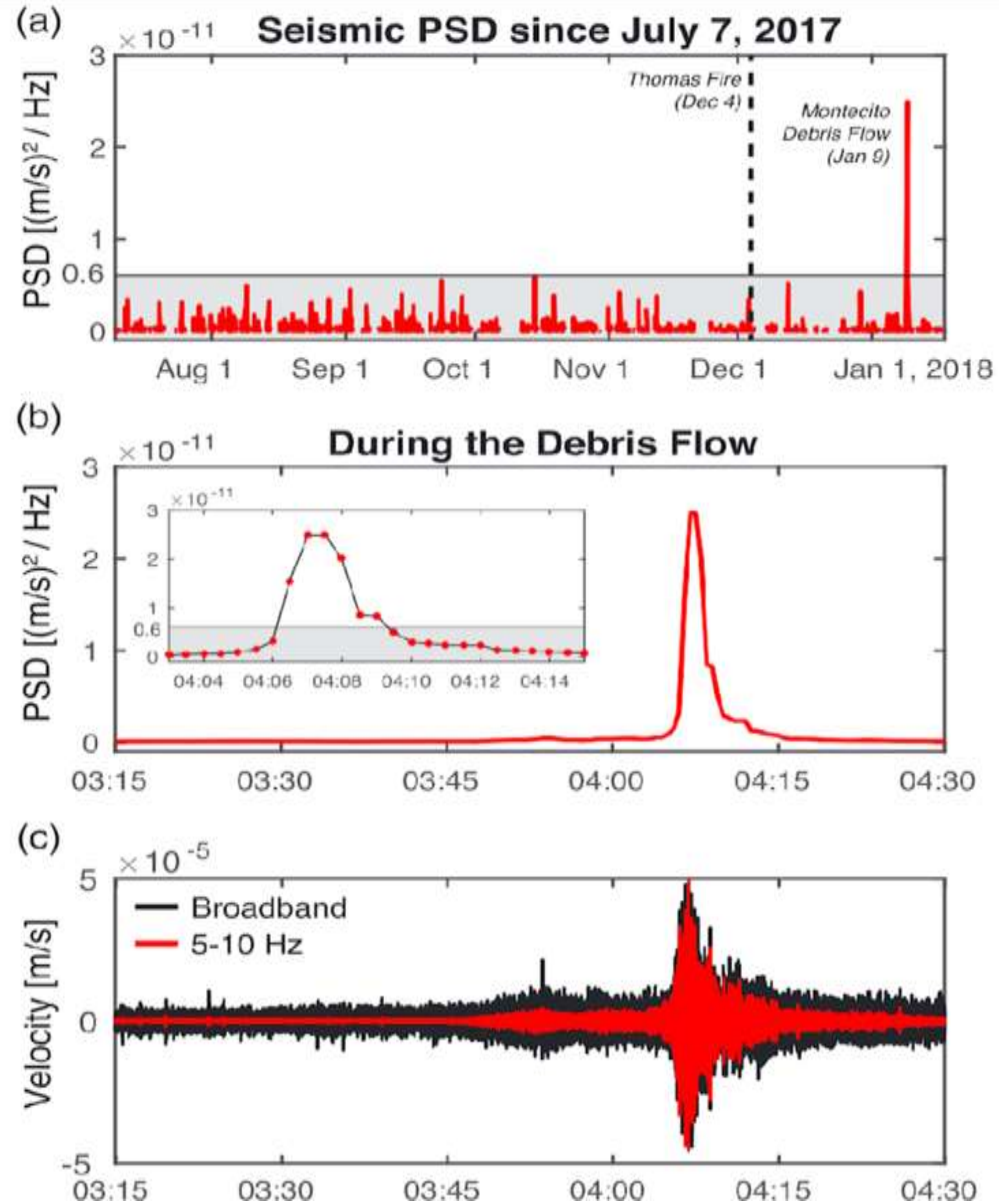


- There was a large wildfire on the hills. The first heavy rainfall after the wildfire caused heavy debris flow downwards.

Seismic Signature of Debris Flow

- Ground motion amplitude exceeding 6 × 10e(-12) (m/s)2/Hz accurately discriminates between the Montecito debris flows and any other event.

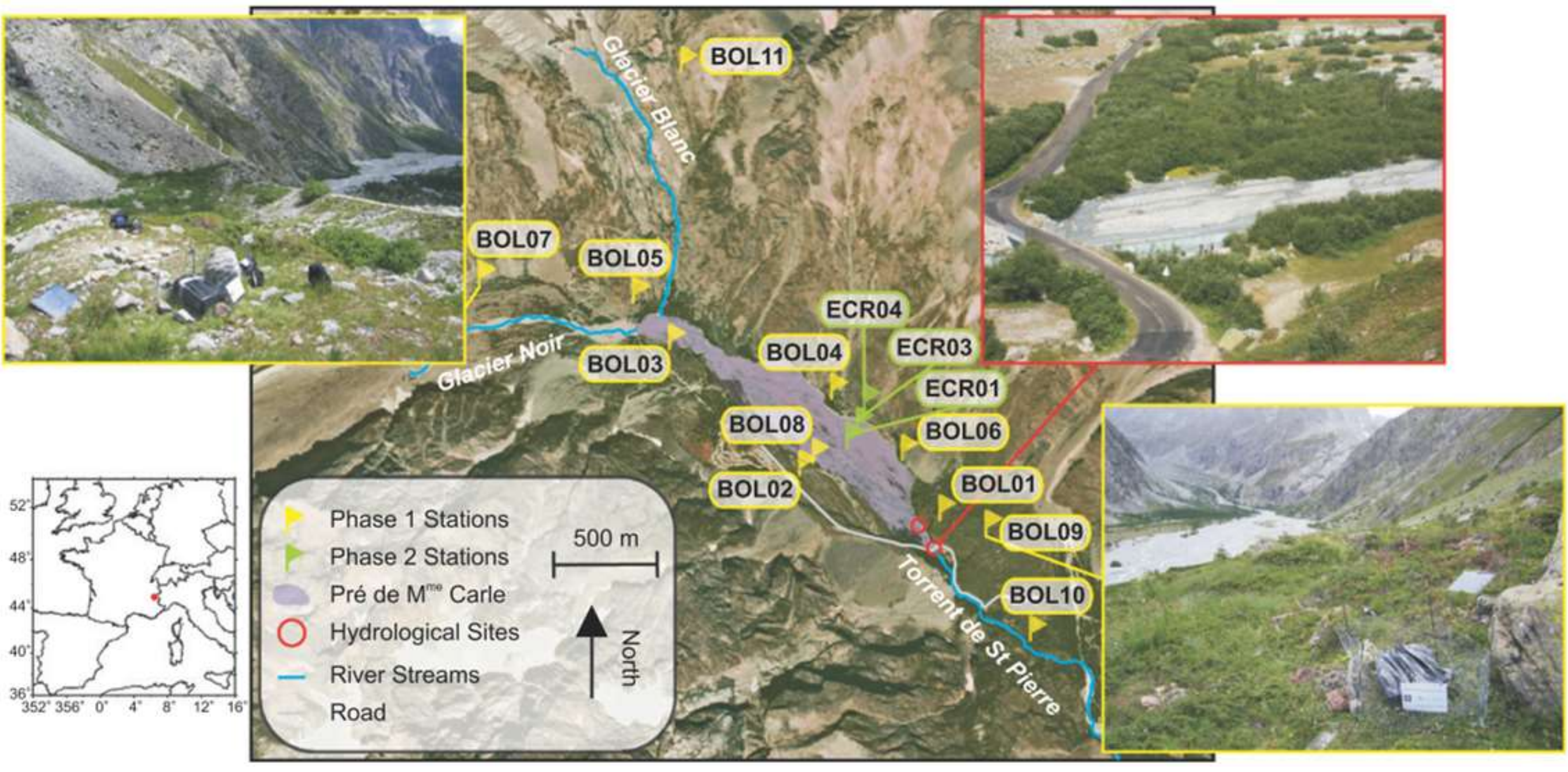
- Ground motion velocities of 5-10hz with amplitudes in excess of 10e(-5)m/s lasting more than 10 min .



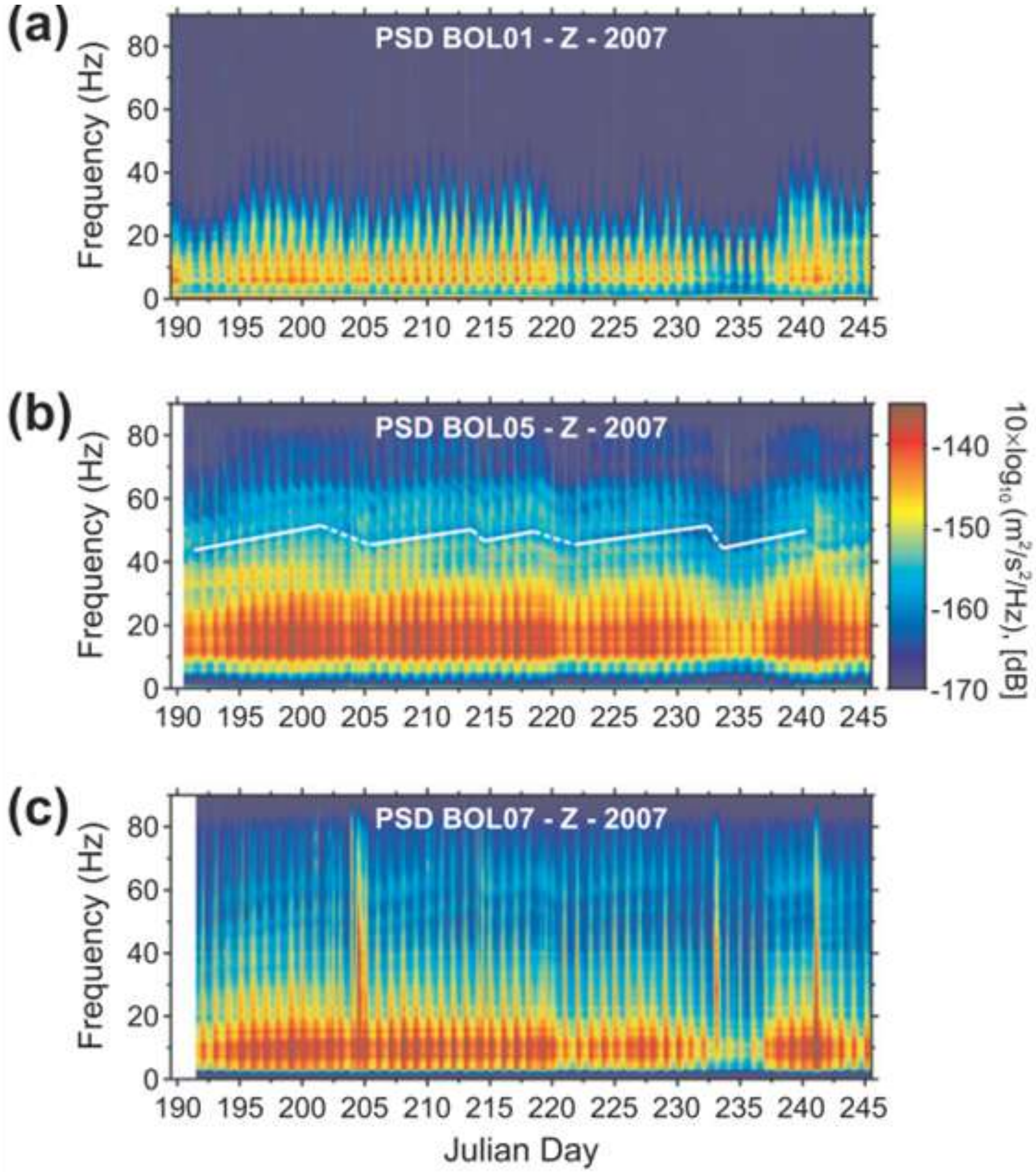
Establish Relation Between
HYDROLOGY AND SEISMOLOGY

Case Study - Braided River(“torrent de St Pierre”, French Alps)

A. Burtin et al./Journal of Hydrology 408 (2011) 43–53



Spectral Analysis

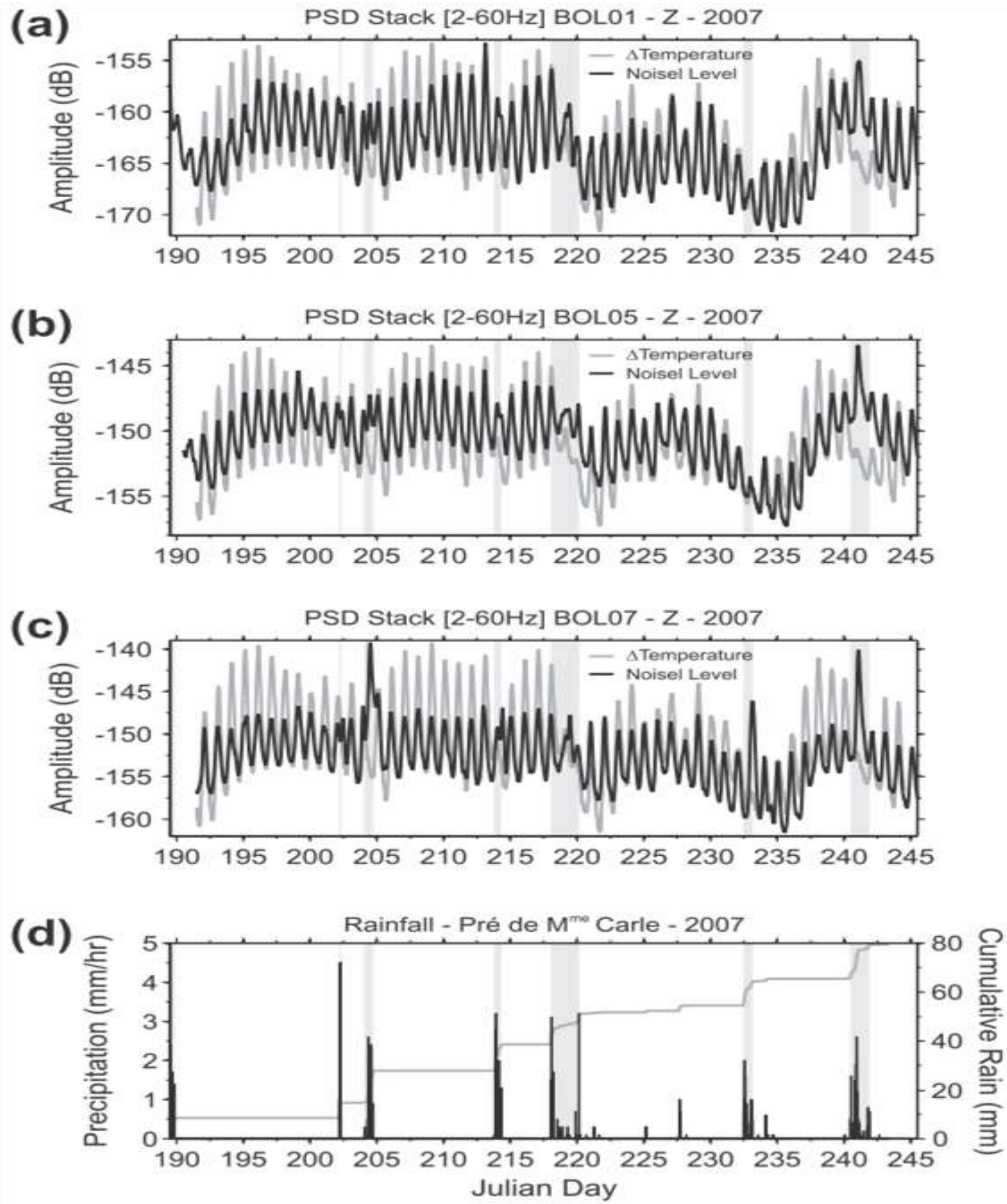


PHASE 1

The spectrograms at BOL01, BOL05 and BOL07 depict a 24 h fluctuation of the seismic energy in the frequency range 2–40 Hz.

- Long period trends are interrupted by strong bursts of high-frequency seismic noise that are well revealed at BOL07.

Seismicity Vs Temperature variation

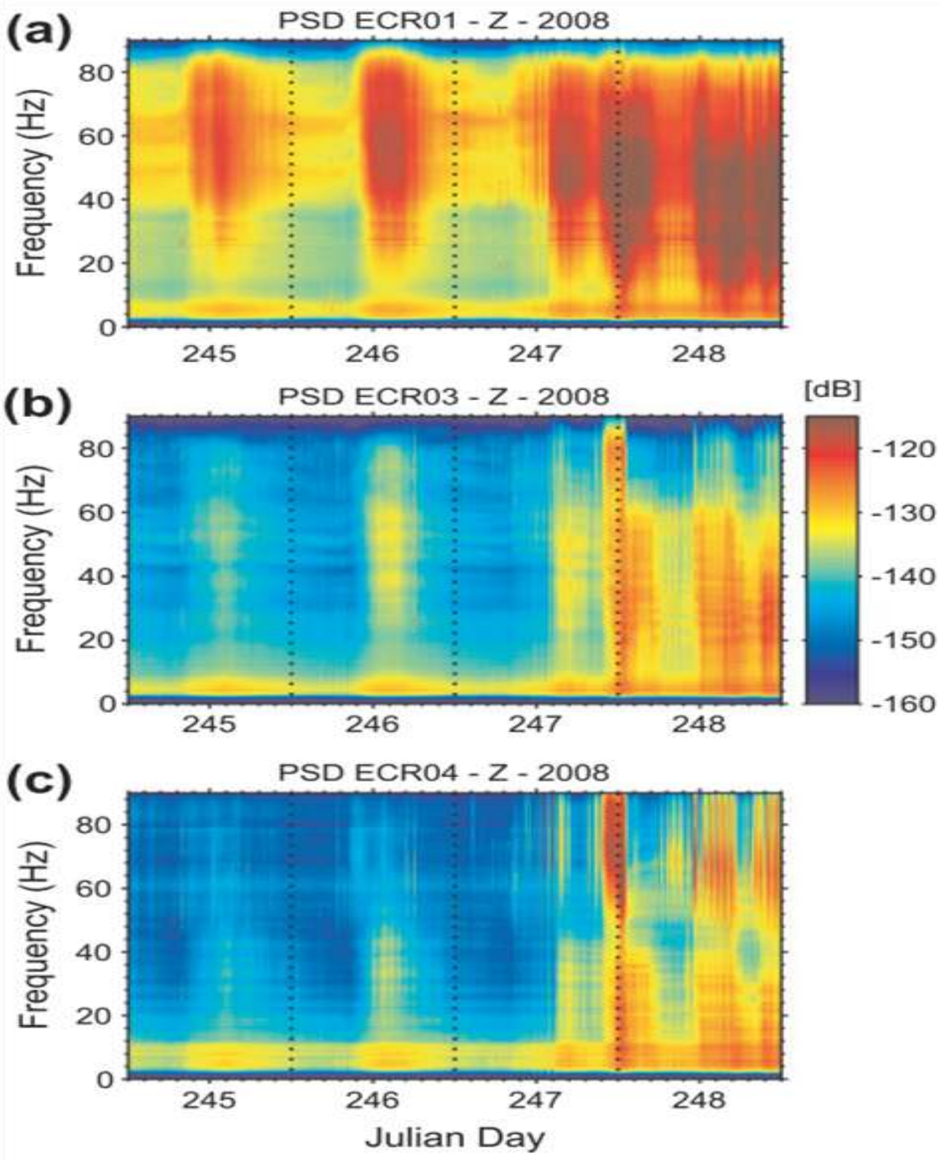


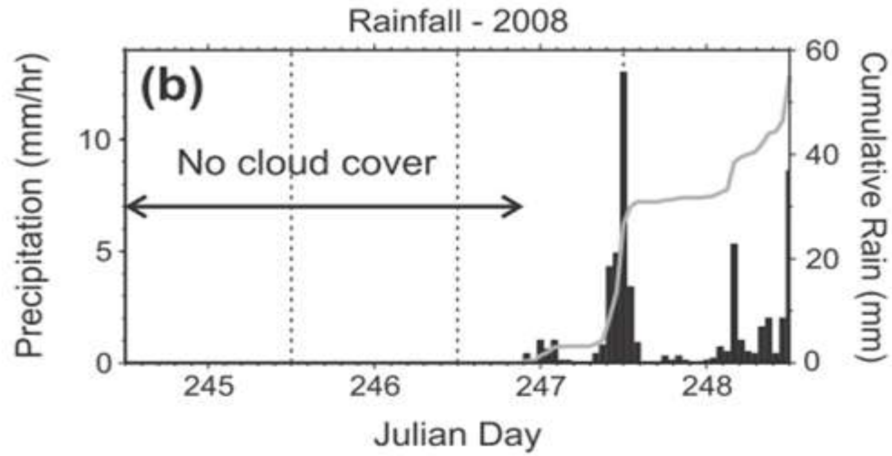
- These observations suggest a strong link between the recorded seismic noise and the hydrology of the stream for which the water supply is mainly controlled by melting.

- **In grey shaded area**, we record larger amplitudes of seismic noise than if temperature was the only key parameter of the stream hydrology. **These anomalies of seismic energy actually occur while bursts of seismic noise are well detected at BOL07**

  - The comparison with precipitation rates indicates that these particularly ''noisy'' days are generated by **large rainfall events.**

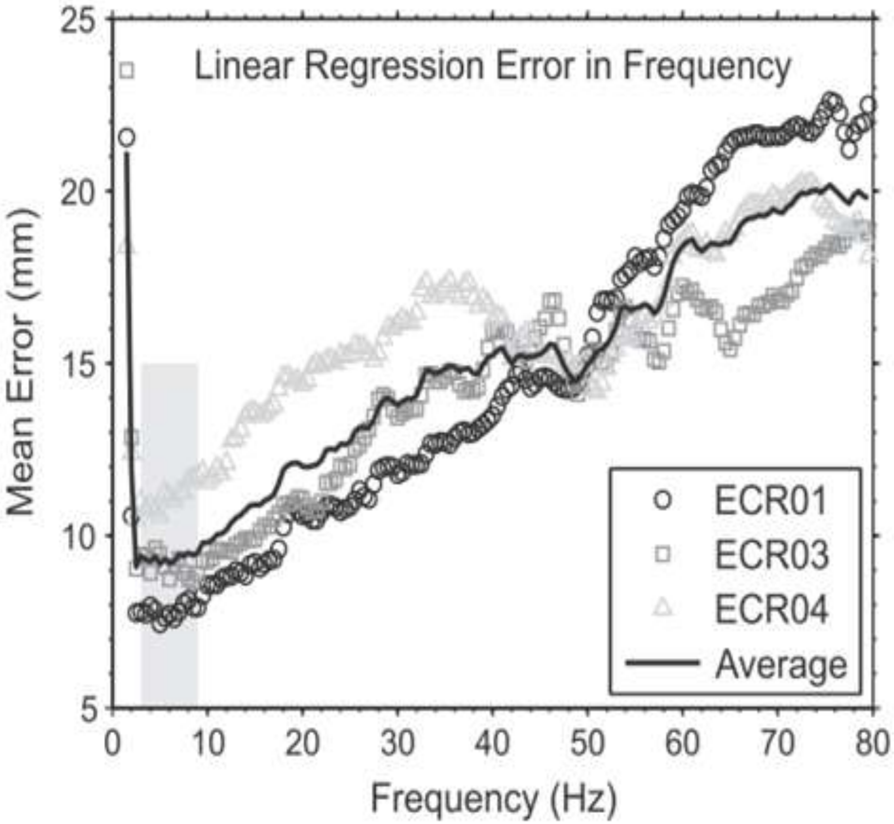
PHASE 2

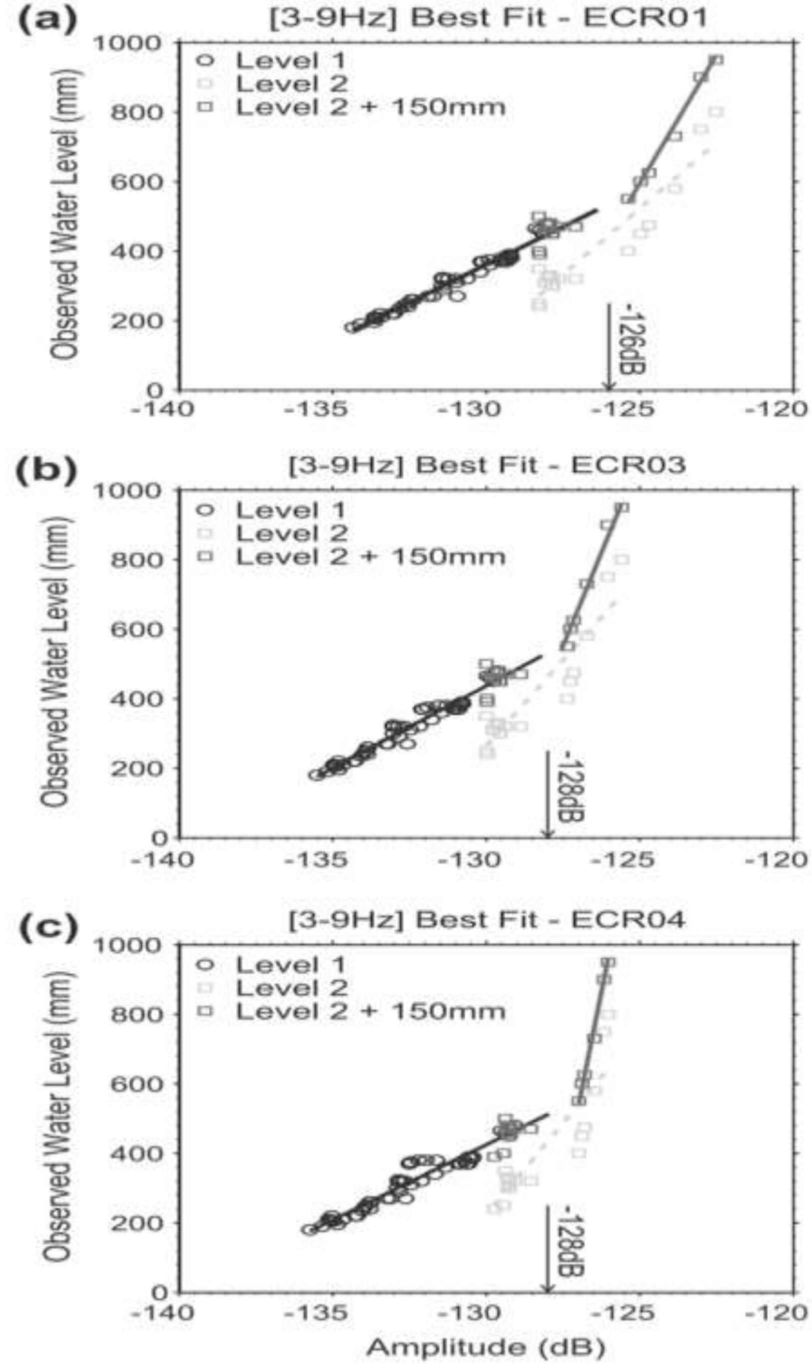




- Glacial melting only source of water on 245and 246 days.
- On 247 and 248 heavy rainfall occur.
- We also see that high frequency energy attenuate with distance . May be because of unconsolidated sediment that compose the braided plain.
- We see energy between 60-90 hz frequency , this is because of rain falling on rock debris.

Hydrologic – Seismic Relationship





Observation

- It appears that the 3–9 Hz frequency band is best related to the water level . The three stations give a similar result, especially for seismic noise amplitude lower than -126 (at ECR01) and -128 dB (at both ECR03 and ECR04) where the slope of this linear regression is equivalent.
- Above the seismic noise values of -126 dB for ECR01 and -128 dB for ECR03 and ECR04, the statistical relationships between noise and water level exhibit a threshold.

Explanation

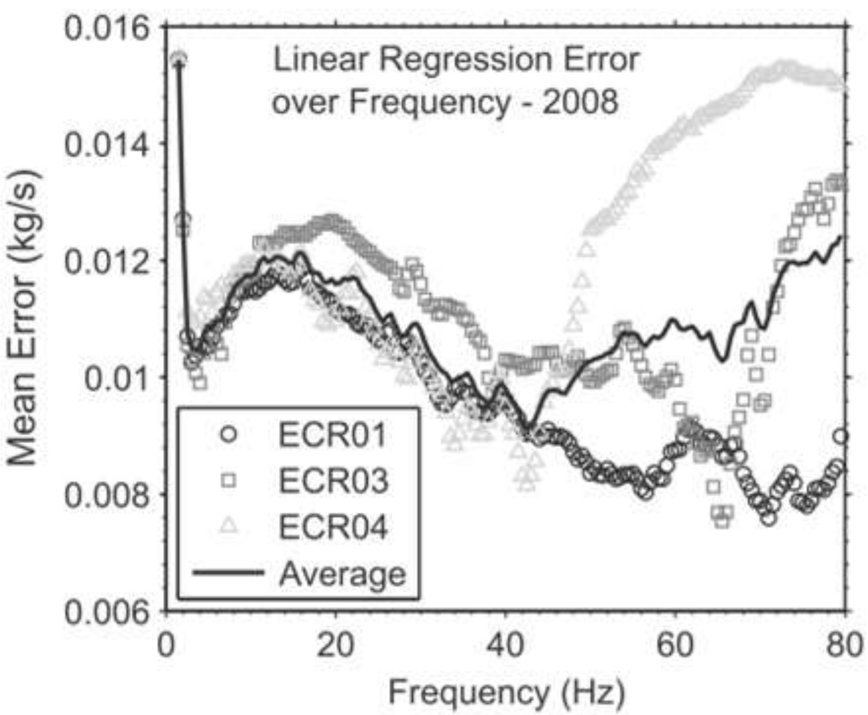
- This feature may be related to the classical concept of critical shear stress used to describe the river transport capacity . If the stress of the flowing water on a stream bed is less than a critical shear stress, particles within the river will remain motionless. Movements will be observed only if the stress exerted by the flowing water exceeds this critical shear stress.
- The fluvial shear stress exerted by the flowing water is defined as

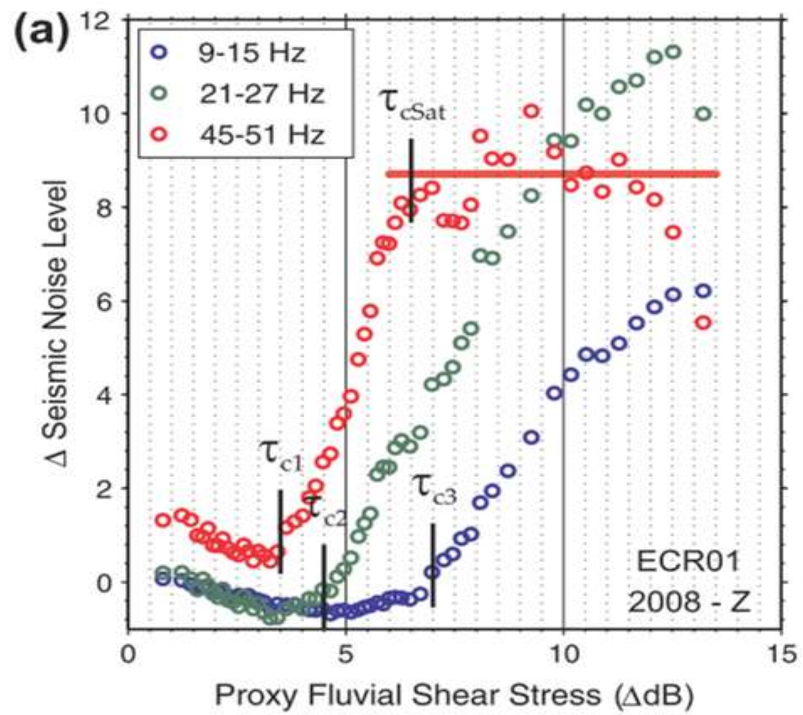
$$\tau = \rho g S R,$$

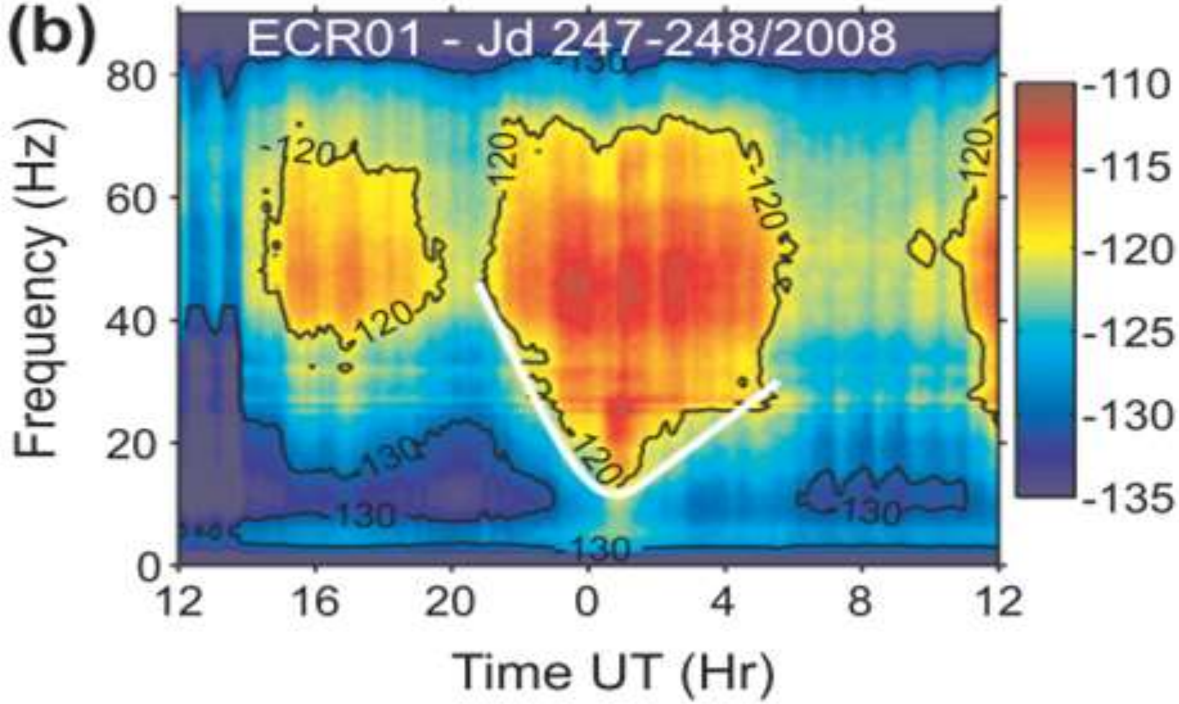
R = Hydraulic Radius
S = Slope
p = density of fluid

Sediment – Seismic Relationship

- We see that for **lower frequency band critical stress is greater** while for **higher frequency band critical stress is lesser**.
- In the 45–51 Hz frequency band, with a continuous increase of the fluvial shear stress and the overpass of a second threshold **, we notice a constant seismic noise level**







- During the night of Julian day 247–248 , with the occurrence of a large rainstorm , we initially record a seismic energy at high frequencies that shifts to lower ones following an increase of the water discharge. As a consequence, a constant level of seismic energy displays some delay to activate low frequencies . Afterwards with the ending of precipitation, we notice the extinction of the lowest frequencies before the highest ones while water discharge decreases. These observations suggest again a link between the frequency content and the transport capacity of the river.

Conclusion

- We show that an increase of water supply leads to an **enhanced transport** capacity of the stream that **mobilizes the largest particles**. Hence, the spectrograms exhibit a **frequency content that shifts to lower frequencies**, and agree with a relationship between the frequency content of the ground vibrations and the grain size of bed load.

Now, we have the methods of identifying bed-load transport as the ‘’hysteresis’’. But is this signature enough to predict the flood or amount of sediments coming downstream?

- We don’t have much models to relate the observed seismic quantities with the amount of sediment flux.

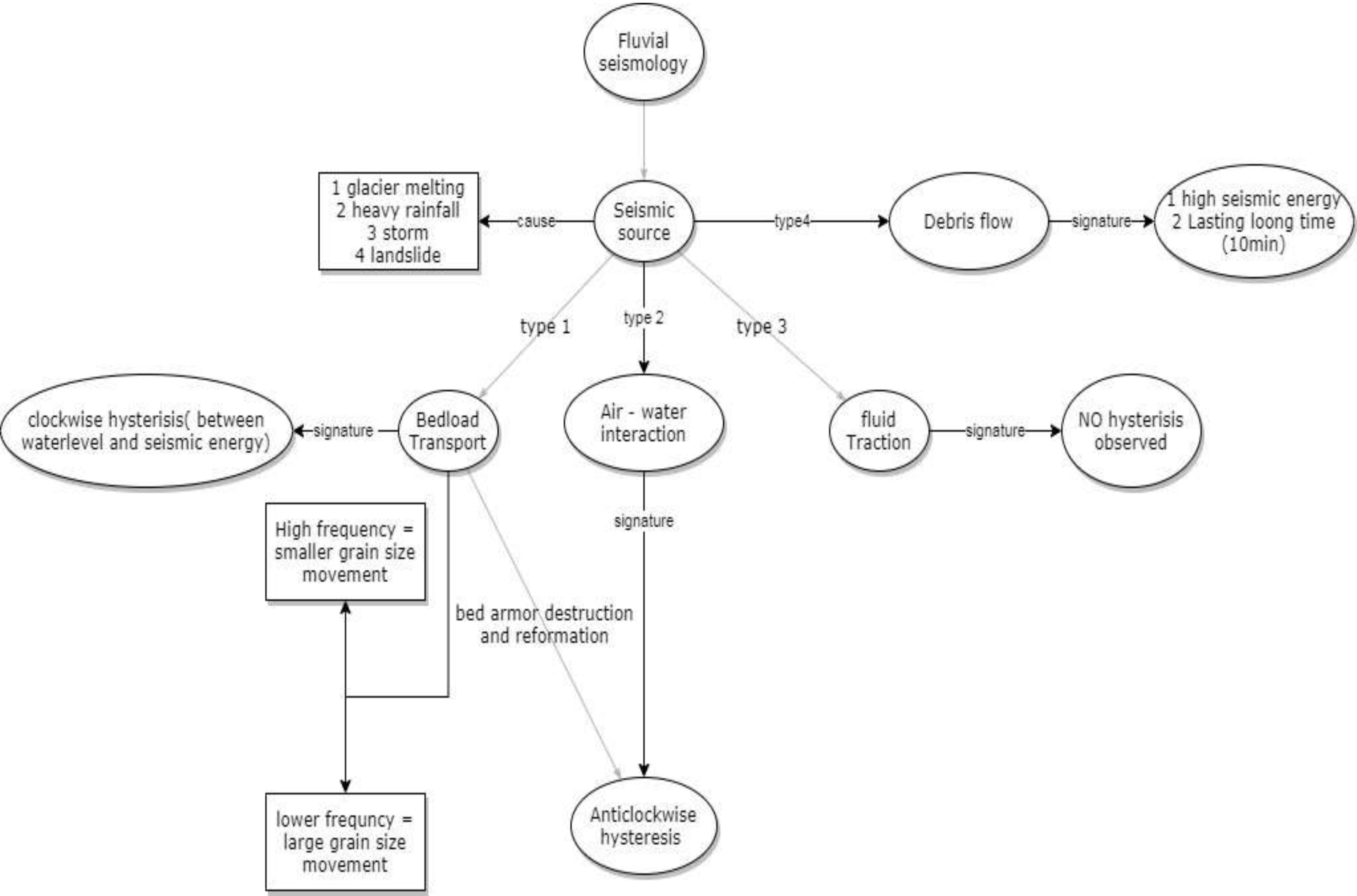
- Until we have good correlation between sediments and seismic data we cannot use it to predict flood or debris.

- Tsai et al. 2012 has developed a physical model to describe the seismic noise induced by the transport of sediment in rivers.

- According to this model, we use PSD of the Rayleigh waves generated by impulsive impacts of saltating particles.

- This PSD of Rayleigh waves depends on-
  - Size of particles
  - Number of particles of given size
  - Square of linear momentum.

Overview


Fluvial seismology
Seismic source
cause
1 glacier melting
2 heavy rainfall
3 storm
4 landslide
type4
Debris flow
signature
1 high seismic energy
2 Lasting loong time (10min)
type 1
type 2
type 3
Bedload Transport
signature
clockwise hysterisis(between waterlevel and seismic energy)
Air - water interaction
fluid Traction
signature
NO hysterisis observed
High frequency = smaller grain size movement
lower frequncy = large grain size movement
bed armor destruction and reformation
signature
Anticlockwise hysteresis

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-

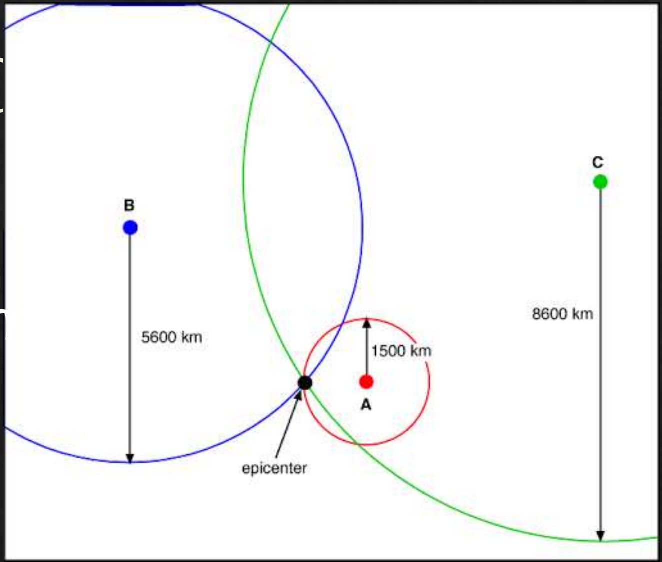
- Among all the other methods, seismic imaging provides us good resolution of data and precise estimates.

- 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 seism source?



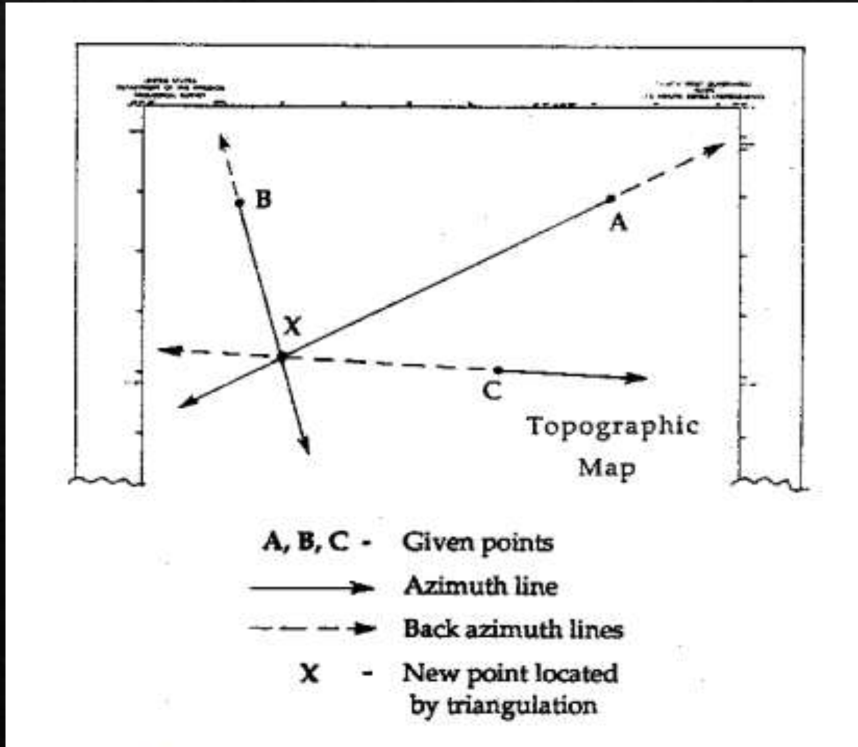
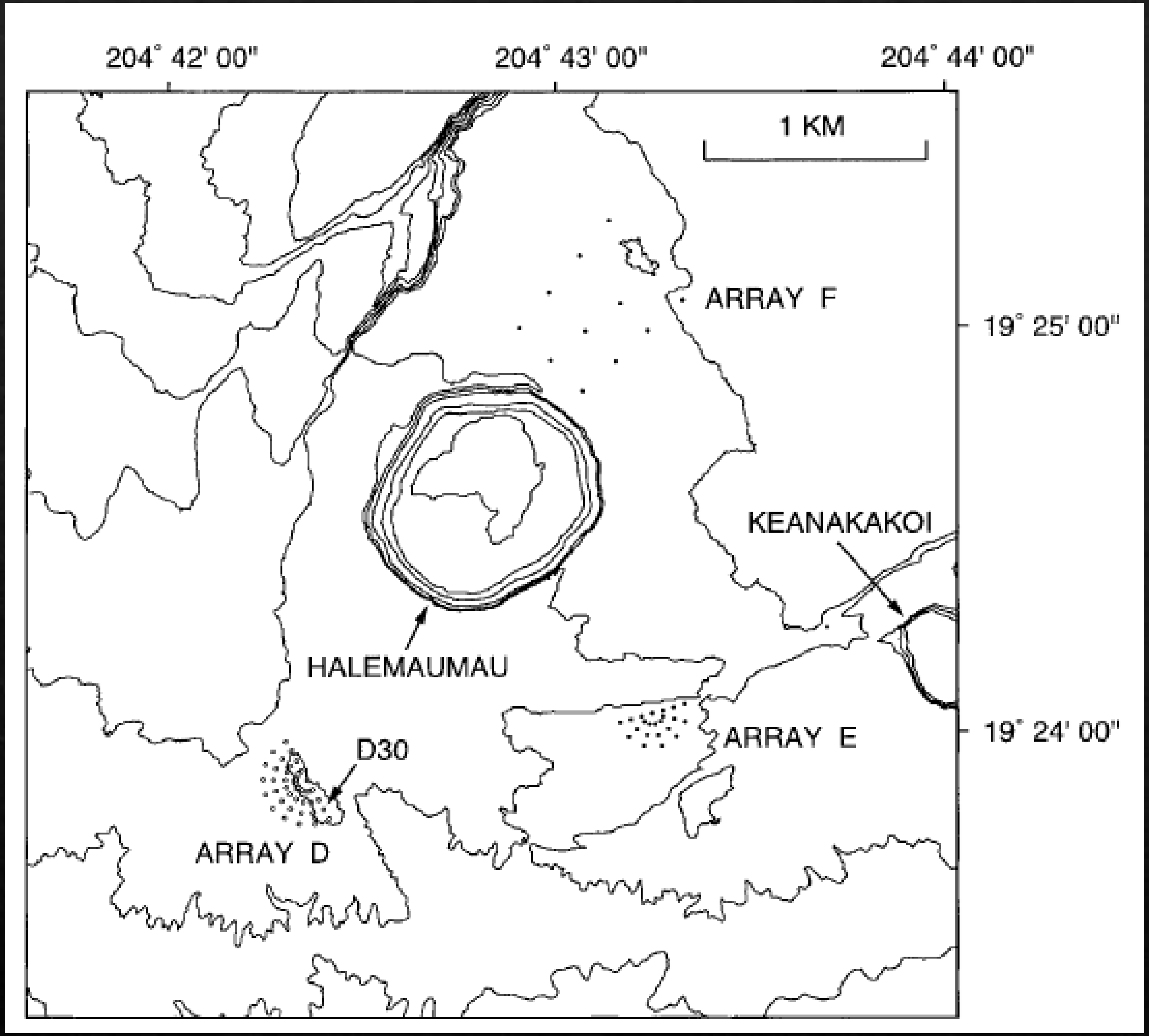


Figure 3. A typical triangulation diagram.

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 ???

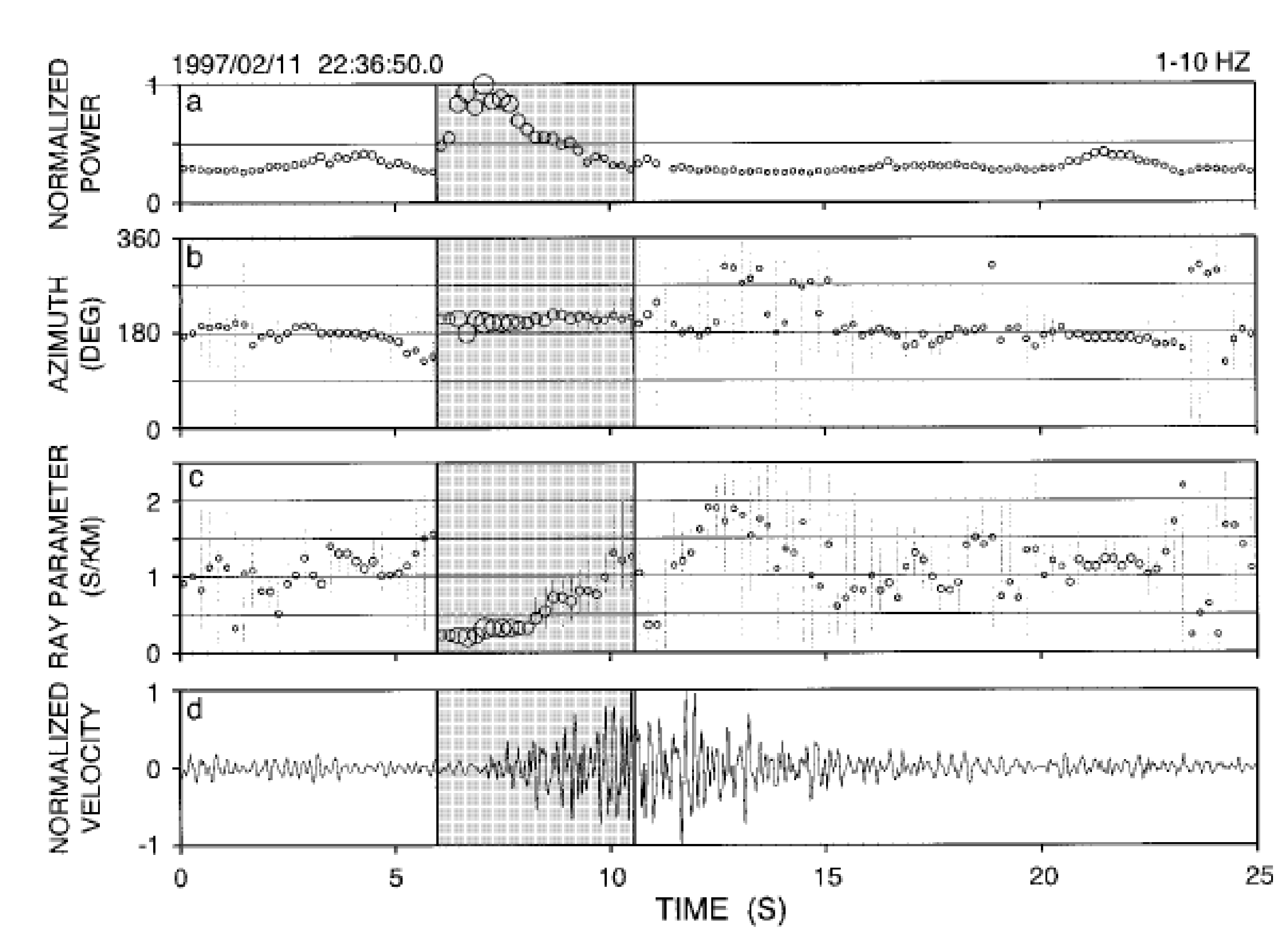
= This shapes are chosen according to place's topography so to record maximum data.

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.

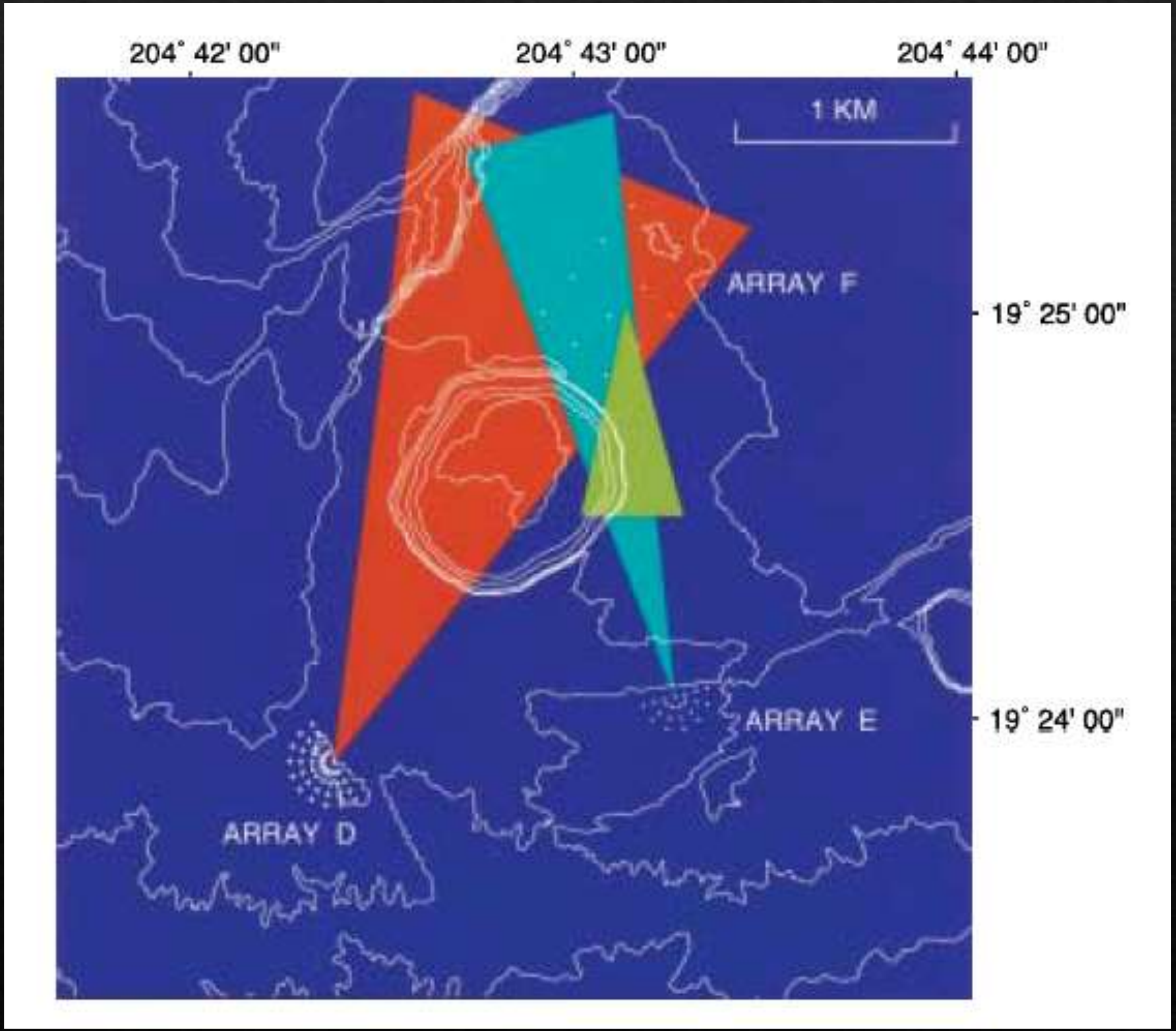
Using the time interval of shaded region, we recorded the azimuths, and then find out their corresponding back-azimuths.

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.

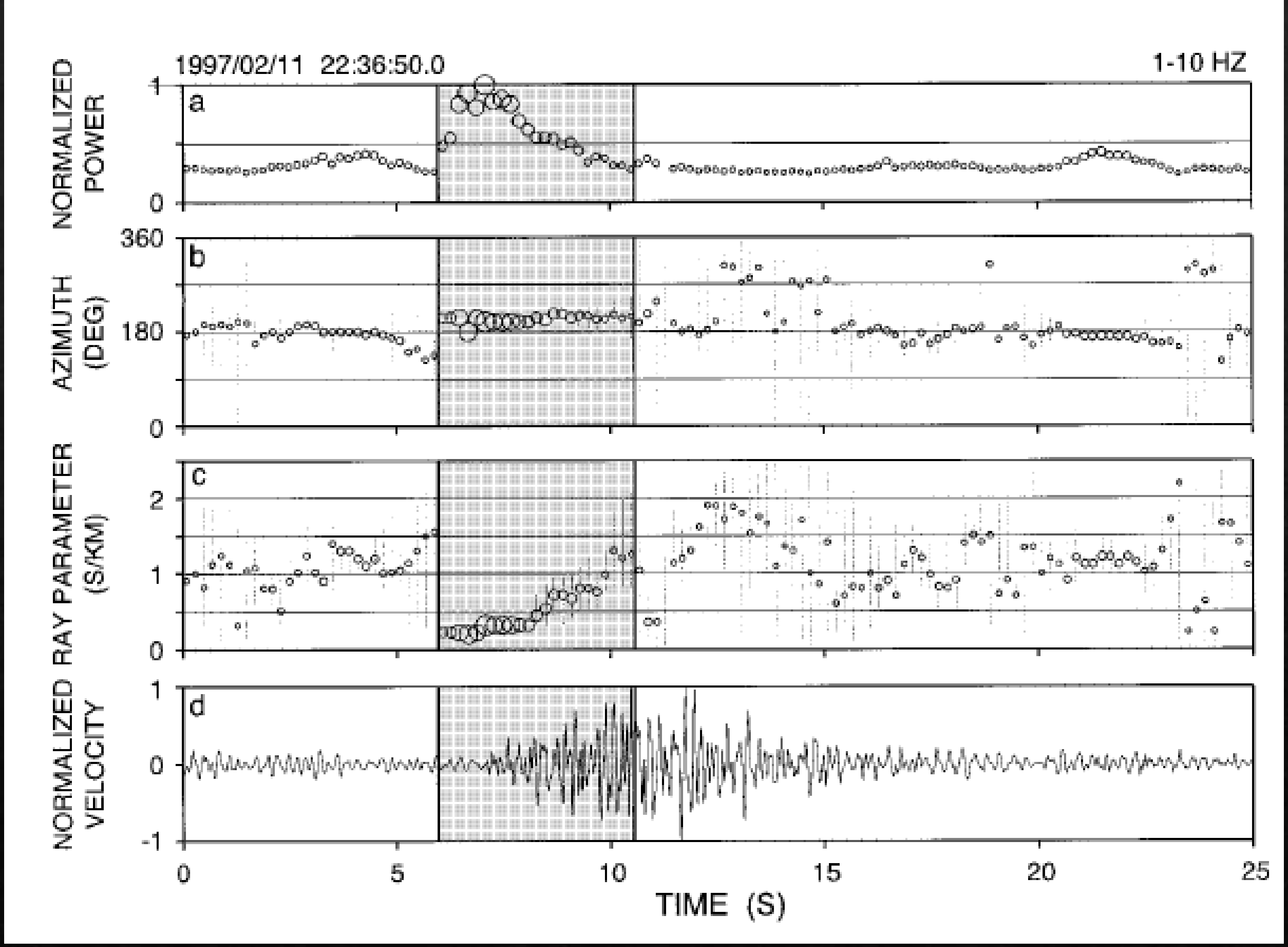


The back-azimuths for 5 sec interval formed wedges as in figure.

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

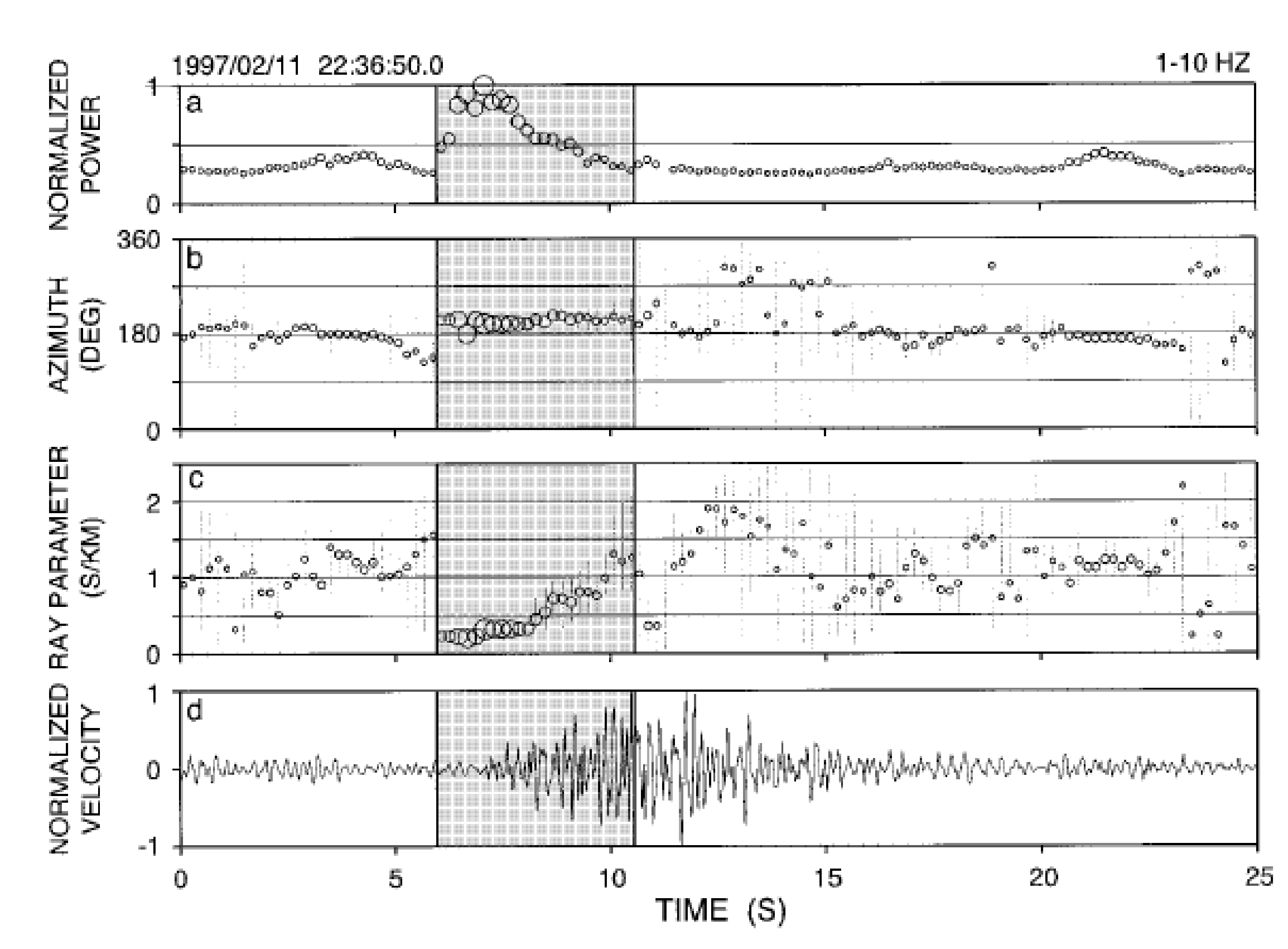


This shaded region five seconds time interval from 6th – 11th sec was used to plot azimuths. But why do we use this particular time slot and not some other set of time? THINK!



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.

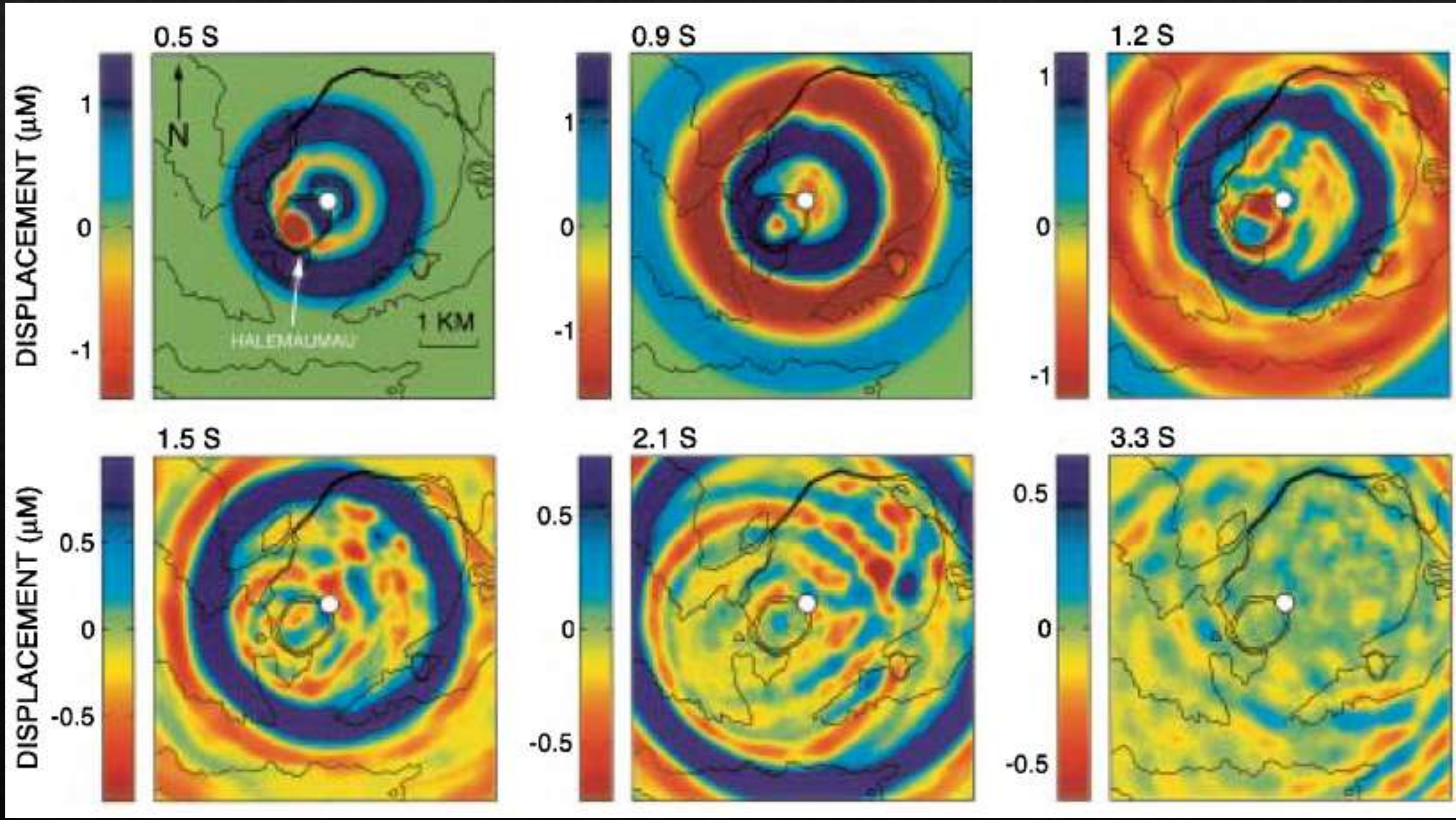
- 3-D topography modeling – assumes homogenous medium - gives details about how topography affects wave propagation
- 3-D velocity structure- assumes heterogeneous medium - gives more precise estimate than topography method.

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).

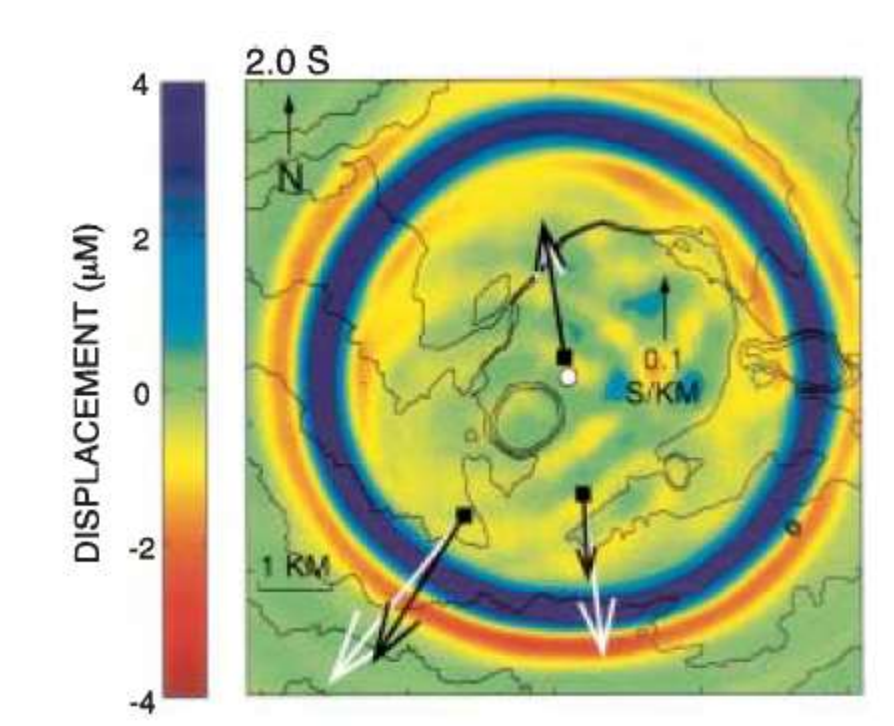


3-D modeling of velocity structure- give better estimate of source location.

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.

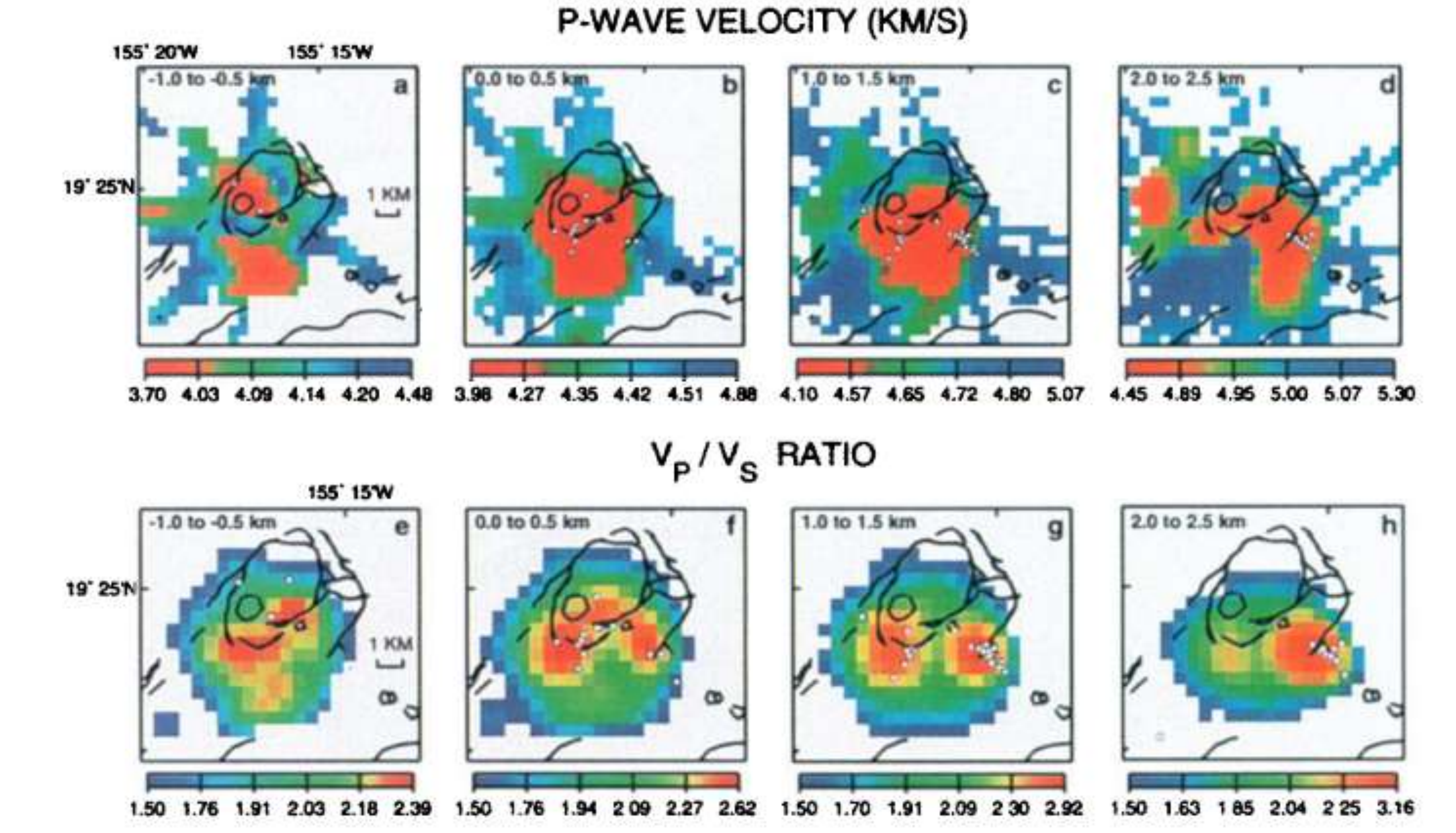
➢A low velocity anomaly in P-wave is seen beneath Kilauea.

➢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.

$$v_P = \sqrt{\frac{\lambda + 2\mu}{\rho}}$$

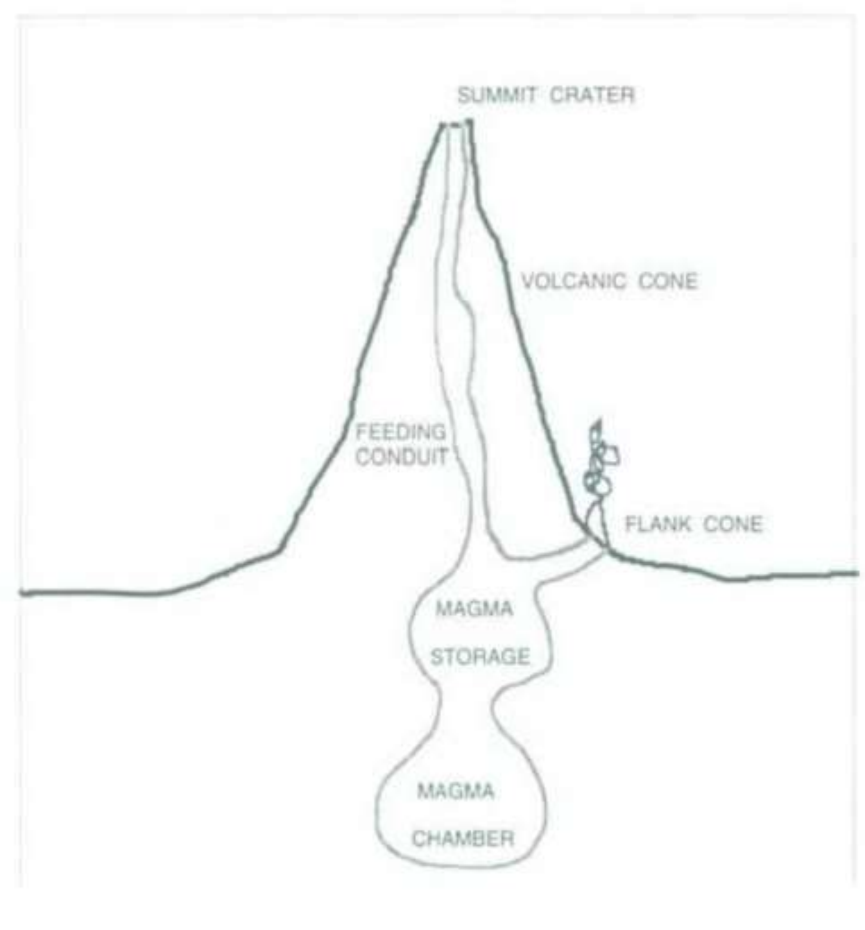
$$v_S = \sqrt{\frac{\mu}{\rho}}.$$

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?

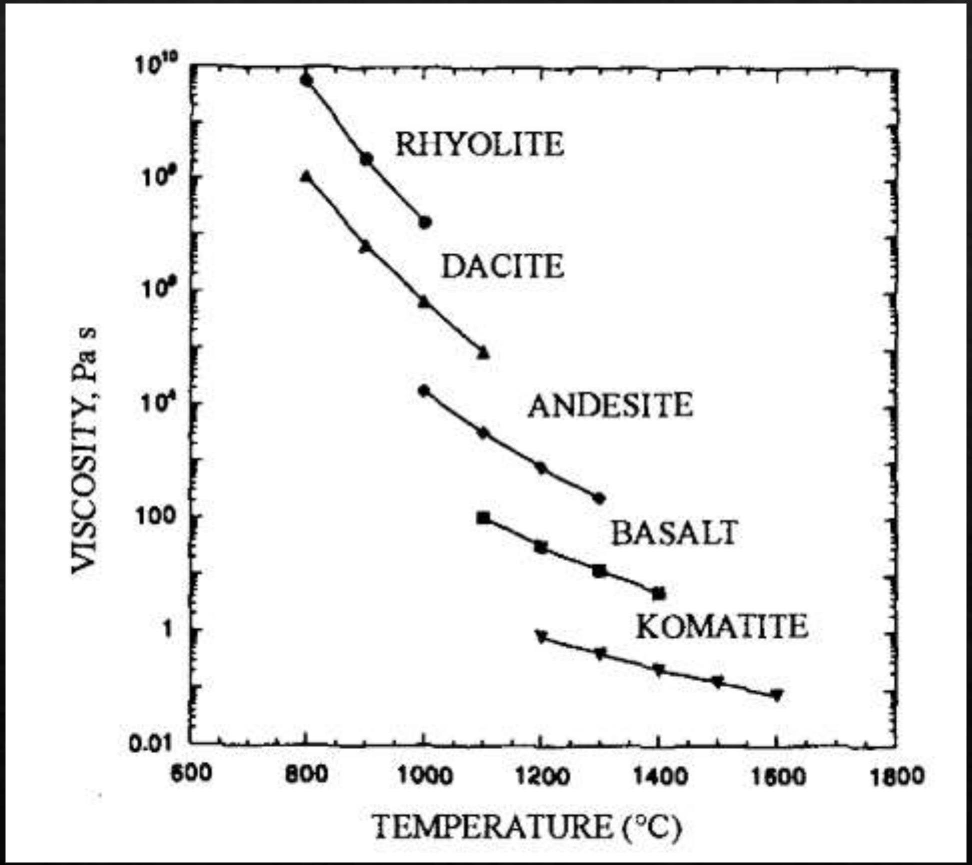


VISCOSITY – viscosity of magma determines the pathway of magma up to the surface.

- ➢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

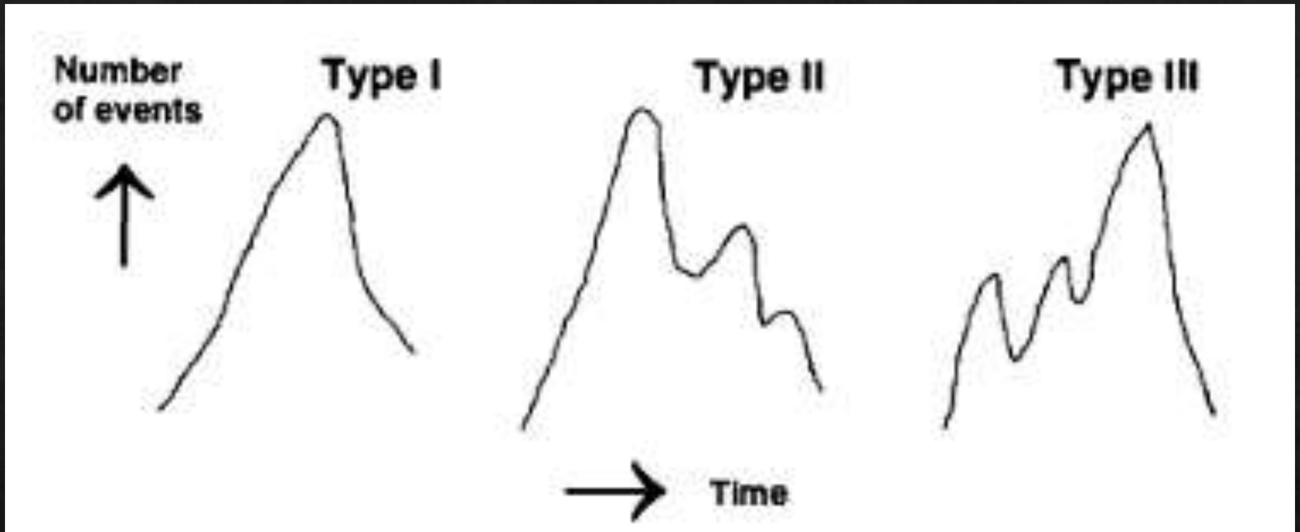
1. Strombolian - andesitic basaltic lava- (INTERMIDEATE)- strong eruption without pyroclastic flow, lava flow, dark eruption clouds

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-

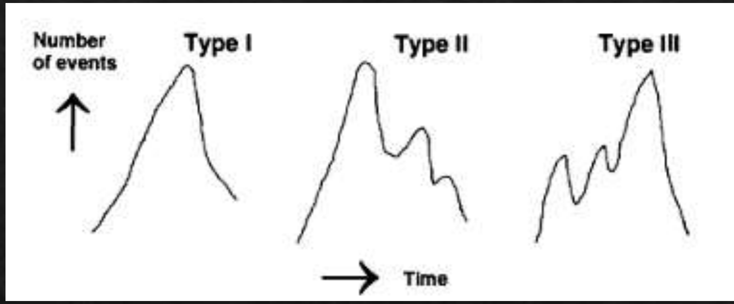
Type I – One peak [Very Rare]
Type- II – Multipeak with highest peak at the start of events [Found mainly in Basaltic and Dacitic]
Type III – Multipeak with highest peak at the end of sequence [Found mainly in Andesitic and sometimes in Dacitic]



- ❑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.

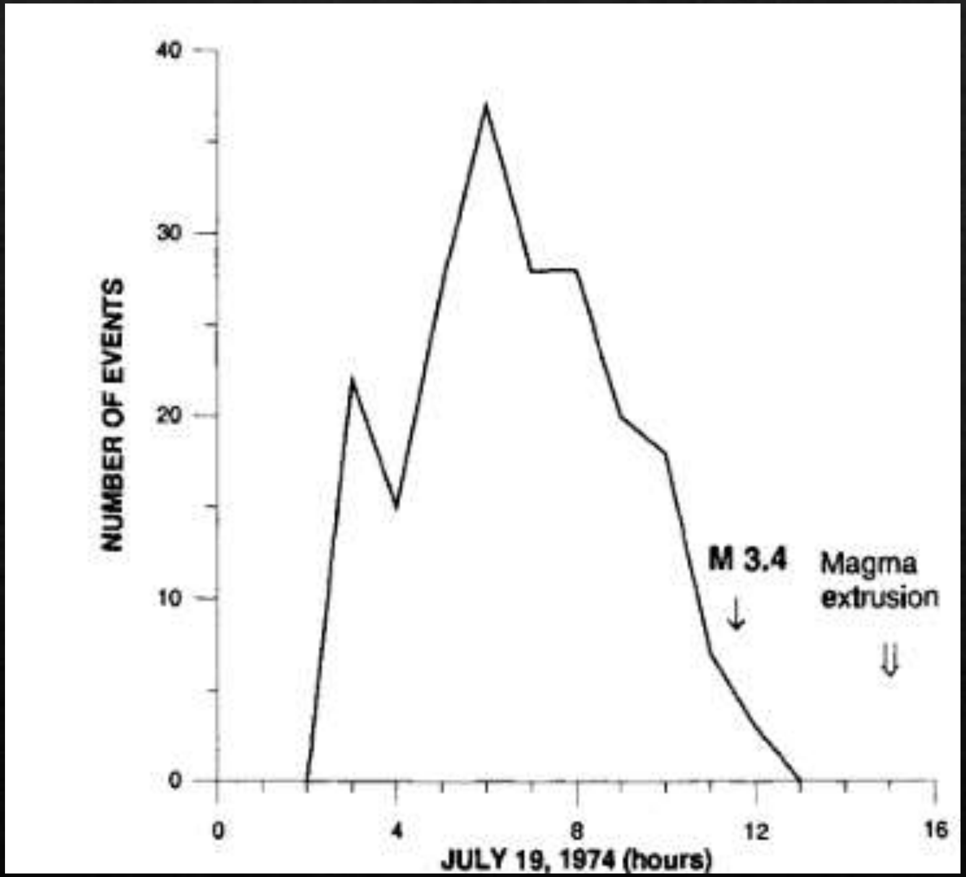
What do you think is the possible reason for these multipeaks?

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.

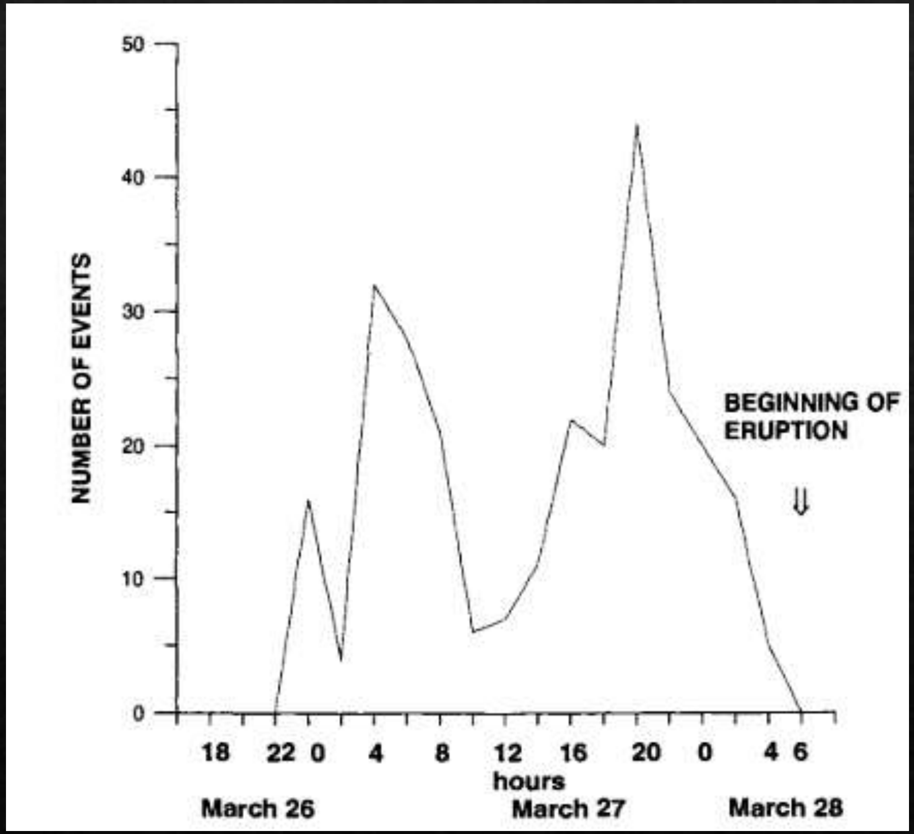


- *We will see a few examples of temporal distribution of earthquake swarms, i.e. , no of events vs time graphs of a few volcanic eruptions.*

Temporal distribution of events for Basaltic magma (Low viscosity)

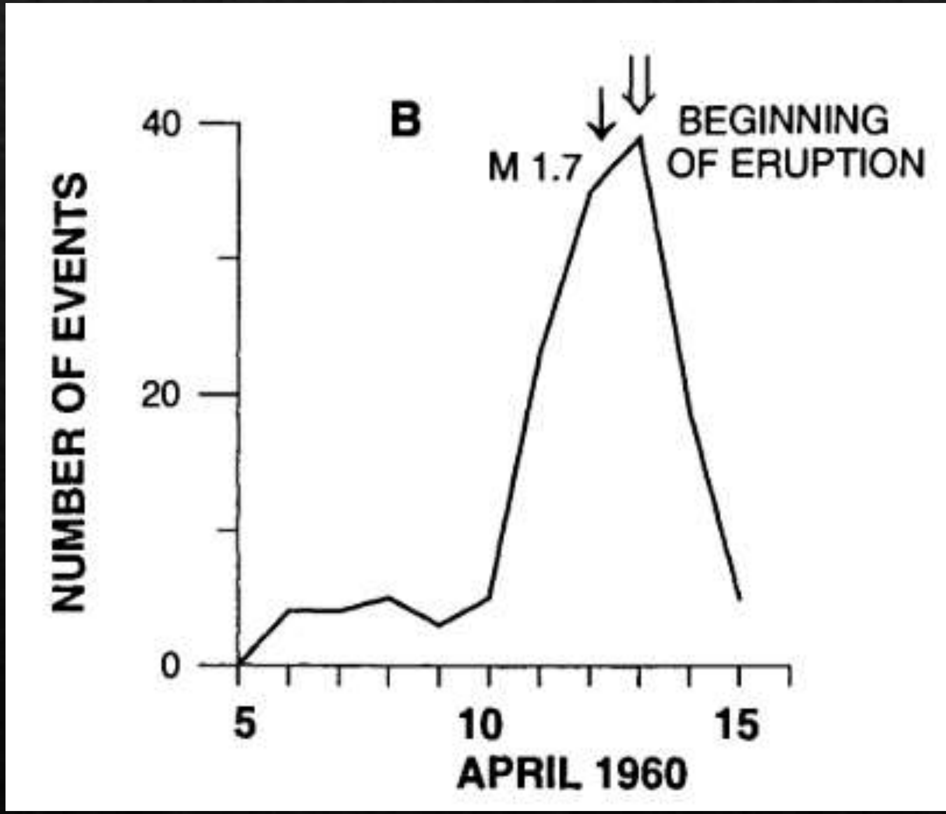


Kilauea
volcano

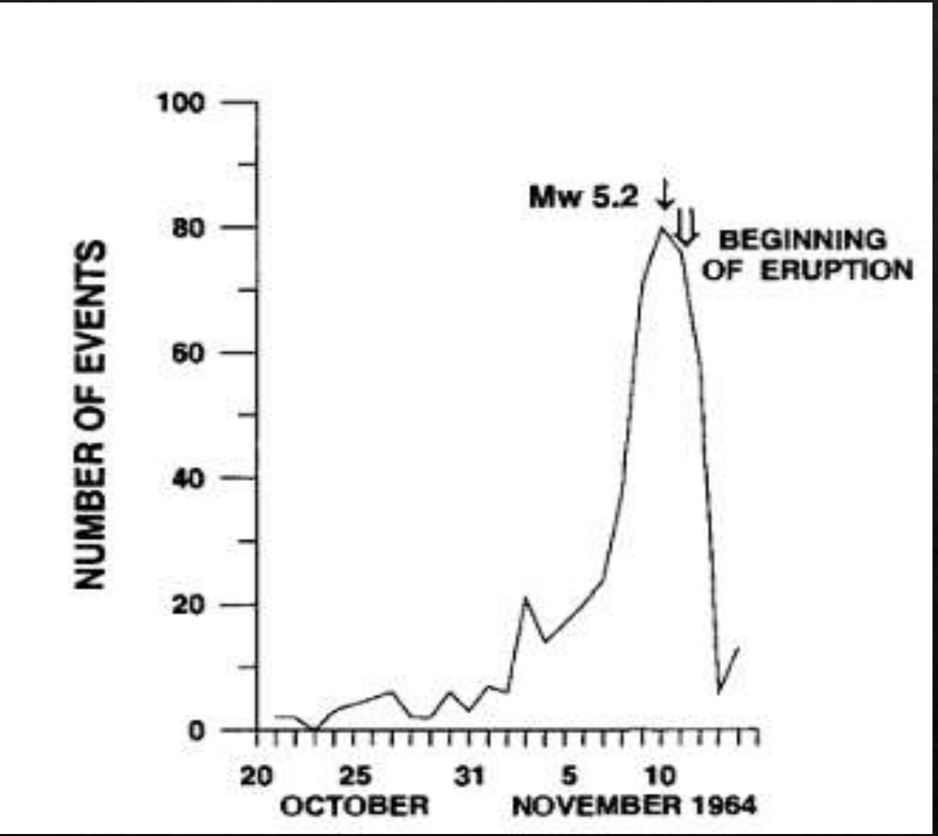


Mt. Etna , Sicily

Temporal distribution of events for Andesitic magma (Intermediate viscosity)

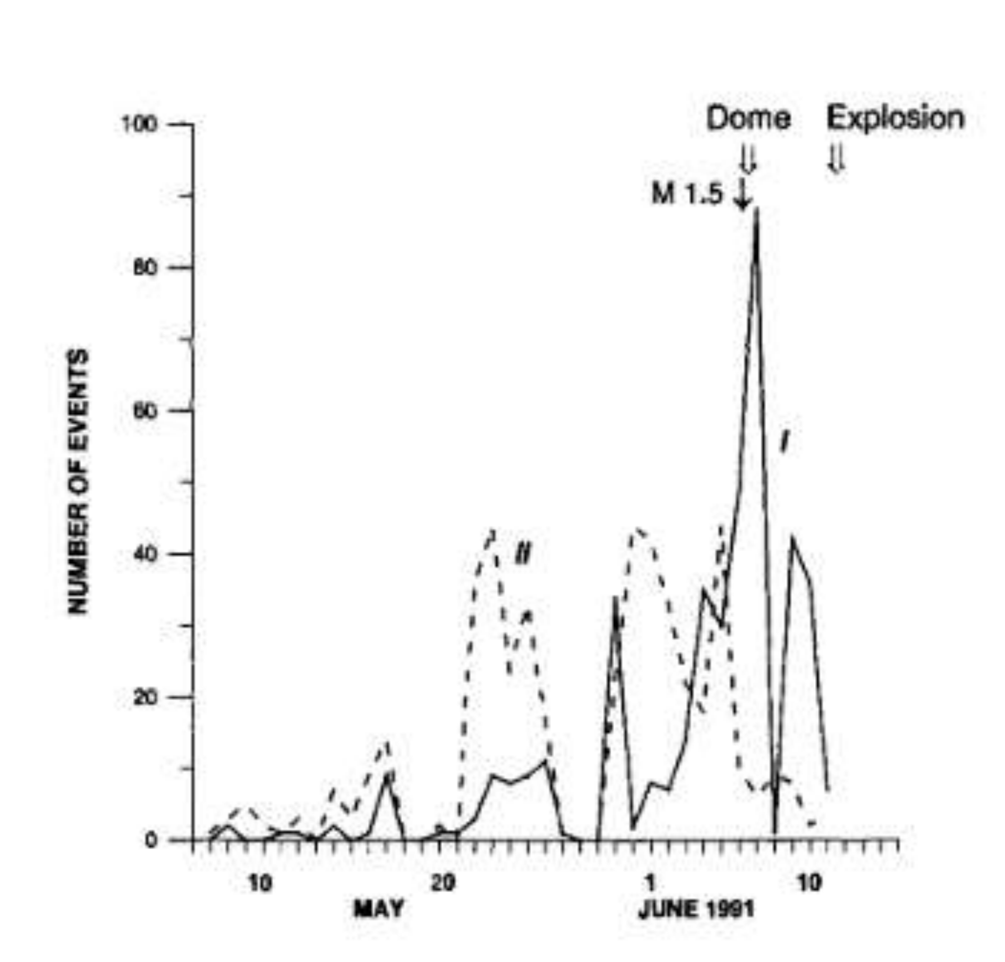


Bezymianny Volcano, Russia

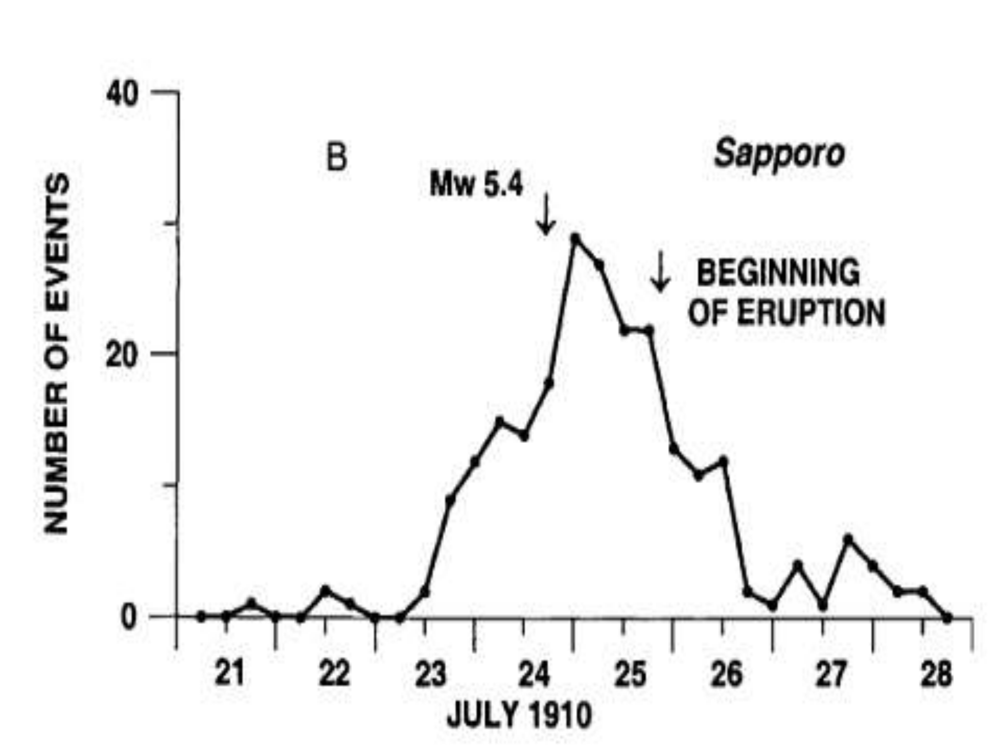


Sheveluch Volcano, Russia

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 <u>sometimes viscosity may be different from previous eruptions during a particular eruption</u>.

- Now if we could identify if there is going to be some change in predetermined viscosity type then it could be <u>of great use in predicting eruption hazards and warning people</u> 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.

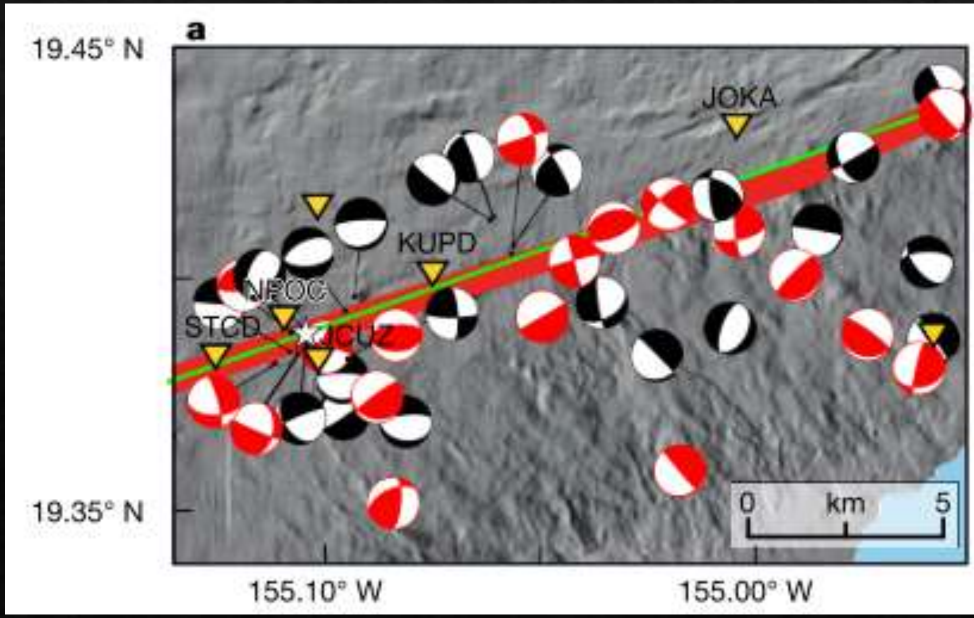
From where does this high viscous magma came?

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

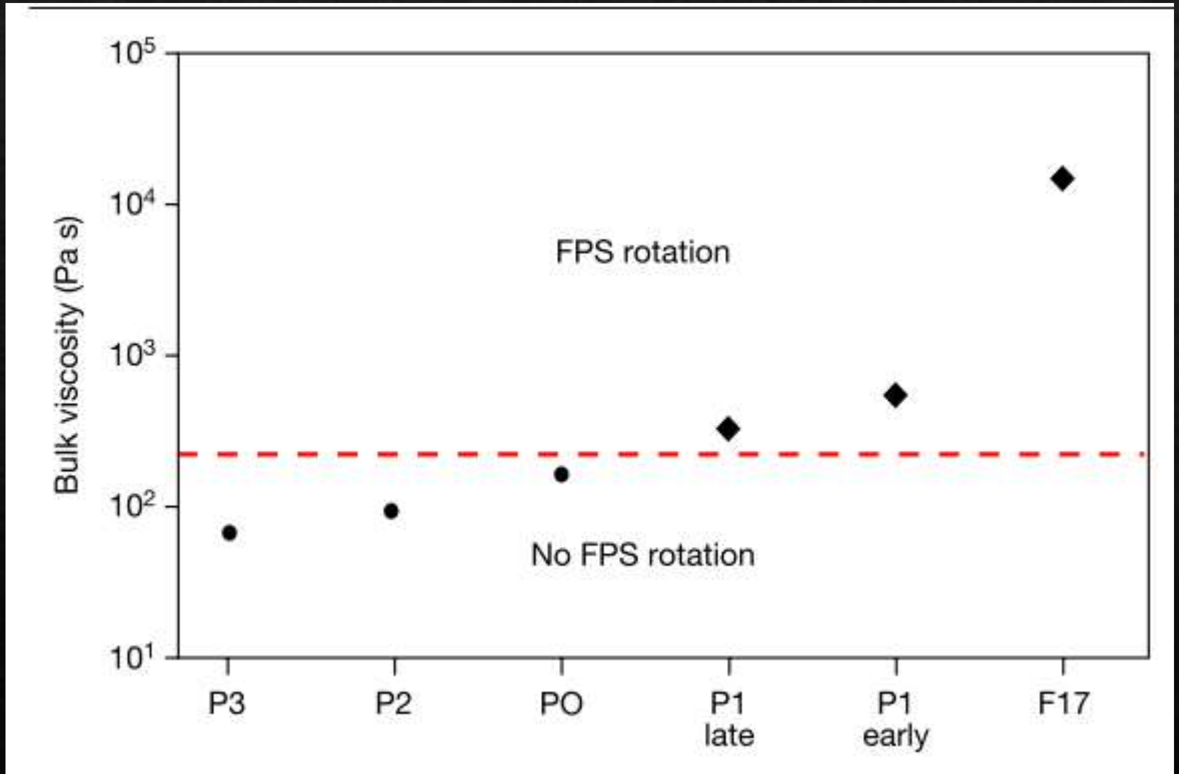


Fig. 4 | Bulk viscosity of Kīlauea 2018 and Pu‘u ‘Ō‘ō (PO) eruptive products.

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***.

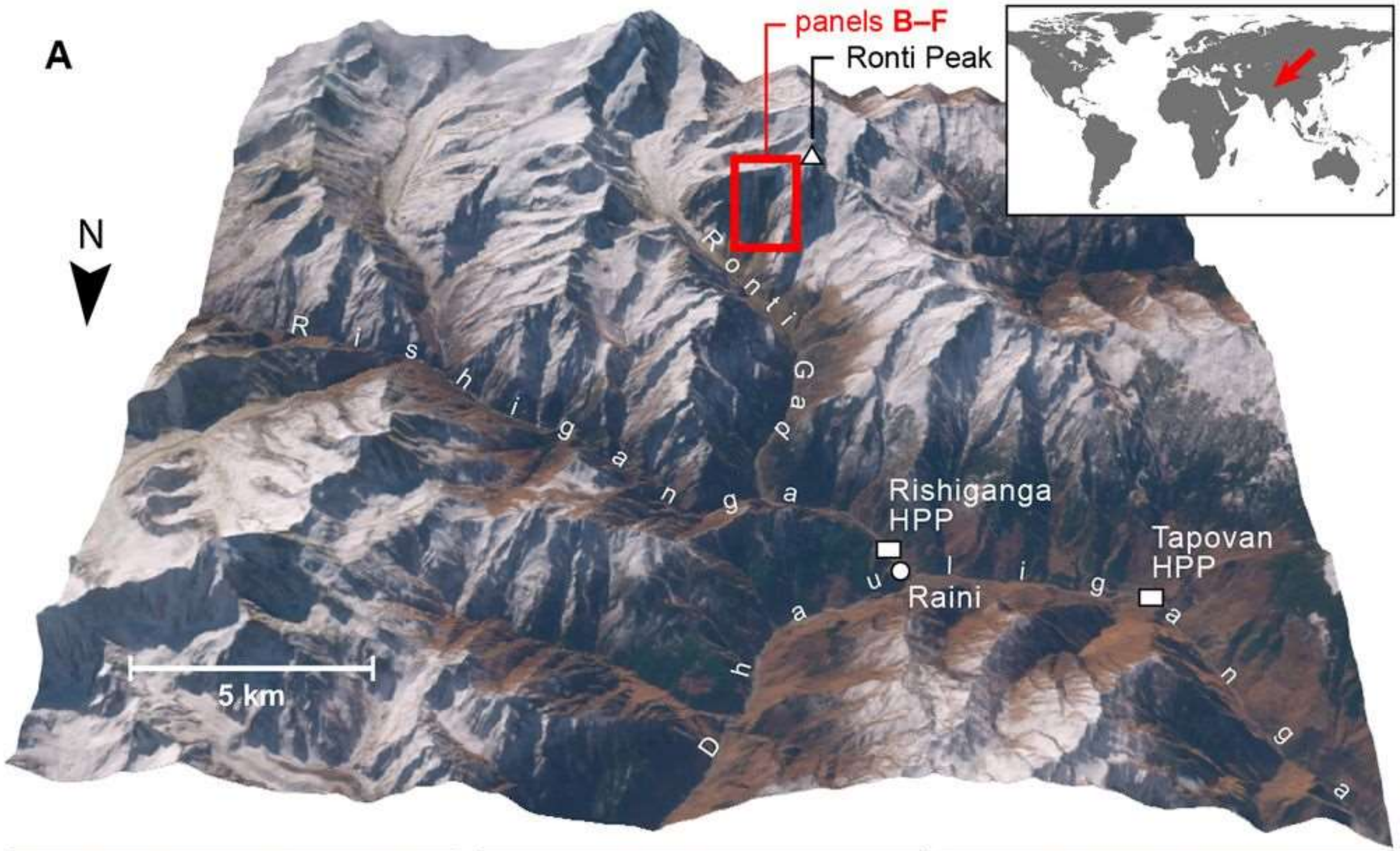
➢***Dynamic normal stresses may result from a volume increase during flow of highly crystalline*** magma under a velocity gradient, via a nonlinear process known as shear dilatancy.

➢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.

Chamoli Disaster, Himalayas
7 Feb 2021 by massive ice and rock avalanche

D. H. Shugar et al. 2021

This disaster severely damaged two hydropower projects and over 200 people were killed or are missing.

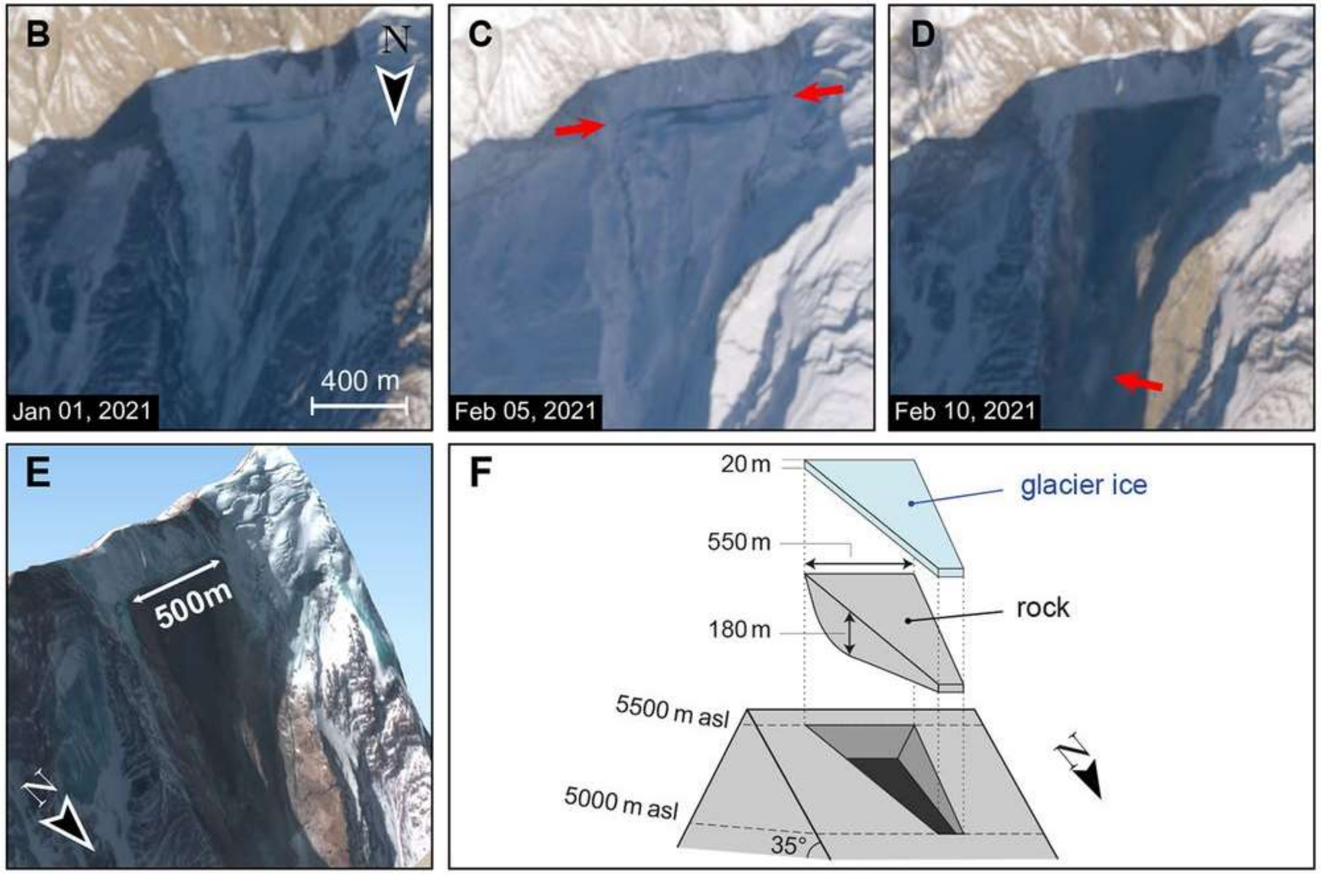


Overview of the Chamoli disaster, Uttarakhand, India.
3D rendering of the local geography, with labels for main place names mentioned in the text. HPP=hydropower project.

1. Origin events
2. Debris mass flow components
3. Effects in far areas
4. Seismic analysis results
5. Its causes
6. Its physics
7. Warning system
8. Conclusion

Optical feature tracking detected movement of the failed rock block as early as 2016, with larger displacements in 2017 and 2018.

The fig B, C, D shows the crack before and after incident.



- Geodetic analysis showed that in total rock-ice broken part - 80% ~ rock and 20% `~ ice by volume.
- DEM images revealed failure scar has vertical difference of up to 180m and slab width approx. 550m.
- Analysis of satellite imagery and eye witness videos showed that total volume of ice-rock that was broken from scar was nearly equal to 26.9e6 cubic meter, i.e., 26.9e9 liters.

If we imagine this much volume of water, then One month water supply of whole Bengaluru city was poured down in the valley in few minutes.

Acc to the Bangalore Water Supply and Sewerage Board (BWSSB) wiki page, BWSSB currently supplies approximately 900 million liters of water to the city per day, i.e., 9e8 liters per day.

- 29.9e9 / 9e8 = 29.88 days.

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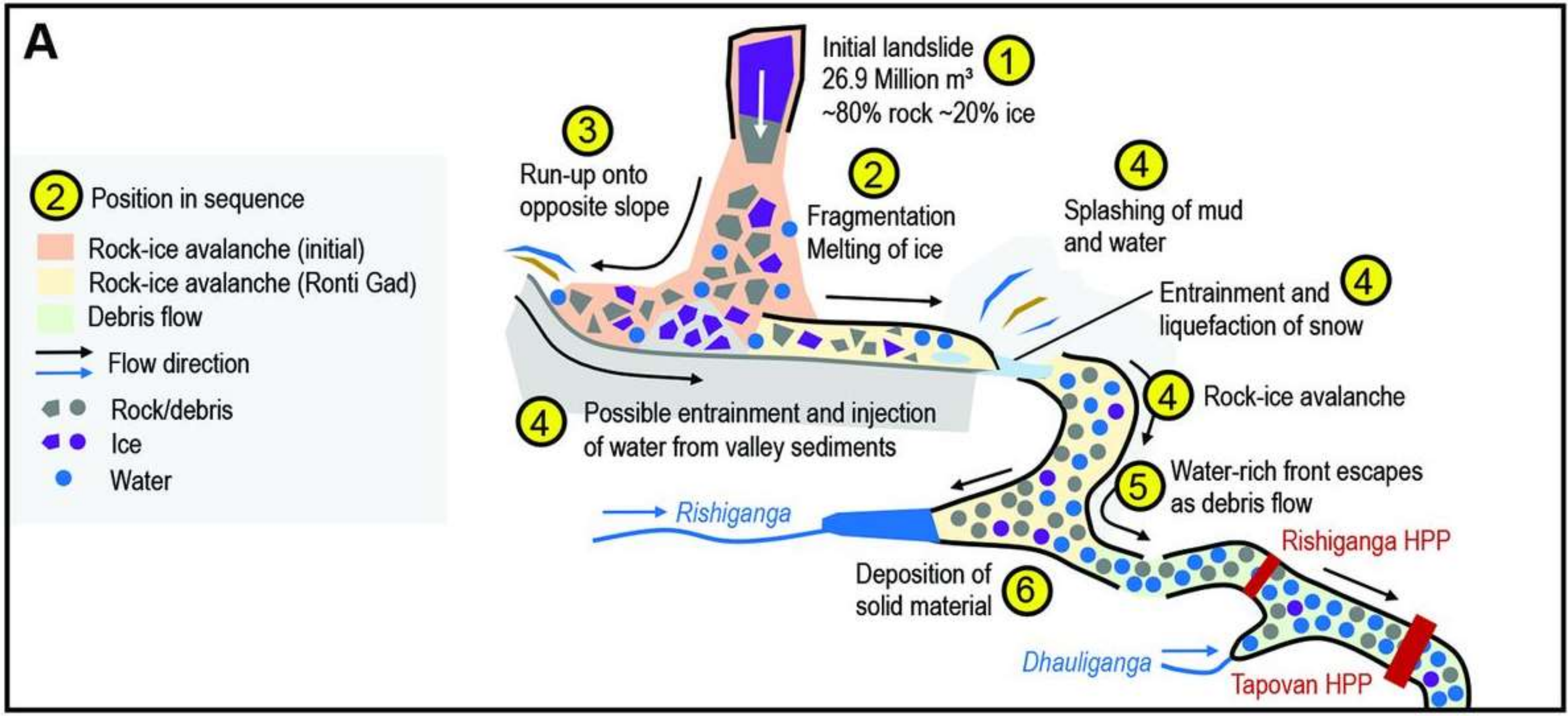
- The catastrophic **mass flow** was divided into four main component-

1. <u>Main Rock and Ice Avalanche</u> from Ronti Peak.

2. <u>Splash deposit-</u> Relatively fine grained, wet sediments that become airborne as the mass flow ran up the adjacent slopes upto 220m.



3. <u>Airborne dust deposition-</u> smooth layer of debris, estimated from satellite imagery to be only few cm thickness was deposited upto 500m above valley floor.

4. <u>Debris flow</u> through river.

❑ **Deposition** of debris

-At junction of Ronti Gad and Rishi Ganga river, a 40m thick deposit of debris blocked the Rishi Ganga Valley.

-Due to deceleration of mass flow at sharp turn

-lake of 700m formed behind these deposits in Rishi Ganga valley upstream of its confluence with Ronti Gad. DEM images estimate deposit volume ~ 8e6 cubic meter.

-It require careful monitoring as there is now risk of GOLF, if ice melt.

- A flood warning system has been installed 400 m upstream of Raini Village.

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- A substantial fraction of the fine-grained material involved in the event was transported far downstream.

- 24 hrs later- 150km downstream- sediment plume was visible in hydropower project's reservoir on the Alaknanda River at Srinagar.

- 8 days later- officials of Delhi water quality board reported unusual spike in suspended sediment 80 times the permissible level, from the canal drawing directly from Ganga river.

- 2.5 weeks later- ~900km downstream- turbidity was observed in Ganga waters at Kanpur.

- Water level also was high in river ganga for many days.

- From eye-witness, the farmers in plains using Ganga's water for irrigation reported that this summers the water was much muddy than it usually is during this time of year.

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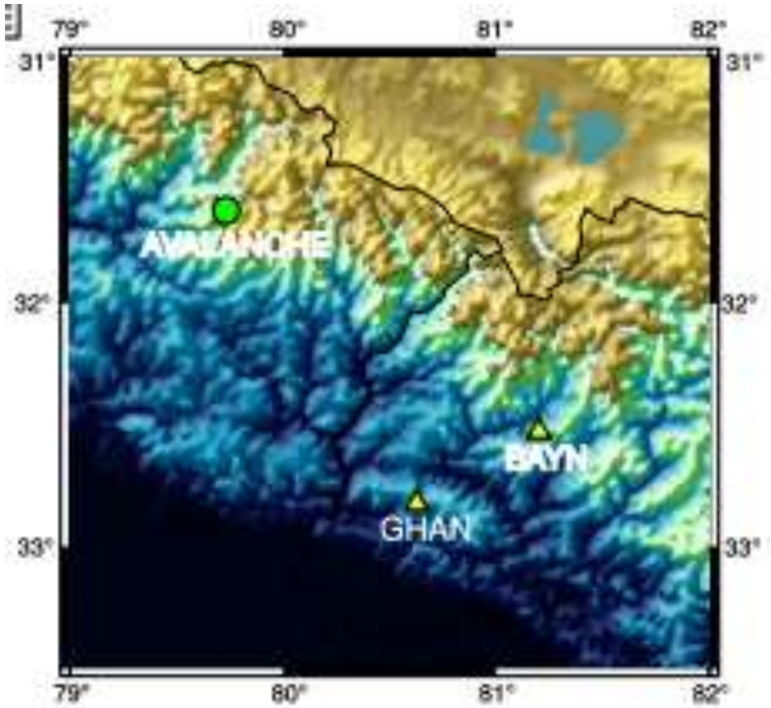
Continuous seismic data was observed from 6th and 7th Feb from two seismic stations from Nepalese seismic network (DMG/NEMRC). (location shown in fig)

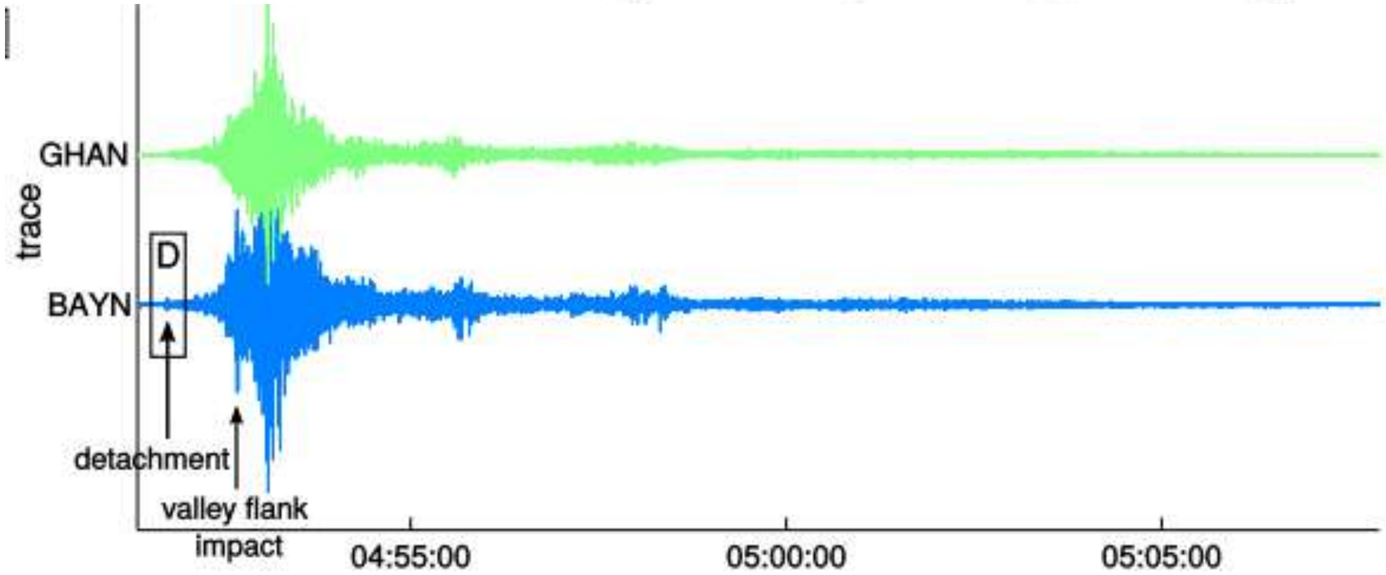
1. BAYN- Bayana - vertical sensor (ZM 500) – 174 km
2. GHAN- Ghanteshwar - 3 component broadband – 160km



No earthquake was observed before avalanche that may have dynamically triggered the rock slope failure. It showed that the block detached in one piece.

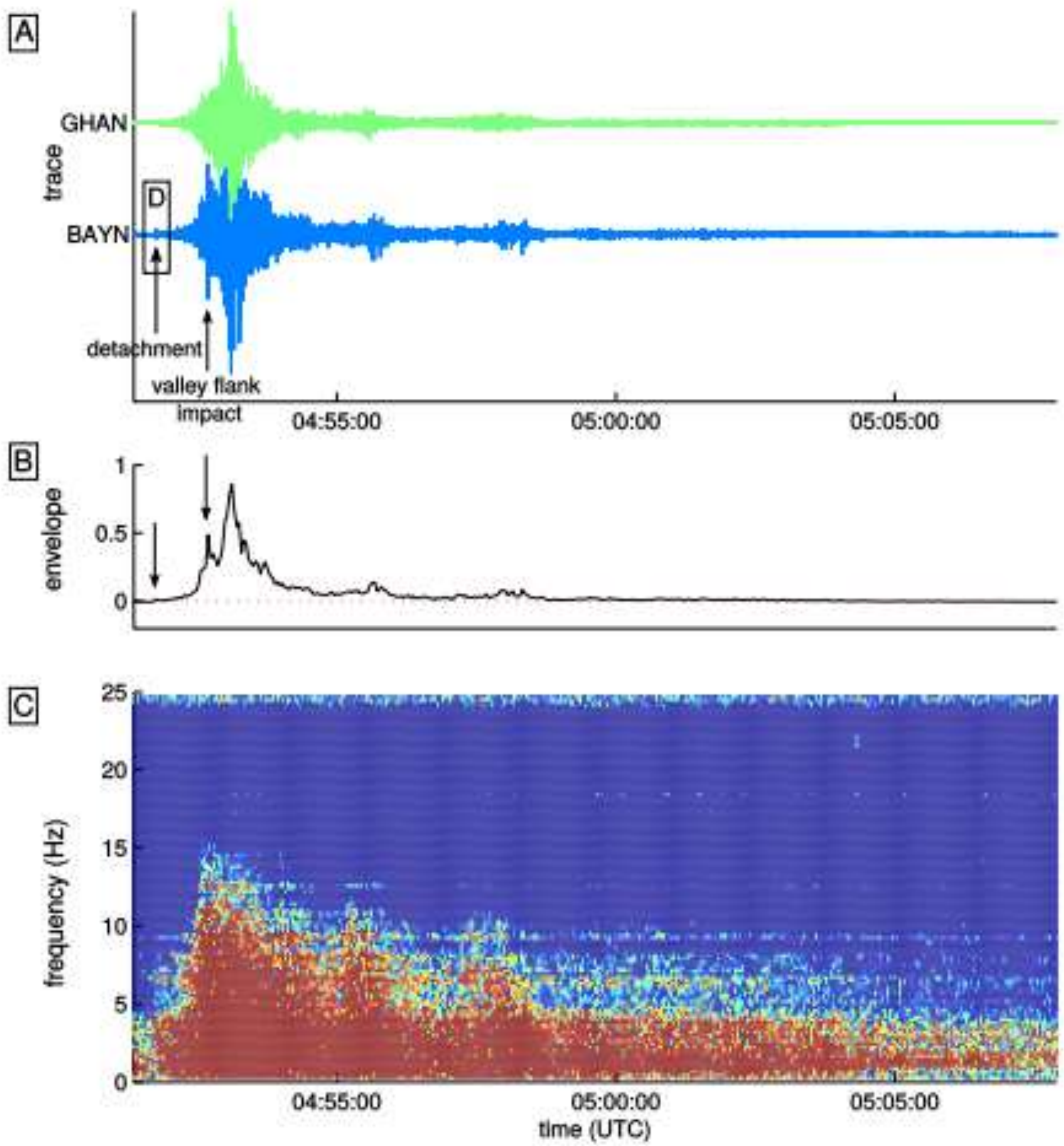
First pulse is seen in BAYN but not in GHAN due to higher noise of the traces.

The time zone on x-axis is in UTC.
The rock failure [rectangular D] occurred at 4:51 UTC = 10:21 IST



- The time shifts between these two stations provided mean wave apparent velocities between 5.8 – 7.2 km per sec.
- These values are consistent with P-wave velocity estimates of the crust and upper mantel in high Himalaya region.

<u>This shows that P-wave dominate the high frequency content of the signal</u>.



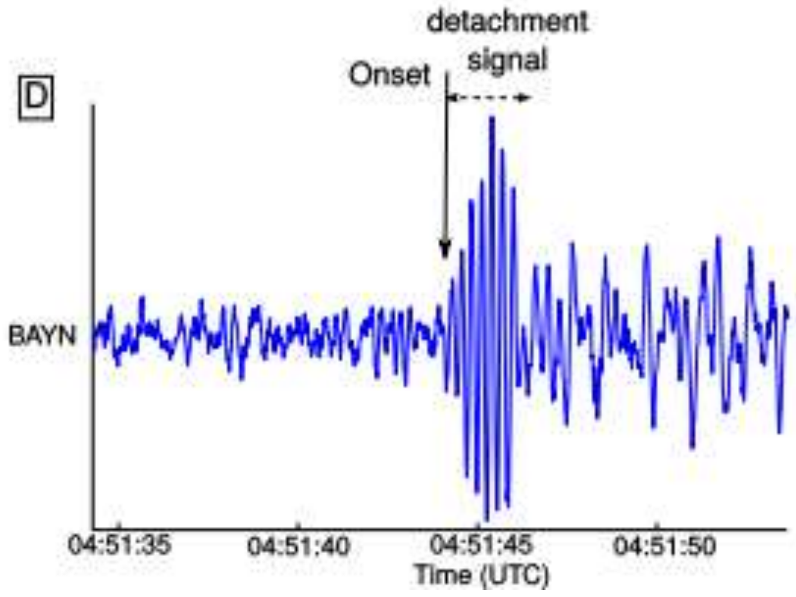
<u>The frequency spectrogram-</u>

- The triangular asymmetrical shapes on the spectrogram of about 5 mins – due to large rockslide sources.
- The main frequency content for 5 min is 15 Hz.
- Then followed by long coda of at least 10 mins with frequency – below 5 Hz.

The wave propagation travel time is consequently estimated at between 24.2 and 30.3 seconds at station BAYN

- So, the onset time of the rockslide detachment between 4:51:13 UTC and 4:51:21 UTC
- i.e., 10:21:13 IST to 10:51:21 IST

* Error on the physical origin of the detachment signal included.



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❑ Geologic features that contributed-

- Slope is extremely steep and high relief of Ronti Peak
- Rock type- schist and gneiss [these rocks are soft and platy and disintegrate into fine materials easily]
- The large expanding crevasse at the head scarp may have allowed liquid water to penetrate into bedrock, which would have enhanced freeze-thaw weathering.
- No other source of water or glacial lake was found near peak.

❑ Combination of ~20:80 ice:rock ratio and large fall height of the rock ice avalanche helped in faster melting of ice which in turn contributed in easy flow of debris downstream.

❑ Climatic cause-

Climate change cannot be directly claimed to be the cause of Chamoli disaster. It may be seen in the context of change in geomorphological sensitivity-

Glacier shrinkage uncovers mountain flanks making them destabilized. It strongly alters the hydrological and thermal regimes of the underlying rock.

Thermal reason- According to Gruber et al 2017, most of the south faces in central and eastern Hindu Kush Himalaya are permafrost free due to radiation.

- ❑ South face of Ronti Peak is certainly warmer with rock temperature around or above zero degree Celsius.
- ❑ Rock on the north face of Ronti peak likely contains cold permafrost with rock temperature several degrees below zero degree.
- ❑ This causes strong south to north lateral heat flow.

- ❑ Increase in ground temperature would have reduced strength of the frozen rock mass by altering the rock hydrology and the mechanical properties of discontinuities and the failed rock mass.

1. Origin events
2. Debris mass flow components
3. Effects in far areas
4. Seismic analysis results
5. Its causes
6. Its physics
7. Warning system
8. Conclusion

Early warning System

- ❑ Similar mass failures have occurred on north face of Ronti peak in Jan 2000, Sep 2016 and now in Feb 2021.
- ❑ Considering this repeated failures from same slope in past two decades, there should be monitoring of this area for early warning system. But the people at direct risk had no warning.

- ❑ **If we had dense seismic network near landslide, it may have provided up to 20 min of warning before arrival of debris flow at Tapovan Project.**

Along with good monitoring instrumentation, Remote sensing, seismology and climate check, we <u>also require public education</u>, which would increase awareness of potential hazards and improve ability to take action when disaster strike.

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Summarizing :

3 primary drivers for the severity of Chamoli disaster –

1. Extraordinary fall height, which increased gravitational energy
2. The ice:rock ratio ~ 20:80 which resulted in complete melting of ice and enhanced mobility of debris flow.
3. Unfortunate location of hydropower plants.

My opinion:

There are many glaciated peaks in direct vicinity of population that either direct affects people down the valley or affect the level of water in tributaries and rivers in valley. These peaks and glaciers should be continuously monitored, especially those which had some catastrophic history and are posing treat in near future.

Such peaks should be identified and rather than studying them for small time, there should be continuous monitoring system and effective pre-warning system.