Periodically-triggered seismicity at Mt. Wrangell volcano following the Sumatra-Andaman Islands earthquake

Michael West¹, John J. Sánchez¹, Stephen R. McNutt¹ and Stephanie Prejean²

¹Geophysical Institute, University of Alaska Fairbanks, Fairbanks, AK 99775.
²U.S. Geologic Survey, Anchorage, AK 99508

Seismic waves generated by the magnitude 9.0 Sumatra-Andaman Islands earthquake on December 26th, 2004 propagated around the world with long period amplitudes unmatched in 4 decades (1). As the surface waves swept across Alaska they triggered an 11-minute swarm of at least 14 earthquakes near Mt. Wrangell Volcano in Alaska, 11,000 km from the epicenter. Swarms have been documented at many volcanically active areas following large earthquakes (2-4). The Wrangell episode is unique however, in that local earthquakes occurred at intervals of 20-30 s in phase with positive vertical displacement during the passage of the Rayleigh surface waves. This timing strongly suggests that local events were triggered primarily by simple Coulomb failure. We calculate horizontal and vertical normal stresses specific to Rayleigh wave motion and show that maximum transient (dynamic) stresses reach ±10 kPa, largely as a result of horizontal strain. The proportionality between ground displacement and stress provides a low pass filter mechanism to explain why long period teleseismic oscillations are more effective triggers than waves from smaller nearby earthquakes.

Following the earthquake in Sumatra evenly-spaced earthquakes occurred at Mt. Wrangell—one of the world’s largest andesite shield volcanoes. Located in south-central Alaska, it anchors the eastern end of the Aleutian-Alaska chain of arc volcanoes (Fig. 1). Fumaroles, frequent seismicity, and historical steam plumes attest to Wrangell’s active geothermal system (5). Because of its volcanic and seismic activity, a network of seismometers is jointly operated in the Wrangell area by the Alaska Volcano Observatory and the Alaska Earthquake Information Center. Surface waves from the Mw=9.0 Sumatra-Andaman Islands earthquake on December 26, 2005 propagated across the regional network with vertical trough-to-peak ground displacements of 1.5 cm. The swarm of at least 14 earthquakes near Mt. Wrangell occurred during the passage of the Rayleigh waves (Fig. S1), about one hour after the initial rupture in Indonesia (Fig. 2).

Six of the local events were large enough to be located. All of the locatable events were within 10 km of the summit caldera. The local signals were strongest near the summit at station WANC, suggesting
even tighter clustering. More precise locations are inhibited by emergent waveforms and the modest four station local network. Locatable events occur at depths of two km or less with one exception. Magnitudes range up to ML 1.9. The variation in waveforms and amplitude, and the scatter in event locations, indicate that the triggered events are not coming from a single source but are dispersed around the summit. Some of the waveforms may be composites of more than one simultaneous event. Though 90% of the routinely located seismicity at Wrangell is of the long-period type (6), the events in the triggered cluster appear to be high-frequency tectonic in origin, except for the event labeled number three in Fig. 2B.

Small earthquakes are common at Wrangell. A comparison to the two days before and after the Sumatra earthquake, however, shows a less than 1% probability of recording 6 randomly occurring events of any type in any 10-minute window. This probability is further decreased by the requirement of: magnitudes up to 1.9; high-frequency tectonic origin; consistent spacing between events; and coincident timing with the Rayleigh wave ground motion from Sumatra. While these additional constraints are hard to quantify formally, they remove any doubt about whether the timing of the local swarm and the Sumatra event could be coincidence.

Remotely triggered seismic swarms have been documented following numerous earthquakes. The first documented example of widespread triggering was the 1992 Mw 7.3 Landers earthquake which initiated swarms at several geothermal and volcanic centers in the western U.S. (3). The Mw 7.9 Denali Fault earthquake in 2002 provided the most comprehensive set of triggered swarms to date at distances up to 4000 km (4). The recent Wrangell episode extends this paradigm even further by demonstrating that massive earthquakes can perturb geothermal/volcanic systems around the world.

The hydrothermal system at Wrangell has a history of being disturbed by large earthquakes (7). The seismicity has been perturbed in the past as well. Following the Denali Fault earthquake the seismicity rate at Mt. Wrangell dropped by 50% during the following five months (6). In the Denali case static stress changes due to motion on the fault, less than 100 km away, present a possible control on seismicity that cannot be invoked in the recent episode. No change in the seismicity rate has been observed since the Sumatra earthquake. While different mechanisms may be at work in each period, the post-Denali changes indicate that the open hydrothermal system at Wrangell exists in a tenuous equilibrium.

The events at Mt. Wrangell are distinguished from all remotely triggered swarms that have been previously documented by the one-to-one correspondence between local earthquakes and cycles within the teleseismic wave train. The path from Sumatra is almost entirely continental resulting in a well-dispersed train of similar amplitude pulses. Of the 14 Wrangell earthquakes that occurred during the passage of large amplitude Rayleigh waves, all 14 occurred during the same phase of the teleseismic waveform (Fig. 2B and S2). This resulted in a quasi-periodic distribution of events separated by intervals
of 20-30 s. It is this feature that stood out during a post-Sumatra check of volcanic seismicity, particularly in spectrogram representation (Fig. 2C). The best comparison between local and teleseismic records is provided by station WANC (Fig. 2B). The 30 s surface waves are clearly recorded despite the 1 Hz natural frequency of the vertical short-period sensor. A formal instrument response correction is applied to the data. Conceptually this correction consists of an amplification of several orders of magnitude and a phase shift of 180° for relatively long periods such as those recorded here (8). Because short-period instruments are not designed for interpreting teleseismic surface waves, we compared the corrected traces to nearby broadband instruments, each corrected for individual response. The broadband sensors are too far away to record the local swarm. They are essential, however, in verifying the short-period instrument response correction and providing more reliable ground motion amplitudes. We were pleased by how faithfully the short-period instrument captured the phase of the surface wave signal (Fig. 2D) despite a relative gain of less than 0.001 for 30 s periods relative to 1 s periods.

To compare with the local events, we consider the arrivals recorded at station WANC, with the caveat that event origin times may be 2-3 seconds earlier than the arrival time. A shift of 2-3 s will have a negligible effect on the correlation with the 20-30 s surface waves. We integrate the original velocity records to displacement for conceptual ease. All local events are observed to correlate with periods of positive vertical ground displacement. In addition, there is a rough correspondence between the amplitude of displacement and whether or not local events are triggered. None of the phases with amplitudes below 0.2 cm have triggered events. Using the derivation described below, this corresponds to a threshold transient stress of about 3 kPa. An Mw 8.1 earthquake near the Macquarie Island three days earlier produced stresses an order of magnitude lower and was not accompanied by anomalous earthquakes at Mt. Wrangell.

Nearby broadband three-component seismometers provide the key to understanding these triggered events. Since the teleseismic particle motion ties the local events to radial retrograde motion, we can use stress calculations specific to Rayleigh waves in lieu of using a plane wave approximation. We use a simple two-dimensional half space model to estimate normal stresses in the vertical and radial directions (9). Local earthquakes are undoubtedly a response to the combined effects of transient normal and shear stresses. Because we have no constraints on the orientation of faults deep within Mt. Wrangell, we cannot evaluate the role of shear stresses. We treat the normal stresses here while recognizing that faults are further influenced by the shear stresses which are similar in magnitude. We start with equations for particle displacement for a 30 s Rayleigh wave traveling with a phase velocity of 3.7 km/s. We calculate spatial derivatives to obtain strain and estimate normal stress across horizontal and vertical planes using constitutive laws assuming a poisson ratio of 0.25 and a shear modulus of 35 GPa (Rayleigh wave-specific strain and stress fields are derived and illustrated in the supplemental online material). The
horizontal and vertical normal stresses, $\sigma_{xx}$ and $\sigma_{zz}$, vary in phase with one another and in phase with vertical ground displacement. At the surface $\sigma_{zz}$ necessarily vanishes and the stress change is strictly in the horizontal direction. Away from the surface, $\sigma_{xx}$ diminishes but is partially compensated by increases in the magnitude of $\sigma_{zz}$. As a result, the transient pressure ($10$), which reaches a minimum value during positive ground displacement, decays only modestly with depth. At 5 km depth, the pressure effect is diminished by about 20%. Using this model, the observed displacement data suggest transient pressures of ±10 kPa in the top few km beneath Mt. Wrangell where triggered events were observed. This change in pressure is largely the result of variations in the normal stress acting in the horizontal direction along the great circle path connecting Mt. Wrangell and Sumatra (Fig. 1).

A direct correlation between local events and a specific phase of ground motion has not been observed before. This relationship allows us to narrow the possible mechanisms from the suite of processes that have been proposed. Any mechanisms must account for triggered seismicity that occurs (i) concurrent with ground motion, (ii) during periods of positive vertical displacement and (iii) only for pulses in the wave train exceeding a threshold displacement.

The correlation with ground deformation suggests that triggering is not due to a cumulative stress effect over many cycles. Rather, the triggered events are the result of ground motion over the preceding several seconds only. This is further confirmed by the observation that local events begin immediately following the onset of large amplitude Rayleigh wave displacements. Our favored explanation is simple Coulomb failure. Decreases in any of the three principle stress directions will reduce the overall confining pressure and bring faults closer to failure ($11$). Subsets of the Coulomb failure model are certainly possible. In the case of Rayleigh wave triggering, the horizontal stress in the direction of propagation is primarily affected suggesting preferential failure on faults that strike perpendicular to the great circle path. We do not have fault mechanism information to consider this possibility here, however, the analysis of individual stress components provides a powerful tool for future studies when fault mechanism are known. Many different behaviors are encompassed under the broad label of triggering and more than one mechanism is undoubtedly at work. In this case, however, immediate fault failure as a result of transient stresses can explain most of the features we observe.

An additional attraction to Coulomb failure is its simplicity. In the case of Mt. Wrangell, secondary effects involving fluid movement, bubbles or crack weakening are not required. During phases of reduced confining pressure, faults are shifted closer toward failure. The events at Wrangell occur during this time. This does not explain how such minute stress changes are capable of stressing a fault to failure. After more than a decade of documented triggering episodes it is clear that most occur in geothermal systems suggesting that high pore fluid pressures are an essential component. The critical role of elevated pore pressure has been explored by several authors ($12$-$15$). The current study is similar to
prior triggering episodes in that high existing pore pressure may have primed fractures for failure in response to small transient stresses. The geothermal system at Mt. Wrangell has a 50 year history of responding to large regional earthquakes (7) and has demonstrated that small stress perturbations can drive significant changes in fumerolic discharge.

While the Mt. Wrangell episode does not explicitly require the movement of pore fluids, a fluid pumping model may be compatible with our observations. In this model, a pressure increase squeezes fluids from interconnected pore space into nearby fault zones (16). The assumption of an extensive hydrothermal system is reasonable in light of persistent steam emissions from the summit of Mt. Wrangell. While increased pressure pumps the fluids, it is the total volume of fluid in the fault zone which influences fault friction. Darcy’s law controls the fluid flow. The total fluid volume in the ensemble of fault zones is the integral of the flow. Thus the maximum fluid content should lag roughly one-quarter phase behind the maximum pressure (Figure 3). It is possible such a fluid mechanism provides the first step of a two step process in which high pore pressures prime the fault zone, followed a few seconds later by minimum confining pressure, which triggers Coulomb failure. Without further knowledge of the geothermal system, we cannot quantify this effect or determine if it is a significant factor. However, the fact that local events are triggered during periods of decreased confining pressure indicates that the fluid effect, if it exists, is a secondary factor.

One of the greatest puzzles surrounding remotely triggered seismicity is why low frequency waves from distant events are more effective triggers than nearby earthquakes that can generate much higher ground velocities (17, 18). In this case, since we know the full ground motion, we can apply stress calculations specific to Rayleigh waves. This stress is proportional to the vertical ground displacement, not the velocity. By considering the waves as displacement records, it becomes clear why distant teleseismic events may be more effective triggers than nearby earthquakes. Long period surface waves are more effective at generating large ground displacement since displacement is the time integration of velocity. If a triggering threshold is defined by displacement, there may be dependence on frequency than in the velocity-based approach, at least within the frequency range of typical seismic ground motion. Validation of this approach will require an evaluation of other triggering episodes from the perspective of displacement. The Rayleigh wave-specific stress calculations we present provide a basis on which to proceed and suggest that many prior estimates of transient stress, based on a plane wave assumption, may have been overestimated. Further, the analysis of individual stress components provides the tools to consider triggering effects on faults of specific orientations when a suitable dataset becomes available.
Acknowledgements

This study was possible because of the combined seismic network efforts of the Alaska Volcano Observatory and the Alaska Earthquake Information Center. Interpretations and data analysis were improved by conversations with Emily Brodsky and Josh Stachnik. This work was supported by National Science Foundation grant EAR-0326083 and by the Alaska Volcano Observatory—a cooperative program between the U.S. Geological Survey Volcano Hazards Program, the Geophysical Institute at the University of Alaska Fairbanks and the Alaska Division of Geological and Geophysical Surveys.

References

10. The change in pressure is defined as \(-\frac{1}{2}(\sigma_{xx} + \sigma_{zz})\) where \(\sigma_{xx}\) and \(\sigma_{zz}\) are the normal horizontal and vertical stresses. The negative sign accommodates the convention that inward pressure is defined as positive, while inward-pointed stresses are negative. See supplemental Online material for full derivation.
Figure 1. Map with great circle paths from Sumatra to Wrangell Volcano. Surface waves arrive at Wrangell from the west-northwest. Station WANC is at the summit of Wrangell. Three other short-period stations, including one three-component instrument (not shown), are located within 10 km of WANC. Stations PAX and HARP are nearby broadband instruments that are 115 and 72 km from WANC, respectively.
Figure 2  Seismic records of the Sumatra earthquake and local events at Mt. Wrangell. (A) Vertical component displacement record from short-period station WANC. Large amplitude Rayleigh and Love coupled phases arrive in Alaska one hour after the earthquake. (B) Expanded view of surface wave displacement. Top record is from WANC, bandpass filtered on 0.5-20 Hz to highlight high frequency local earthquakes. Lower record is filtered instead on 0.01-0.1 Hz to show teleseismic ground motion. Note the correlation between large-amplitude vertical excursions of the teleseismic signal and local events. Scale is left in counts because ground motion estimate is unreliable at long periods for this short-period instrument. (C) Spectrogram showing frequency content of local events. Obtained by applying a Fourier transform to 5-second windows of WANC velocity record. (D) Comparison of WANC to nearby broadband stations. Dashed lines mark time axis that has been skewed to adjust HARP and PAX to appear as if they were recorded at WANC. HARP and PAX records are shifted by 24 and 37 s, corresponding to a velocity of 3.1 km/s. All three records show excellent phase correlation, affirming the reliability of short-period station WANC. The sensors at WANC, HARP and PAX are a Mark products L-4, Güralp CMG-3T and a Streckeisen STS-2, respectively.
Figure 3. Schematic showing the influence of trigger mechanisms relative to short and long period displacement records. The minimum confining pressure is reached at the time of maximum ground displacement. The secondary effect of high pore pressure due to fluid pumping into the fault zone may occur a quarter phase earlier. Though the flow into the fault zone peaks at the point of minimum displacement, the total volume of fluids in the fault would lag by roughly a quarter phase.
Online supplemental material

Derivation of pressure field

To estimate transient stress and strain resulting from passing Rayleigh waves, we derive these quantities in a simplified half space. The concept is similar to Gomberg and Davis [J. Geophys. Res. 101, 733 (1996)] though we use a different formulation. Following Stein and Wyssession [An Introduction to Seismology, Earthquakes, and Earth Structure (Blackwell Science, Oxford, 2003)], the particle displacement for a Rayleigh wave in a homogeneous poisson half space reduces to

\[
U_x = A\kappa_x \sin(\omega t - \kappa_x x) \left[ \exp(-0.85\kappa_x z) - 0.58\exp(-0.39\kappa_x z) \right]
\]

\[
U_z = A\kappa_x \cos(\omega t - \kappa_x x) \left[ -0.85\exp(-0.85\kappa_x z) + 1.47\exp(-0.39\kappa_x z) \right]
\]

Where A is amplitude, \( \omega \) is frequency, and \( \kappa_x \) is horizontal wavenumber. The normal strains induced by the motion are then

\[
\varepsilon_{xx} = \frac{\partial(U_x)/\partial x}{U_x} = -A\kappa_x \cos(\omega t - \kappa_x x) \left[ \exp(-0.85\kappa_x z) - 0.58\exp(-0.39\kappa_x z) \right]
\]

\[
\varepsilon_{zz} = \frac{\partial(U_z)/\partial z}{U_z} = A\kappa_x \sin(\omega t - \kappa_x x) \left[ 0.85\kappa_x \exp(-0.85\kappa_x z) - 1.47(0.39)\kappa_x \exp(-0.39\kappa_x z) \right]
\]

The transient stresses, again assuming a poisson solid, are (negative for compressional stress)

\[
\sigma_{xx} = \mu \left( \varepsilon_{xx} + \varepsilon_{zz} \right) + 2\mu \varepsilon_{xx}
\]

\[
\sigma_{zz} = \mu \left( \varepsilon_{xx} + \varepsilon_{zz} \right) + 2\mu \varepsilon_{zz}
\]

making the transient pressure (defined as inward pressure positive)

\[
p_{\text{trans}} = -\frac{1}{2} (\sigma_{xx} + \sigma_{zz})
\]

For figure S3 we use the following terms

A = 135 Amplitude chosen to scale displacement to 1 cm peak-to-trough

\( \kappa_x = 2\pi / 111000 \) horizontal wave number, where 111000 m is the wavelength of a 30 s wave traveling 3.7 km/s

\( \omega = 2\pi / 30 \) angular frequency, for a 30 s wave

\( \mu = 35\times10^9 \) Pa shear modulus
Figure S1. Three-component displacement record. Broadband records are from station PAX. Traces have been shifted +37 s in time to appear as if they were recorded at station WANC at the summit of Wrangell. North and east components have been rotated to transverse and radial along the great circle path from Sumatra. Original velocity records have been integrated for displacement. The bottom trace is from station WANC and has been filtered on 0.5-20 Hz to show timing of local events. The segment labeled “Love” displays clear transverse particle motion. The Rayleigh label marks the region where retrograde motion is observed between the radial and vertical component. During the Rayleigh waves, the vertical component is roughly 50% larger in amplitude than the radial and lags one-quarter phase behind in time indicating retrograde motion in the radial-vertical plane. Significant Rayleigh particle motion is also observed during the early Love waves. The periods of these waves are similar to the Love wave periods suggesting it is Love wave energy that has leaked into the radial and vertical components as a result of anisotropy. It is also possible that this is higher mode Rayleigh energy. One local event occurs during this time at 1:51. This could be a spurious background event that happened by chance. We note however that the event occurs with the same alignment to the vertical displacement on a pulse which exceeds the amplitude threshold met later in the seismogram suggesting it may well have been triggered by the same Rayleigh mechanism. The transverse component shows considerable energy near 2:00 during the Rayleigh waves. The frequencies on the transverse component are not the same and the phases do not match up as they do on the radial and vertical components indicating that this energy is unrelated to the Rayleigh waves. The spacing of the triggered events matches up with the radial and vertical components but not the transverse demonstrating that the Rayleigh motion is responsible for the triggering. This is further evidenced by the correlation of local events and the amplitude of the Rayleigh waves. The local events occur on large amplitude Rayleigh phases only. No such correlation appears with the energy on the transverse component.
Figure S2. Short and long period records for each local event recorded on station WANC. Each panel contains 40 s of data. The bottom half of each panel contains the vertical component displacement record for station WANC band-pass filtered on 0.1-0.01Hz. The top of each panel contains a short period record, filtered on 0.5-20 Hz. The events labels are the same as in figure 2. The amplitude of the short period traces has been adjusted for display using the relative scaling factor to right of each trace.
Figure S3. Displacement and stress fields as a function of time and depth. (A) Particle displacement. The motion is retrograde though the motion is not obvious since the X-axis is time and not distance. (B) Vertical displacement seismogram. (C) Horizontal normal stress. (D) Vertical normal stress. Note that the horizontal and vertical normal stresses occur in phase with each other and the vertical ground displacement. The horizontal stress is maximum near the surface and drops off with depth. Since the reverse is true for the vertical stress, the mean normal stress decays relatively slowly with depth. At this frequency and phase velocity, the vertical normal stress peaks near 30 km depth (E) Pressure. The sign convention for stress and pressure are opposite so we choose to display the opposite of pressure. Blue colors indicate regions of increased confining pressure.