STRONGLY GLIDING HARMONIC TREMOR PRECEDING ERUPTIONS OF REDOUBT VOLCANO, 2009

V21E-2376

Alicia Hotovec[1], Stephanie Prejean[2], John Vidale[1], Joan Gomberg[3]

[1] University of Washington, Department of Earth and Space Sciences, [2] USGS, Alaska Volcano Observatory, [3] USGS, Seattle

ABSTRACT

Occasionally, volcanic tremor's dominant frequency and its overtones change continuously with time, or 'glide'. Gliding spectral lines have been described on volcanoes of varying sizes and compositions. During the most recent eruption of Redoubt Volcano, Alaska, gliding spectral lines appear prominently before six of the ~19 large explosions. The fundamental frequency glides upward from less than 1 Hz to as high as 30 Hz in the span of a few minutes, followed by seconds of silence just prior to eruption.

Over the years, several different mechanisms have been invoked to explain occurrences of lower frequency gliding harmonic tremor on volcanoes. The most popular explanations attribute the gliding to changing properties of a resonating crack, or to the repeated excitation of a source with gradually varying inter-event time intervals. Indeed, the first case of gliding at Redoubt was preceded by a 9 hour swarm of repeating high-frequency earthquakes in which the earthquakes comprising this swarm became gradually more frequent, eventually blending smoothly into tremor.

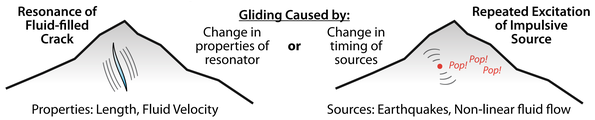
This observation leads us to favor the explanation that the gliding harmonic tremor is created by the superposition of repeating earthquakes, likely driven by instability of the magma column.

BACKGROUND

What is Harmonic Tremor?

Tremor is a continuous seismic signal often seen during volcanic eruptions. Harmonic tremor has a frequency spectrum with evenly spaced peaks. "Gliding" is when these frequencies change with time.

Proposed Causes of Harmonic Tremor



Redoubt 2009 Eruption Timeline

- Last erupted in 1989-1990 with a day of pre-eruptive seismic activity.
- Unrest began again late in 2008, seismic activity picked up in early January 2009.
- Explosive activity lasted March 23 to April 4, 2009, followed by months of dome growth.
- Last explosive event (#19) was a dome collapse, all others Vulcanian in nature.

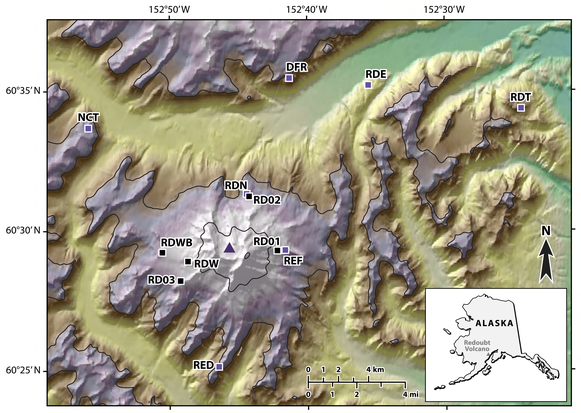


Figure 1. Seismic network functioning at Redoubt during time of eruption. Squares are stations; purple are permanent short-period, black are campaign broadband. Triangle is location of lava dome.

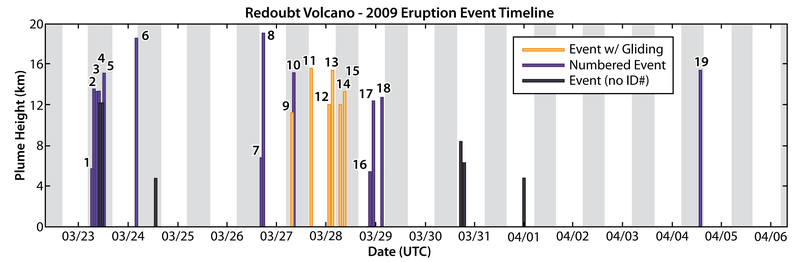


Figure 2. Chronology of major explosive events.

REPEATING PRE-ERUPTIVE TREMOR

- Harmonic tremor was detected across the local network and as far away as Mt. Spurr (100 km) immediately prior to six eruptive events.
- All cases are characterized by a dramatic increase in frequency followed by several seconds of near silence.
- We infer that the same source is most likely acting in all cases, and is not destroyed by the explosions.
- The fundamental tone (lowest peak frequency) during these eruptions is significantly higher than other documented cases of tremor.
- High frequencies indicate either a very short crack or very closely timed sources.

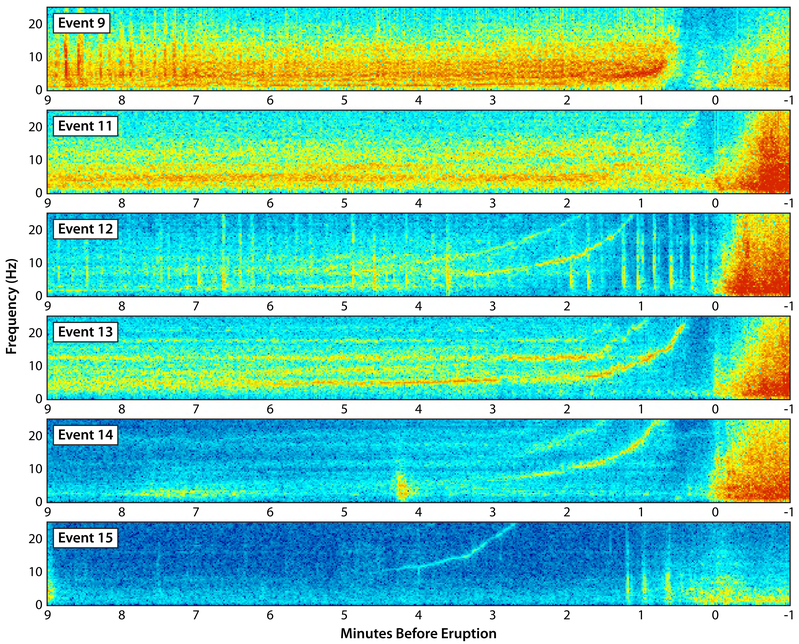


Figure 3. Velocity spectrograms for six eruptions recorded at station RD01, aligned to eruption onsets at t=0. Event 11 is dominated by inharmonic tremor, but a hint of gliding is apparent. Gliding prior to events 12 and 14 extends past the broadband Nyquist frequency of 25 Hz, and can be seen as high as 30 Hz on nearby short-period station REF.

REPEATING EARTHQUAKES

- Swarms of repeating earthquakes (aka "clones" or "drumbeats") also occur prior to Events 9, 11, 12, and possibly 13.
- Cross-correlation and clustering analysis reveal that one earthquake family is active per swarm/eruption. These families are also similar to each other.
- The highest amplitude and longest lasting swarm was before Event 9. The earthquakes become more frequent, and then blend into harmonic tremor.

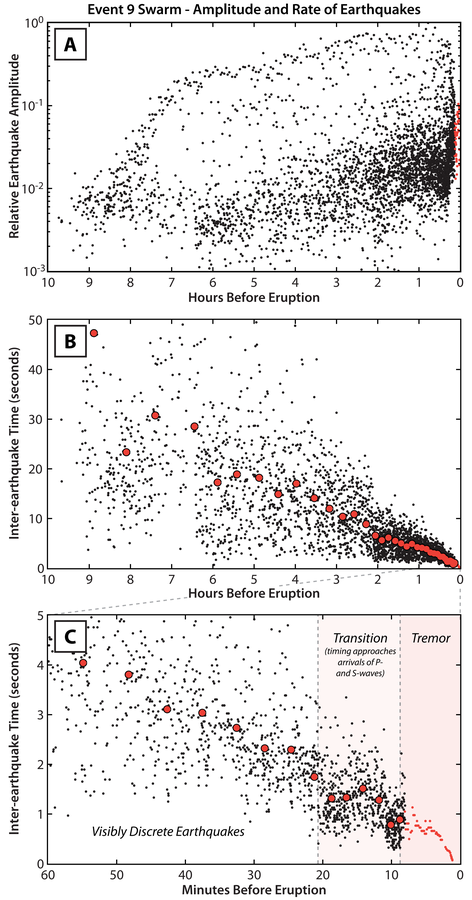


Figure 4. Scatter plots illustrating the behavior of the earthquake swarm. **A:** Distribution of earthquake amplitude, showing two main size groups. **B:** The approximate amount of time between earthquakes. Large red dots are mean times for 100 earthquake bins. **C:** Expanded view of the last hour, showing transition from earthquakes to tremor. Small red dots are 1/frequency of the fundamental tone sampled from Figure 3.

WHAT ARE THE EARTHQUAKES?

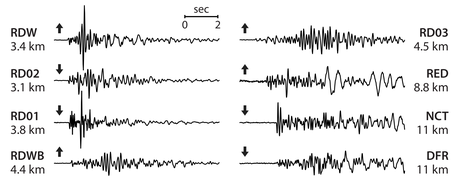


Figure 5. Representative earthquake at closest (non-clipped) stations. Arbitrary amplitude. Arrows show direction of first vertical P-wave motion.

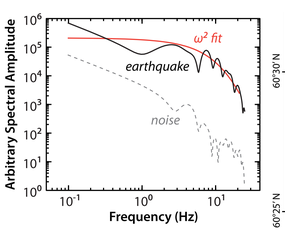


Figure 6. Earthquake spectra at station RDW with a simple ω^2 model fit.

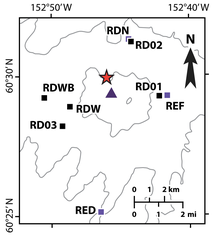
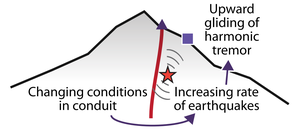


Figure 7. Station map with earthquake location marked.

- The high frequency content and mixed first-motions indicate the earthquakes can be explained by simple slip on a fault.

CONCLUSIONS



- We believe that harmonic tremor on Redoubt is caused by the superposition of closely spaced, repeating high-frequency earthquakes.
- We propose that the rate of the earthquakes is controlled by conditions in the conduit in the hours to minutes before each eruption that change in a repeatable way. This result will help studies of pre-eruptive dynamics on a short time scale.
- Future work includes further study of the earthquakes' source parameters and development of a more specific model to explain the change in rate.

Selected References

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Acknowledgements

The authors would like to thank Bernard Chouet, Michelle Coombs, Silvio deAngelis, Matt Haney, Steve Malone, John Power, Cyrus Reed, Wes Thelen, Cliff Thurber, Matt Wessale, and the rest of the staff at AVO for their insights. Financial support provided by the PNSN at UW, and by the USGS-AVO through ARRA.