in relative intensity, whereas in other crystal orientations the amide I doublet is barely resolved (Fig. 3, inset). A broad peak, characteristic of strongly bonded NH vibrations, is now found near 3290 cm^{-1}. These observations suggest that all ester carbonyl groups in the crystals grown from *o*-dichlorobenzene are only weakly hydrogen bonded (perhaps to residual solvent), and that there are still two distinct types of amide carbonyl groups—one strongly and the other weakly hydrogen bonded. Such features agree with the structure in polar solvent proposed independently [conformation B in (*4*) and conformation II-1 in (*5*)] on the basis of nuclear magnetic resonance, infrared, and optical rotatory dispersion measurements and energy calculations; in this conformation valinomycin has six semifree ester carbonyl groups, and three semifree and three intramolecularly hydrogen bonded amide carbonyl groups.

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15. We have obtained Raman spectra of valinomycin recrystallized from *p*-dioxane solution (nonpolar); these spectra resemble the *o*-dichlorobenzene spectra and hence suggest that this new conformation of valinomycin is stable in more than one environment (*10*).
16. We acknowledge the generous help of E. Shantz of Calbiochem, R. Reed and G. Russavage of Spex Industries, and N. Barnett of Northeastern University. We also acknowledge stimulating conversations with R. C. Lord and W. L. Duax. Supported by grants from the Office of Naval Research, National Science Foundation, National Heart and Lung Institute [grant HL 14322-02 (R. W. Mann, principal investigator)], and Northeastern University. Partial equipment support was provided by NASA cooperative agreement 22-011-070, the Research Corporation, and an NIH Biomedical Sciences support grant (NIH-5-S05-RR07047-08) to M.I.T.

30 May 1973

Microearthquakes at St. Augustine Volcano, Alaska, Triggered by Earth Tides

Abstract. *Microearthquake activity at St. Augustine volcano, located at the mouth of Cook Inlet in the Aleutian Islands, has been monitored since August 1970. Both before and after minor eruptive activity on 7 October 1971, numerous shallow-foci microearthquake swarms were recorded. Plots of the hourly frequency of microearthquakes often show a diurnal peaking of activity. A cross correlation of this activity with the calculated magnitudes of tidal acceleration exhibited two prominent phase relationships. The first, and slightly more predominant, phase condition is a phase delay in the microearthquake activity of approximately 1 hour from the time of maximum tidal acceleration. This is thought to be a direct microearthquake-triggering effect caused by tidal stresses. The second is a phase delay in the microearthquake activity of approximately 5 hours, which correlates well with the time of maximum oceanic tidal loading. Correlation of the individual peaks of swarm activity with defined components of the tides suggests that it may be necessary for tidal stressing to have a preferential orientation in order to be an effective trigger of microearthquakes.*

Earth tides with amplitudes characteristically of the order of 10^3 newton m^{-2} are the largest short-period cyclic stresses in the earth's crust. It has long been thought that they may act as a trigger for the release of tectonic or volcanic stress, but a convincing demonstration of such a cause-and-effect relationship has been elusive. The results of most investigations (*1*) designed to show correlations between tectonic or volcanic events and earth tides have been either inconclusive or negative. A possible exception with respect to earthquakes was reported by Ryall *et al.* (*2*) who found a significant correlation between microearthquakes in an aftershock sequence and the principal diurnal tidal component.

With respect to volcanoes, Eggers and Decker (*3*) have suggested that semiannual and annual clustering of worldwide volcanic activity may be related to corresponding tidal periodicities. Johnston and Mauk (*4*), in a more detailed study, found a definite correlation between the periodicity in the eruptions of Mount Stromboli, Italy, and the fortnightly component of the tides. A similar relationship was reported by Mauk and Johnston (*5*) on the basis of an investigation of a nearly complete catalog of volcanic eruptions from 1900 to 1971. The imprecise determination of eruption times, however, precluded an analysis with the use of diurnal or semidiurnal tidal components.

On the basis of these earlier investigations, we believe that three important conditions must be satisfied if tidal triggering of stress release is to occur or to have a reasonable probability of being discovered, or both: (i) the tectonic stress level must be sufficiently great, and the rate of accumulation of tectonic stress must be sufficiently smaller than the periodicity of the tides in order for the small-amplitude tidal perturbations to act as a triggering agent; (ii) the geographic distribution of events should be small so that there is likely to exist a spatially homogeneous mechanism that will respond in a similar manner to the repetitive tidal perturbations; and (iii) the events should be of sufficiently shallow focus so that the brittle fracturing nature of the rock is maximized. All of these conditions may prevail in aftershock zones and volcanic regions.

St. Augustine volcano, located at

the mouth of Cook Inlet, about 280 km southwest of Anchorage, Alaska, belongs to the Aleutian chain of Quarternary volcanoes. These volcanoes span a distance of some 3000 km between Kamchatka and Alaska, and some 40 of them are known to have been active in the last 200 years (*6*). The Alaskan volcanoes are part of the circum-Pacific belt of andesitic volcanism and deep earthquake zones which are believed to be associated with large-scale lithospheric plate interactions. A conspicuous kink of about 40° in the trend of the Aleutian volcano line occurs just south of St. Augustine volcano at Cape Douglas (Fig. 1b) and may reflect an important change in the stress geometry of the Pacific lithospheric plate in the St. Augustine region of the Aleutian arc structure.

St. Augustine is a composite volcano consisting of an alternate series of outward-dipping layers of pyroclastics and andesitic and dacitic lava flows and a central endogenous lava dome. The lava dome almost fills, and in many places obscures, an older crater rim formed in a violent explosion in 1883. The dome has been actively growing since 1883, and it now has a height of approximately 340 m. Since 1957, when the first photogrammetric survey of the summit was made, the dome has grown 85 m.

The volcano rests on a basement of Mesozoic and Tertiary marine sediments which underlie Cook Inlet adjacent to it. Uplifted and outward-dipping Jurassic and Cretaceous sandstones and shales form much of the southern slopes of the volcano (Fig. 1a), with dips ranging from 20° to 30°. The oldest volcanic unit found on Augustine Island is post-Wisconsin in age (*7*). Marine sediments are not seen in the northern half of Augustine Island. Aeromagnetic evidence also suggests that different geologic structures underlie the northern and southern halves of St. Augustine volcano; these structures perhaps are the result of the superposition on one side of a symmetrical composite cone over uplifted sediments which thus underlie and form a large part of the southern half

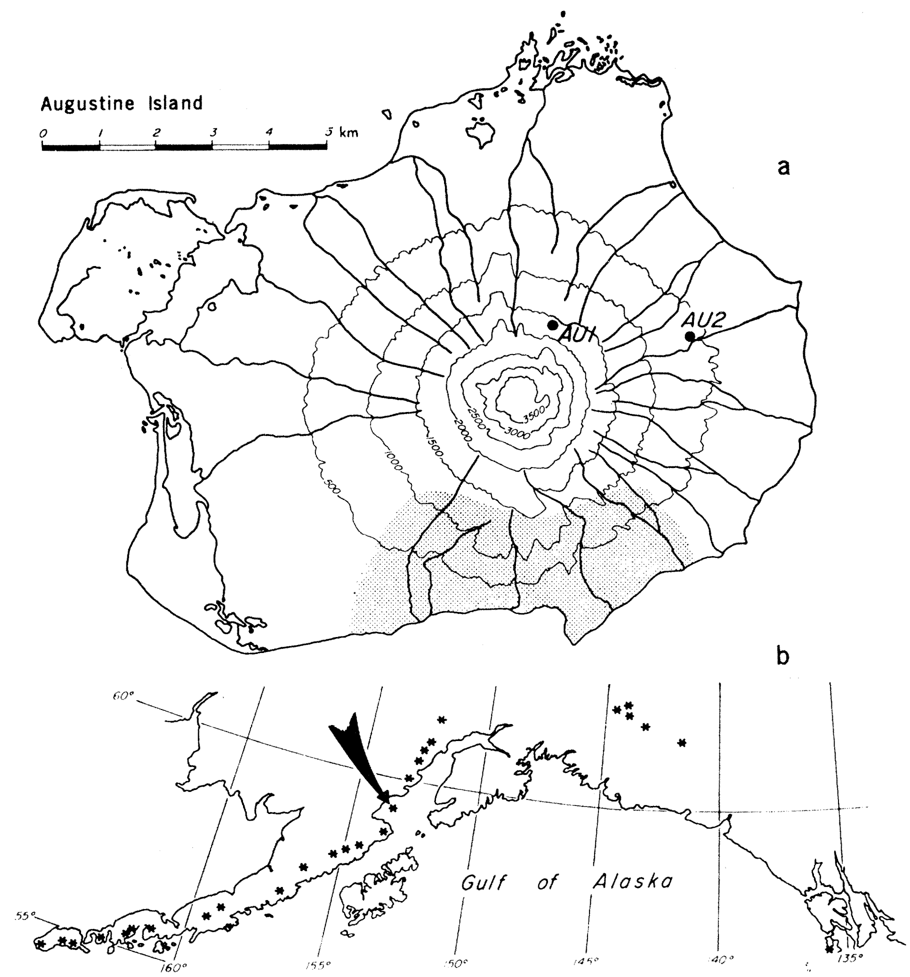

Fig. 1. Topographic map (a) and location (b) of Augustine Island. Stars indicate volcanic cones (*17*); contours are in feet; *AU1* and *AU2* indicate seismic stations; the area largely composed of Mesozoic and Tertiary marine sediments is stippled.

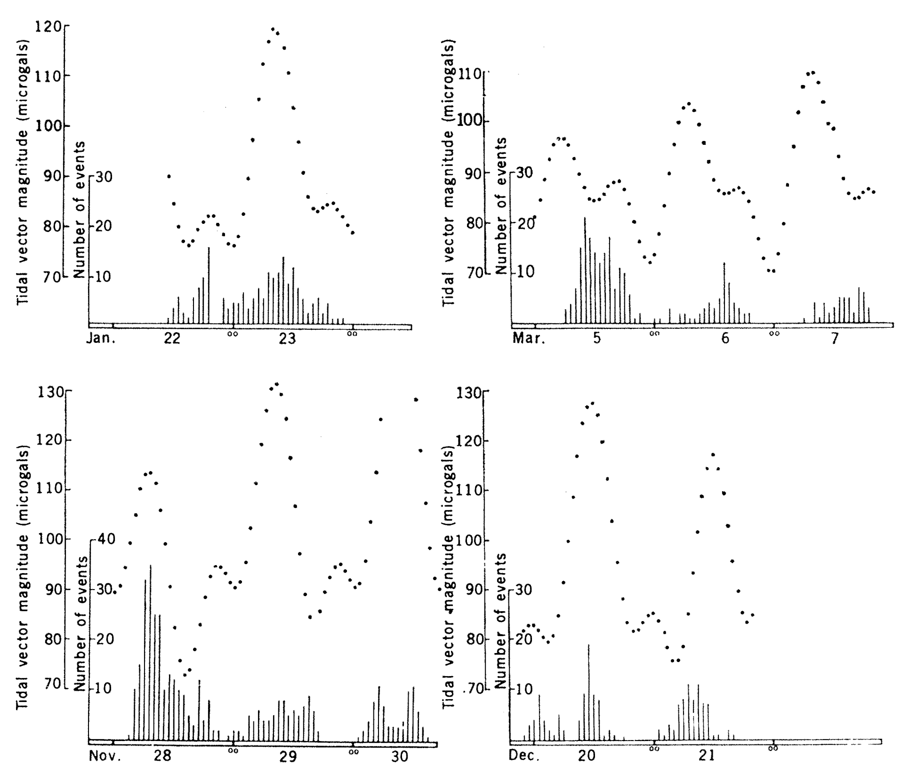

Fig. 2. Four separate microearthquake swarms with high *b* values at St. Augustine volcano, Alaska, in 1971 and corresponding calculated magnitudes of the total tidal vector.

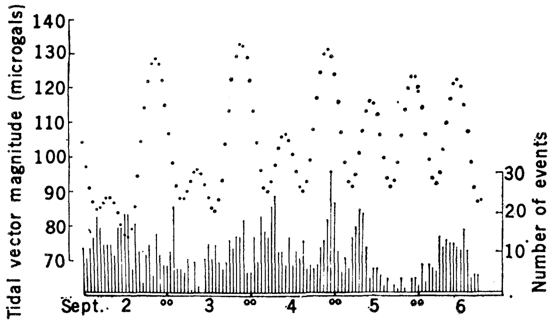

Fig. 3. Microearthquake swarm with low *b* value (1.35) preceding the 7 October 1971 eruption of St. Augustine volcano and corresponding calculated magnitudes of the total tidal vector. This was the only swarm of deeper focus recorded.

of the volcano. This uplift was most likely associated with the initial stages of the development of the volcano. Evidence that this process may still be continuing can be seen along the western and northern sides of the island, where a series of elevated beach ridges and wave-cut sea cliffs are found inland from the present beachline. An uplift of 30 to 33 cm around the shoreline of the northwest lagoon was observed after the Prince William Sound earthquake of 27 March 1964 (*8*).

In August 1970, the University of Alaska established a remote short-period seismic station at the 500-m level of the volcano (*AU1* in Fig. 1a) to monitor microearthquake activity. A second station was added in the summer of 1971 at the 200-m level (*AU2* in Fig. 1a). The equipment at each station consists of a 2-hertz vertical seismometer, a preamplifier, a voltage-control oscillator unit, and a very-high-frequency transmitter. The signals are received, timed, and recorded in Homer, 110 km northeast of Augustine Island. The system has a peaked response curve with a maximum magnification of approximately 140,000 at 30 hertz. Three additional stations became operational in November 1972.

Much microearthquake swarm activity has been observed since 1970 (see, for example, Fig. 2). During swarms, the number of events per day can increase by two to three orders of magnitude compared to the background level. Better location of the hypocenter is now possible, and this information substantiates the data from the first two stations which suggest that most seismic activity is confined to extremely shallow depths. Most likely, seismic activity is related to deformation and fracturing within those parts of the composite volcanic cone above the sea floor that occur during periods of accelerated growth of the central lava dome. Plots of the hourly frequency of microearthquakes often show a diurnal peaking of activity which will be discussed below.

Plots of the logarithm of the frequency versus the logarithm of the amplitude for eight individual swarms were constructed and fitted with lines of the form

$$\log N = a - b(\log A)$$

where N is the number of earthquakes with amplitudes larger than A and a is a constant depending on the magnification of the instruments and the general seismicity of an area. With the exception of one swarm of deeper origin on 2–6 September 1971 ($b = 1.35$) (Fig. 3), *b* values ranged from 1.7 to 2.5. Minakami (*9*) observed high *b* values (between 2 and 3) for volcanic earthquake swarms originating at focal depths of generally less than 1 km. This seems to confirm the postulated shallow origin for most recorded swarms at St. Augustine volcano. Mogi (*10*) has attributed the tendency toward high *b* values for volcanic earthquake swarms to both the heterogeneity of the medium and a concentrated stress situation. Scholz (*11*) has concluded that the high *b* values (2 to 3) of volcanic earthquake swarms are attributable to a nonuniform stress field; that is, the heterogeneity of the stress field rather than the heterogeneity of the medium has the most profound influence on the *b* value. The extrusion of the large central dome of St. Augustine volcano through the heterogeneous composite cone, in reality, produces conditions conforming to both Mogi's and Scholz's hypotheses.

Another indication of the shallow origin of St. Augustine microearthquake swarms is the characteristic attenuation patterns of body waves, which have been observed consistently across the seismic net. Figure 4 illustrates this pattern schematically. In case A an earthquake occurred in the immediate vicinity of station AU1; the same event was recorded in highly attenuated form at station AU2 only 3 km distant. The angle of incidence of the wave front to the outward-sloping low-velocity pyroclastic layers is very shallow, and thus the geometry is conducive to the trapping of much of the seismic energy. Case C shows the reverse situation for

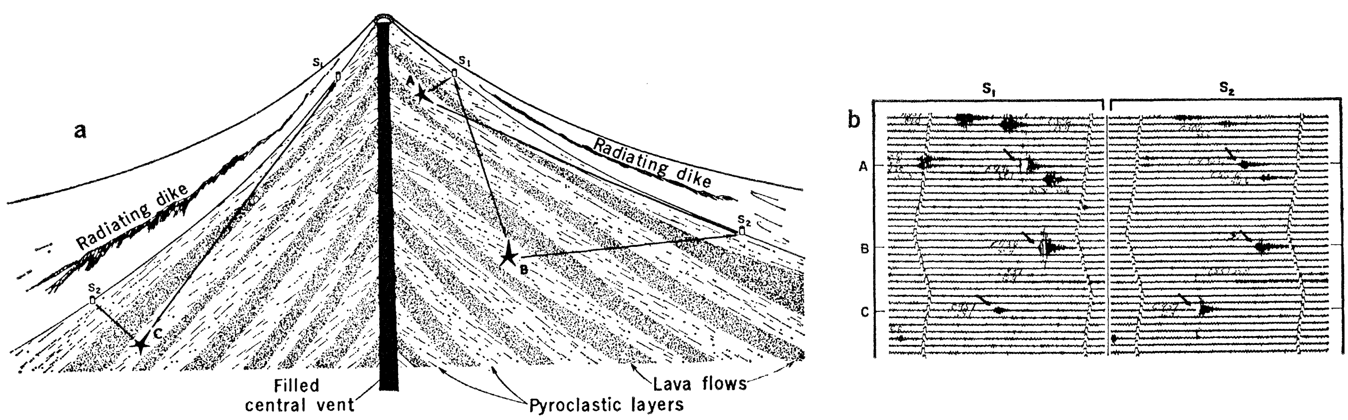

Fig. 4. (a) Schematic cross section of an andesitic composite cone. (b) Seismograms of 30 November 1971, from station AU1 near the summit and from station AU2 on the lower flank of the volcano, which show the characteristic attenuation effects of the body waves on their paths to the two stations.

a microearthquake occurring near station AU2. Case B is an intermediate situation in which an earthquake occurred about equidistant from both stations, somewhat nearer to station AU1. Similar patterns have been observed recently when a swarm was recorded for the first time across the total array of five stations, an indication that the entire volume of the volcano above the sea floor underwent small-scale fracturing. The magnitudes of the individual events in a given microearthquake swarm vary only slightly. On the basis of a method of estimating microearthquake magnitudes of Brune and Allen (*12*), most of these events range in magnitude between 0 and 1.

Two types of tidal data were used in this analysis: calculated theoretical acceleration values and high- and low-water predictions in standard tide tables. Of these, the acceleration values proved to be the more useful for cross correlation techniques, whereas the ocean level data served as an indicator of the time of maximum and minimum ocean tidal loading.

The vertical and horizontal components of tidal acceleration and the magnitude of the total tidal vector as functions of time and location were computer-generated by means of a modification of the methods outlined by Longman (*13*). Computations were made at 1-hour increments for every day on which significant microearthquake activity was recorded.

In addition, we determined the corrected maximum and minimum amplitudes of the ocean tide for Iliamna Bay, Alaska, using the U.S. Coast and Geodetic Survey *Tide Tables for the West Coast of North and South America* for 1970 through 1972 (*14*). Although Iliamna Bay is only 14′ in longitude and 06′ in latitude from Augustine Island, the tides in Cook Inlet have such large spatial gradients that any correlation of the activity of St. Augustine volcano with the ocean tidal extrema at Iliamna Bay may have some apparent phase differences.

Swarms during four disjoint time periods at St. Augustine either before or after the eruptive activity on 7 October 1971 and the calculated magnitudes of the tidal acceleration are displayed in Fig. 2. All of the swarms are characterized by high *b* values characteristic of shallow foci. The only low *b* value (1.35) swarm preceding the eruption is shown in Fig. 3. The visual correlation of both pre- and post-eruptive microearthquake activity with the magnitude of the total tidal vector is quite good. However, there are some interesting variations. For example, in addition to being the only swarm of low *b* value, the activity of 2–6 September 1971, unlike the swarms of higher *b* value, displays little visual coherence with respect to the total tidal vector.

Visual correlation of the numerous swarms of high *b* value with the magnitude of the total tidal vector revealed two dominant phase relationships of nearly equal frequency of occurrence. The slightly more frequent condition is one of no obvious phase shift and is exhibited in the activity of 22–23 January and 28–30 November (Fig. 2). The second relationship, a phase delay in the microearthquake activity by approximately 5 to 6 hours from the time of the maximum tidal perturbations, is exhibited in the activity of 5–7 March (Fig. 2). No significant systematic temporal variation of the swarms either before or after the eruption of 7 October was observable. This finding suggests that the phase relationship of the microearthquake activity with respect to the tidal accelerations is independent of the pre- or post-tectonic stress condition of the volcano, or both.

As a check on the validity of the visual correlation, we compared all of the microearthquake distributions and corresponding tidal computations, using the cross covariance technique described by Blackman and Tukey (*15*). Four important observations emerged: (i) the cross covariance technique confirmed the existence of both of the phase relationships; (ii) operating on the entire swarm catalog, the technique defined, with little variance, the phase delays of the two swarm types at 1 hour and 5 hours, respectively; (iii) the swarm with low *b* value also exhibited a 1-hour phase delay, but with greater standard deviation than the other swarms; and (iv) some of the swarm distributions exhibited both patterns, suggesting that the two distribution types are not mutually exclusive events.

A comparison of the microearthquake distributions with the predicted times of high and low ocean tides for Iliamna Bay exhibited similar phase relationships, but, without accurate continuous tidal records, cross correlation was impossible. A comparison of the predicted times of high and low water with the theoretical tidal accelerations indicated that the predicted maximum amplitude ocean tides were nearly always phase-delayed from the calculated maximum gravitational accelerations by 5 hours. The two swarm distribution relationships, therefore, coincide well with the times of maximum tidal acceleration and the times of maximum ocean loading. The more complex distribution of the September microearthquake swarm may possibly reflect an increased and perhaps nonlinear tectonic stress rate (that exceeded the tidal stress rate) preceding the eruption. Similar behavior has been observed at Kilauea, Hawaii (*16*), and may be applicable to the St. Augustine volcano.

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18. We thank Prof. H. Pollack for the use of his tide-generating program and Profs. H. Pollack and R. Van derVoo for their critical comments on and discussion of this report. Instrumental portions of this work were supported under NASA grant NGL 02-001-063, NSF grant GU-3856, and the Sea Grant Program.

17 April 1973