# ANALYSIS OF VOLCANIC TREMOR ASSOCIATED WITH ERUPTIONS OF SHISHALDIN VOLCANO, APRIL 1999

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## ABSTRACT

Tremor signals associated with eruptions of Shishaldin Volcano on April 19 and April 23, 1999, were the strongest recorded anywhere in the Aleutian Arc by the Alaska Volcano Observatory (AVO) in its 10-year history. During the unrest, reduced displacement ($D_R$) and spectral data were computed with a time resolution of 10 minutes and a frequency resolution of 0.1 Hz. These data are analysed here.

The general temporal patterns of seismicity of these eruption sequences were similar, but the hazards quite different. The April 19 sequence is known to have culminated in a sub-Plinian phase which ejected ash to an altitude of ~ 15 km. Despite higher tremor amplitudes and the largest hotspot, the April 23 sequence produced little ash.

For several hours prior to the sub-Plinian phase on April 19, tremor with a peak frequency of 1.3 Hz intensified. However, in 15 hours after the eruption, 3 bands of stronger tremor occured with a 1.0 Hz peak, alternating with weaker tremor bands with a 1.3 Hz peak. These transitions correspond to $D_R$~10 $cm^2$. Although these strong tremor bands produced higher $D_R$ levels than the sub-Plinian phase, it is thought that only (strong) Strombolian activity occured.

This suite of observations suggests three distinct tremor sources (perhaps corresponding to slug flow, bubbly flow and sustained strong eruptions), or a cyclic change in source properties (e.g. geometry, sound speed, ascent rate). This behaviour occured at Shishaldin only during the April 19 sequence, and we are not aware of similar behaviour at other volcanoes.

## SHISHALDIN

Shishaldin is the most active volcano on Unimak Island, and one of the most active in the Aleutian Arc [Fig. 1]. 12 seismic stations are continuously operated on Unimak [Fig. 2]. Tremor was recorded up to (at least) 160 km away.

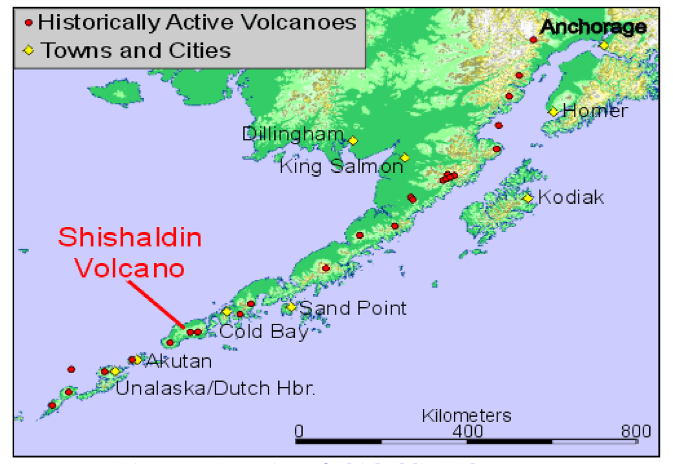



Figure 1: Location of Shishaldin Volcano.

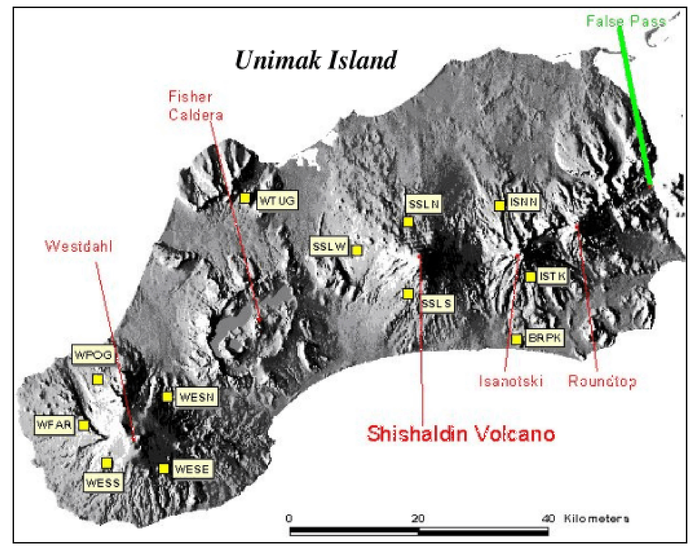



Figure 2: Seismic stations near Shishaldin volcano.

## ERUPTION SEQUENCES

Reduced displacement plots [Fig. 3] and spectrograms [Fig. 4] show three sequences of elevated tremor suggestive of eruptive activity. The VEI=3 eruptions that began on April 19 and April 23 had similar temporal patterns of seismicity, with slow buildups and abrupt ends, but the former produced a significantly larger ash column. In contrast the much smaller sequence that began on April 7 had an abrupt start and gradually declined.

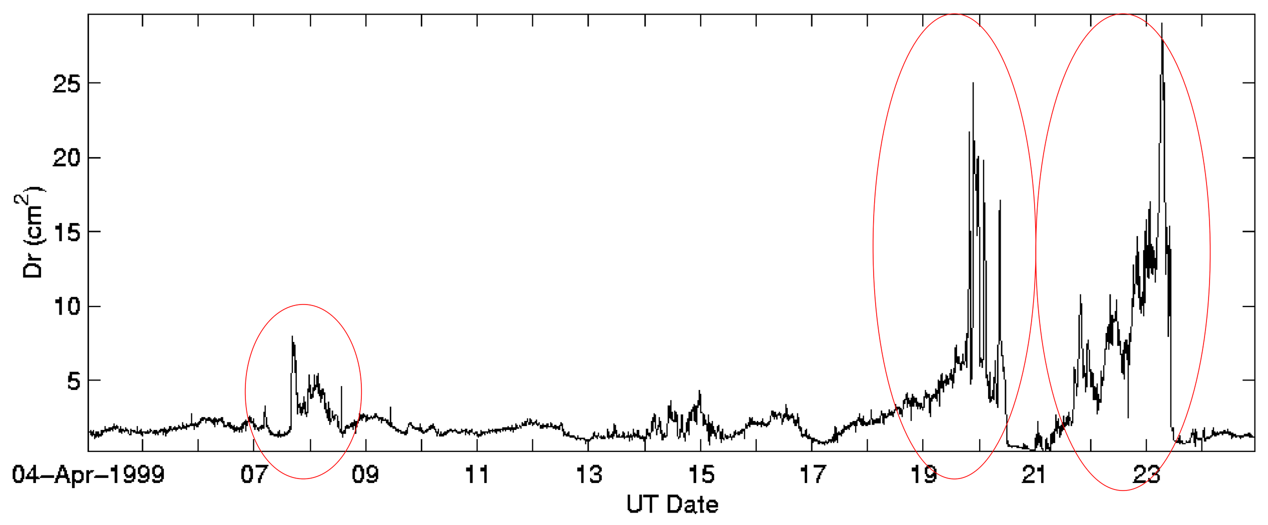
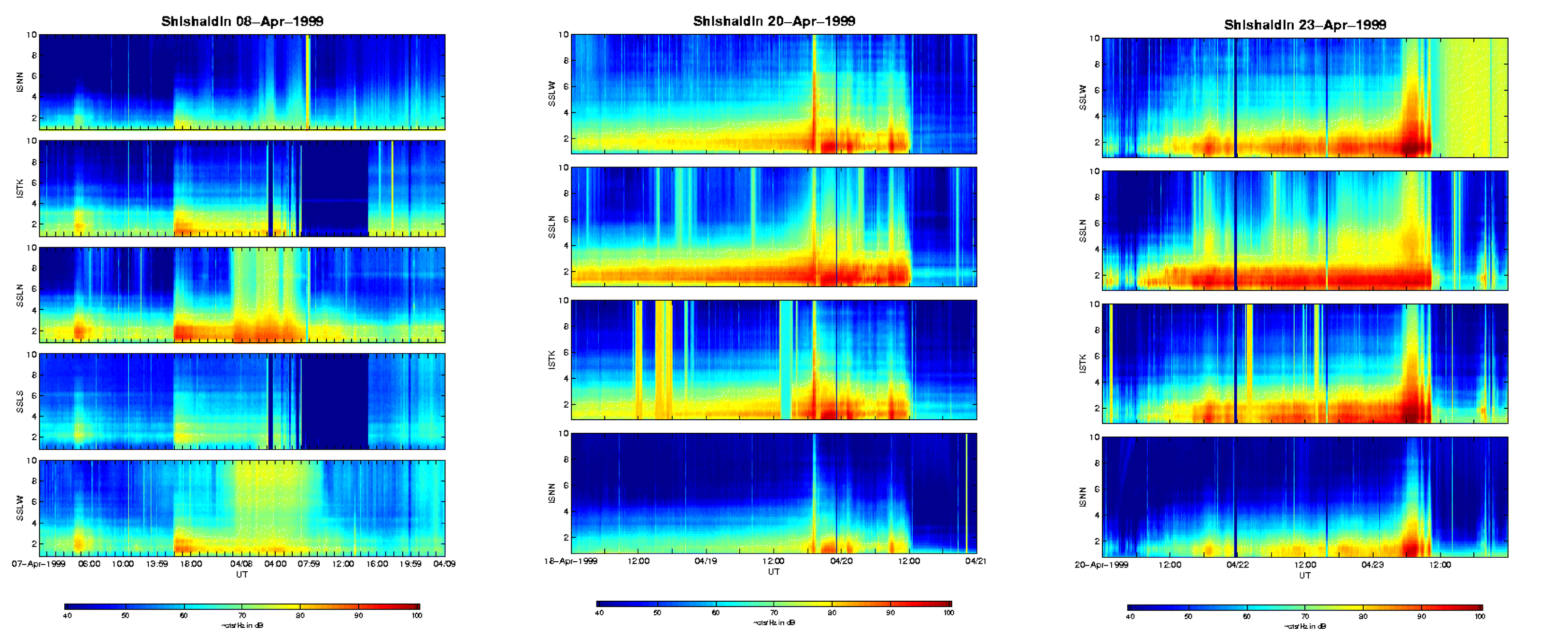



**Figure 3: Reduced Displacement for 4-24 April 1999 at Shishaldin Volcano.** This plot shows how tremor amplitude varied with time. Three eruption sequences are circled.

Abrupt onset, gradual fade. $D_R$ levels indicate VEI=2 eruption. No corresponding deposits have been identified.

Gradual onset marked by Strombolian activity. Climaxed in a VEI=3 eruption which sent ash up to an altitude of ~15 km. Three pulses of strong tremor after main phase. Abrupt end.

More rapid onset. Produced the strongest tremor of the Shishaldin unrest and the largest observed thermal anomaly, but little ash. Two pulses of strong tremor after main phase. Abrupt end.




APRIL 7 APRIL 19 APRIL 23

**Figure 4: Spectrograms for the three main eruptive sequences on April 7, April 19 & April 23.** Red for strong signal, dark blue for weak signal. Tremor frequencies were 1-2.5 Hz.

## DETAILED ANALYSIS OF APRIL 19 ERUPTION SEQUENCE

**Volcanic tremor changed dramatically at the time of the sub-Plinian eruption on April 19.** Figure 5 shows how the mean frequency of the tremor varied at three stations. The signals are very well correlated. These signals were stacked and four behaviours identified [Fig. 6]:

| | | |
|---|---|---|
| A | (grey): | Pre-eruptive tremor with a constant spectral character & gradual increase in amplitude. |
| B | (pink): | The sub-Plinian phase, marked by a broadband signal. |
| C | (yellow): | Bands of high amplitude, low mean frequency. |
| D | (green): | Bands of lower amplitude, higher mean frequency. |

### Observations

- Band A tremor corresponds to moderate Strombolian activity. This has a peak frequency of 1.3 Hz and a mean frequency of 2 Hz.
- The sub-Plinian phase (Band B) corresponds to a broadband tremor signal.
- Band C corresponds to strong tremor with a peak frequency of 1.0 Hz and a mean frequency of 1.7 Hz.
- Band D is spectrally similar to Band A.
- Transition from Band C to Band D (and vice versa) occurs at $D_R$~10 $cm^2$.
- Band C also contains a weak broadband signal. Band B also contains a weak 1.0 Hz signal.

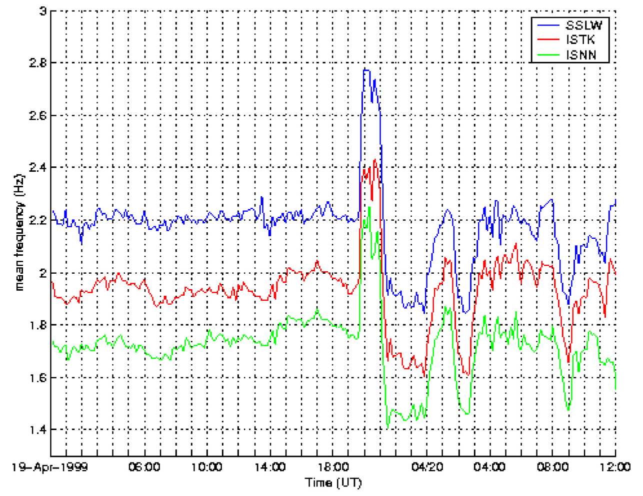



**Figure 5: Mean frequency of the signal between 0.5-5 Hz plotted for all unclipped stations against UT.** These traces have a high correlation coefficient. The sub-Plinian eruption corresponds to a high frequency burst. Immediately after this eruption the mean frequency is 10% lower than that observed before the eruption.

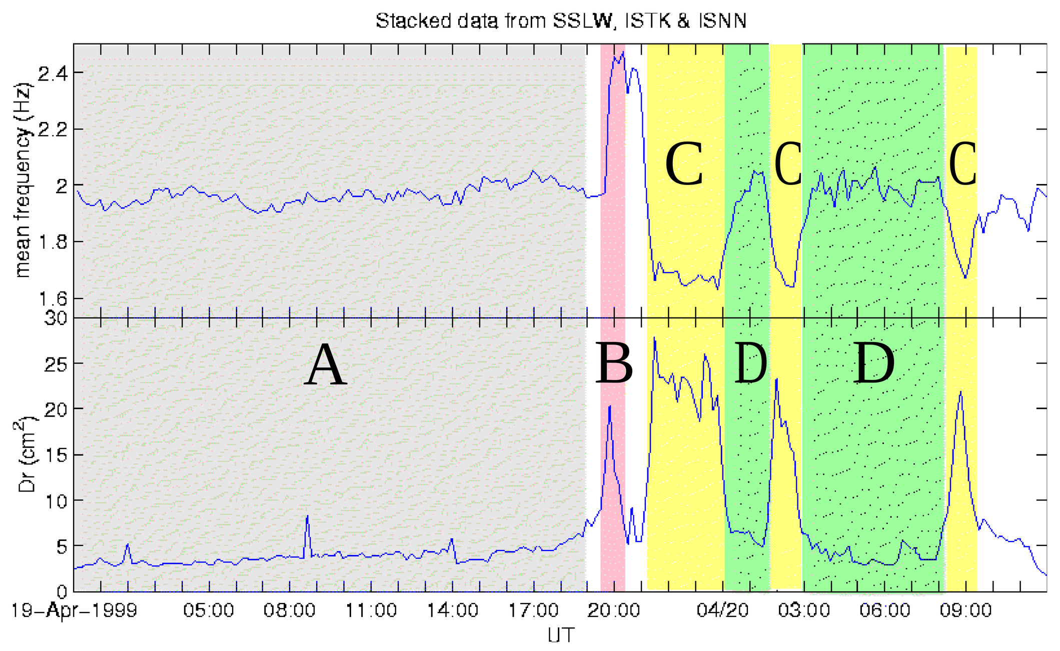



**Figure 6: Mean frequency (top) and Reduced Displacement (bottom) versus time.** The sub-Plinian eruption (B) is characterised by a high amplitude signal with a high mean frequency. Prior to this is a gradually increasing signal with constant mean frequency (A). After the eruption, bands of high amplitude, low mean frequency signal (C) alternate with bands of low amplitude, higher mean frequency signal (D).

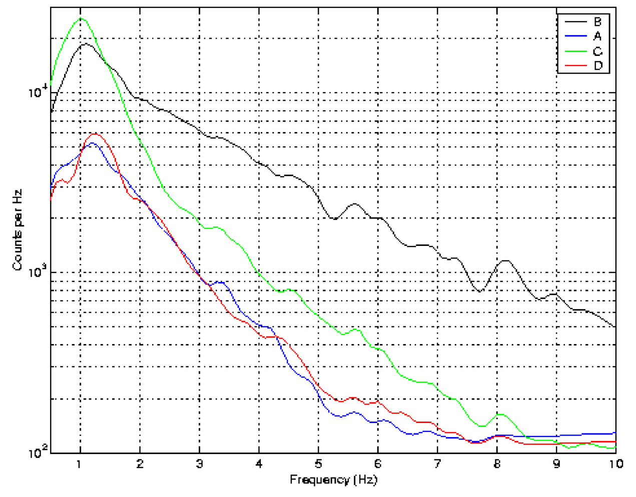



**Figure 7: Spectra from bands A, B, C and D.** Peak for Band C is at 1.0 Hz. Peak for bands A & D are at ~1.3 Hz. Data are from station ISNN.

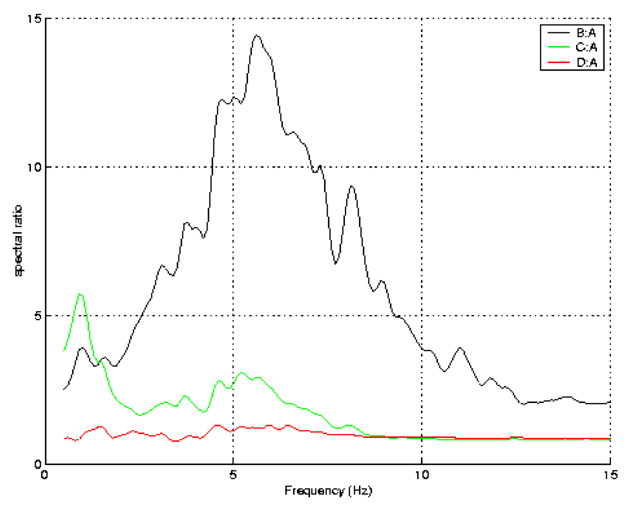



**Figure 8: Spectra from bands B, C and D divided by band A.** Data are from station ISNN.

## INTERPRETATION

The existence of three distinct tremor spectra suggests there may be three distinct tremor source mechanisms, corresponding perhaps to different flow regimes such as slug flow (Strombolian activity), bubbly flow and sustained strong explosions (sub-Plinian phase). The transition from one flow regime to another may be caused by variations in gas flux and/or magma ascent rate, or by a change in viscosity. Unfortunately, there is no record of how gas or magma flux varied during these eruptions.

Alternatively there may be only one tremor source, but (assuming a resonator) the peak frequency varies because of changes in source geometry or sound speed of the fluid.

To distinguish between these possibilities, further data analysis and modelling are required.

## FURTHER WORK

Important questions we wish to answer are:

1. How does the transition from Strombolian to sub-Plinian activity occur?
2. How could higher $D_R$ levels be sustained after the sub-Plinian phase without leading to another sub-Plinian phase?

In order to answer these questions we plan to:

- Analyse pressure sensor records and, if air waves were recorded throughout the eruptions, see how the strength & frequency of occurence of explosions varied with time.
- Analyse in more detail how the transition from band D to band C (and back) occured.
- Test these observations against various source models for volcanic tremor such as resonating cracks, pipes & non-linear models.
- Analyse seismic data from the April 7 and April 23 sequences.
- Analyse scaling relationships of tremor for the different modes of behaviour

## CONCLUSIONS

Tremor signals recorded in the hours prior to and immediately after a sub-Plinian eruption at Shishaldin on April 19 show completely different patterns of behaviour. Prior to this event tremor with a constant spectrum gradually increased in amplitude. After this event, alternating bands of strong and weak tremor occured.

Further analysis of the alternating bands of strong & weak tremor shows that dramatic changes in tremor frequency occured at the same times. Tremor amplitudes below ~8 $cm^2$ correspond to peak at 1.3 Hz. Tremor amplitudes above ~15 $cm^2$ correspond to a peak at 1.0 Hz. This pattern of seismicity did not occur at any other time at Shishaldin, nor has it been noted at other volcanoes.

Further analysis of seismic and pressure sensor data from the April 19 sequence may elucidate the relationship between tremor amplitude and eruptive activity and provide valuable information about how the transition from Strombolian to sub-Plinian activity occurs.