stant T and pressure. The effect of T is dominant on the North American eastern continental shelf, typically being ten times larger than the effect of S. For this idealized situation, the extra heat, Q, stored in the upper layer is

$$Q = \rho_1 c_p h \ \Delta T \simeq c^2 \rho c_p / g \alpha \quad (3)$$

where c_p is the specific heat of seawater at constant pressure, and where we have used Eqs. 1 and 2 and ignored the effect of S on ρ and the effect of variations in ρ on c_p per unit volume. For more complicated density stratification, one can still take the square of the propagation speed to be approximately proportional to the heat storage.

We measured the wave packet spacings in enhanced Landsat images for the period June through August in 1972, 1973, and 1974. We found that, plotting histograms of packet spacing, there appear to be at least three dominant spacings but these are apparently multiples of a fundamental, minimum spacing. But remembering that internal wave groups are only visible in surface images in the presence of capillary waves or short gravity waves (which only occur when there is wind), we interpreted the finding to mean that there is only one wave packet spacing in a given location in a 2-month period. Doing this, we assumed that the observation of a multiple of the minimal group spacing simply means that one has missed some groups since they are not visible because of an absence of surface ripples which can be modified by the velocity field of the internal waves. On the basis of this hypothesis, we assumed that there was a single wave packet spacing and obtained the histogram shown in Fig. 2, including all the wave packets measured. This interpretation may give an overly favorable result, since it suppresses variations from the mean larger than the mean (such values are modified by the subtraction of a multiple of the mean).

Since the data suggest that there is a single predominant wave spacing, one may wonder why. If, as suggested by the Landsat data, internal waves propagate all over the continental shelf area in a variety of directions, their presence provides a smoothing mechanism for variation in the propagation speed. At a locality with smaller propagation speed there would tend to be an accumulation of wave energy, associated with large wave amplitude and wave breaking. Wave breaking causes mixing, leading to a deepening and cooling of the layer with no change in wave propagation speed at first. But a cooler surface layer will absorb more heat from the atmosphere and lose less heat through evaporation and radiation. Eventually, a local discrepancy in propagation speed will be smoothed out.

With these crude assumptions we have calculated the heat stored in the upper heated layer and compared the results with the in situ observations made from ships in the area within 2 weeks of the time of the satellite observations (Fig. 3). The results indicate that the heat storage estimated from satellite data is smaller than the results of calculations based on in situ observations. One reason for this is that, as found by Halpern (*2*), the wave packets propagate into the region when the layer depth is a minimum during the tidal period, whereas the in situ data contain an unknown contamination from internal tides. The internal tide amplitude of the seasonal thermocline can amount to half its mean depth, as shown by Halpern's observations.

Our method thus provides a way of estimating the upper ocean heat storage uncontaminated by the internal tides. The preliminary results are sufficiently encouraging to warrant further exploration and attempts at refinement of the method.

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5. This work was supported by the U.S. Office of Naval Research under contract N00014-75-C-0291. A.S.M. was supported by a fellowship from the National Research Council of Brazil.
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14 September 1978

Hydraulic Transients: A Seismic Source in Volcanoes and Glaciers

Abstract. *A source for certain low-frequency seismic waves is postulated in terms of the water hammer effect. The time-dependent displacement of a water-filled subglacial conduit is analyzed to demonstrate the nature of the source. Preliminary energy calculations and the observation of hydraulically generated seismic radiation from a dam indicate the plausibility of the proposed source.*

Some of the most enigmatic seismic waves are those of low frequency (1 to 5 Hz) associated with both volcanoes and glaciers. These waves are routinely recorded by earthquake seismographs to distances of a few hundred kilometers (*1*). Typically, the signals recorded exhibit emergent onsets and have either weakly developed or no seimic phases that can be ascribed to compressional (*P*) and shear (*S*) waves. Generally, the signals are unusually monochromatic. When associated with volcanic activity, they are classified as "B-type" earthquakes (*2*). Events of the same character in glaciological investigations are termed "type-II" icequakes (*3, 4*).

The B-type earthquakes are monitored as a means of predicting volcanic eruptions; however, their origins are unknown (*5*). The type-II icequakes are assumed to be associated with the movement of glaciers (*1*). Microearthquake investigations on glaciated volcanoes have shown that the type-II and B-type signals cannot be differentiated from one another (*5*). We propose a source mechanism that suggests a hydraulic origin for both types of waves. We develop the hydraulic source in terms of the familiar water hammer phenomenon that is generally associated with piping systems.

According to Minakami (*2*), B-type earthquakes are of shallow focus (less than 1 km) and are associated with active vents. These tremors are inferred to be a result of magmatic activity. Matumoto and Ward have suggested that volcanic earthquakes are caused by stress concentrations that result from the transport of magma (*6*).

Relatively high-energy, type-II glacier signals have been recorded at the University of Alaska's high-gain seismic station (SCM) in southern Alaska (*1*). The recorded waves had weakly developed *P* phases and well-developed, nearly monochromatic *S* wave trains. Hypocentral determination showed them to be of shallow focus with their epicenters near the Harvard Glacier, Alaska. The events described were monitored at stations up to 420 km from their sources and in some instances had Richter magnitudes of 2.0 to 2.5.

Local microearthquake surveys made

directly on the surface of the Variegated Glacier, Alaska (3), indicate the presence of type-II events similar to those recorded at SCM. Close-in monitoring showed that the character of the signals was essentially the same as that of the signals recorded at more distant stations.

To evaluate the source mechanism of the volcanic and glacial signals, we consider the nature of water flow in glaciers. It is well established that water transport in intraglacial and subglacial channels is a major mechanism of drainage in temperate glaciers (7). Moreover, the flow is not necessarily steady in these channels (8) and various mechanisms operate within the glaciers to cause transient disturbances of the flow. When such disturbances are introduced, they may cause fluctuations in fluid pressure which result in displacements of the conduit walls. Such displacements are capable of producing seismic radiation similar to that detected and identified as the type-II icequake.

According to the analysis of Streeter and Wylie (9), the equations of motion and continuity for transient flow in elastic conduits can be formulated in terms of two quasi-linear hyperbolic partial differential equations. The equation of motion is

$$g\frac{\partial H}{\partial x} + V\frac{\partial V}{\partial x} + \frac{\partial V}{\partial t} + F(v) = 0 \quad (1)$$

and the equation of continuity is

$$\frac{\partial H}{\partial t} + \frac{a^2}{g}\frac{\partial V}{\partial x} + V\frac{\partial H}{\partial x} + V\sin\alpha = 0 \quad (2)$$

In Eqs. 1 and 2, H is the hydraulic head (in meters), V is the fluid velocity (in meters per second), $F(v)$ is the frictional loss function, x is the linear distance along the conduit, t is the time (in seconds), α is the inclination of the conduit, g is the acceleration due to gravity (in meters per square second) and a is the speed of sound in the fluid modified by the interaction of the fluid and the conduit. The wave speed when the conduit is in an infinite medium is determined by the equation

$$a = \frac{(K/\rho)^{1/2}}{\left[1 + \left(\frac{2K}{E}\right)(1 + \nu)\right]^{1/2}} \quad (3)$$

where K is the bulk modulus of the fluid, ρ is the fluid density, E is the elastic modulus of the conduit, and ν is Poisson's ratio for the conduit material. Equations 1 and 2 can be transformed into four ordinary differential equations and solved by numerical methods for H and V as a function of t and x. Once H is determined, the displacement of the conduit wall can be calculated.

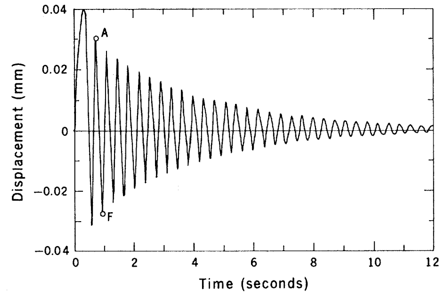

Fig. 1. The radial displacement of the wall of the ice conduit as a function of time. The displacement is at the point of closure of the tunnel (L = 100 m). Point A refers to the maximum displacement of the conduit wall at time t = 0.759 second and point F refers to the minimum displacement at time t = 0.939 second.

To demonstrate the manner in which altering the steady-state flow condition can produce a time-dependent displacement of the conduit wall, we present the following example. Röthlisberger (7) considered the steady-state flow of water in subglacial channels and related his analysis to the hydraulics of the Gorner Glacier, Switzerland. We construct the following situation from his data. We assume that at the bottom of the lake of the Gorner, Gornersee, an ice tunnel extends down the glacier nearly parallel to the glacier bed. To generate a hydraulically induced displacement of the walls of the ice tunnel, we interrupt the flow of water at some point in the tunnel.

In Fig. 1 the resulting radial displacement of the tunnel wall is displayed as a function of t at the point where the closure of the tunnel takes place. The numerical values of the variables and the boundary conditions used to solve Eqs. 1 and 2 are given in (10). The tunnel closure time (0.4 second) is selected to produce a maximum displacement of the conduit without introducing cavitation in the fluid. The sudden onset of the displacement (Fig. 1) is a result of the imposed valving. A reduced rate of closure or a different closing function could be applied to make the onset of the displacement more emergent. The conduit length (L) of 100 m produces a wave with a period of 0.361 second. For single-conduit geometries, the period of the oscillating displacement (T) is given by

$$T = 4L/a \quad (4)$$

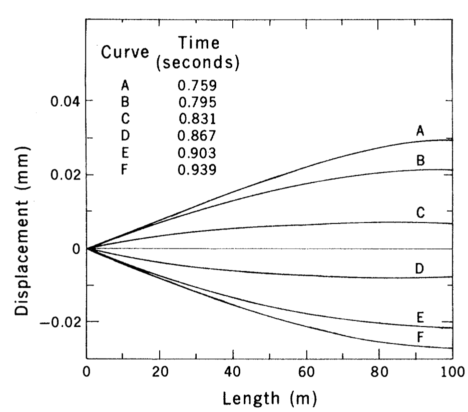

Fig. 2. The radial displacement of the conduit as a function of the conduit length for several values of time (A through F); L = 0 is at the reservoir end of the conduit, and L = 100 m is the point of closure. The six values of time for which the displacements are plotted are taken between points A and F in Fig. 1.

Figure 2 exhibits the radial displacement of the tunnel wall as a function of distance along the conduit at several instances in time. The six values of t for which the displacements are presented are taken between the point of maximum displacement, A in Fig. 1, and the point of minimum displacement, F in Fig. 1. Although we cannot speculate on the manner in which waves radiate from our source, the harmonic nature of the conduit displacement is strikingly similar to that observed for both B-type and type-II wave trains.

For our calculations, we have used data values representative of those that might be found on the Gorner Glacier. The near-sinusoidal nature of the displacement (Fig. 1) is a result of the single-conduit geometry and the linear closure law assumed. We expect the actual glacier conduit geometry to be more complex, with an interconnected network of tunnels. Moreover, cessation of flow would not necessarily follow the simple linear law that is used in this example. Changing either or both of these factors (geometry or valving) would tend to change the frequency and shape of the wave form but would preserve its periodic character. The actual boundary conditions of a hydraulic system would also change the displacement magnitudes.

Direct observations on glaciers establish that transient changes in the flow of water do take place in glaciers within the time frame of our example (on the order of seconds). In the extreme, geyser-like waterspouts have been observed to rise to a height of 60 m with a duration of 3 minutes (8). More conservatively, we can consider that any change in a steady-flow condition generates a transient response. Röthlisberger (7) suggested that fluid connections between intraglacial and subglacial conduits might act to valve the fluid flow.

Preliminary energy calculations and observations of hydraulically generated seismic signals indicate that detectable seismic radiation may be generated from the proposed source. We assume that 10 percent of the kinetic energy of the moving water column is converted to seismic energy as the column is brought to rest. For the Gorner Glacier, 10 percent of the kinetic energy of the water column is 6.4×10^3 J, which produces an equivalent Richter magnitude of −0.4. A signal of this magnitude is detectable at a range on the order of kilometers from its source.

For hydraulic signals to generate the 10^8 J required for an earthquake of Richter magnitude 2.5, the flow quantity must increase substantially. A flow rate of 1000 m^3 sec^{-1} in a subglacial conduit 200 m long and 11.3 m in diameter produces the required energy. Both the flow rates and tunnel dimensions are compatible with values calculated from observed large outruns of water from glaciers (*11*). Seismic signals traceable to hydraulically induced vibrations in the penstock of the Edward Hyatt power plant near Oroville, California, have also been recorded on seismic stations in northern California (*12*).

In the above examples we have used the relatively large value of 10 percent for the energy conversion factor because of the elastic nature of the problem. However, if the conversion efficiency is reduced by an order of magnitude or more, the above arguments still remain valid.

In the case of the volcanic earthquake, we assume that the movement of magma is analogous to the flow of water in glaciers. Quantitatively, the difference between hydraulically generated displacements of lava tubes, as opposed to ice tunnels, is a function of material properties. The properties of the materials required to solve Eqs. 1 and 2 are the elastic constants of the conduit and the bulk modulus, density, and kinematic viscosity of the fluid. A functional description of the frictional interaction of the fluid and the conduit is also required.

Several observations can be made that relate to the seismic waves from both volcanoes and glaciers. The characteristics of the type-II seismic signal indicate that the waves are not associated with ice tectonics. In terms of the wave forms observed, a hydraulically generated signal produces a much more plausible source mechanism. In volcanic earthquakes, it would appear that the A-type volcanic event, which exhibits a wider spectrum of frequencies, is associated with hydraulic fracturing due to magma flow (*6*). However, we interpret the relatively low-frequency signal from B-type earthquakes to be associated with a less catastrophic deformation of the lava tubes.

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10. To solve Eqs. 1 and 2, we consider that the Gornersee represents a reservoir that is at a constant level. The orifice of the ice conduit is considered to be at a constant piezometric head of 50 m (H = 50 m at L = 0). The steady-state discharge of the tunnel is assumed to be 1 m^3 sec^{-1}, which with a tunnel diameter of 1 m gives a flow rate of 1.273 m sec^{-1}. At a point 100 m from the entrance (L = 100 m) of the tunnel, we assume that the flow is terminated. For demonstration purposes, we apply a linear closure to the tunnel which takes place over a period of 0.4 second. Using the elastic properties of ice [K. Neave and J. Savage, *J. Geophys. Res.* **75**, 1351 (1970)], we calculate a wave speed a for the fluid of 1107 m sec^{-1} [(*9*), p. 18]. The damping term in Eq. 1 is considered to be proportional to the square of the velocity. A Darcy-Weisbach friction factor is calculated [H. Rouse and J. W. Howe, *Basic Mechanics of Fluids* (Wiley, London, 1953), p. 141], based on a conduit roughness k of 15. The value of α is taken to be 11.5°.
11. W. H. Mathews, in *Symposium on the Hydrology of Glaciers* (Publication 95, International Association of Scientific Hydrology, Paris, 1973), p. 100.
12. On 17 June 1976 the Edward Hyatt power plant at the Oroville dam site, Oroville, Calif., was temporarily closed as a result of a faulty valve seal. Vibrations felt in the power plant on the morning of 17 June were the reason for closing the plant. Signals emanating from the penstock were recorded at the seismic station of the University of California at Berkeley in the Lake Oroville area. Seismic activity ceased when the flow to the power plant was terminated.
13. We thank Dr. L. Johnson of the University of California at Berkeley for calling our attention to the seismic signals associated with the Edward Hyatt power plant. We also thank W. Curry of the California Department of Water Resources for providing us with the details regarding the valve malfunction. We thank Dr. S. Colbeck, Dr. G. Ashton, D. Calkins, and Dr. W. Hibler of the Cold Regions Research and Engineering Laboratory, who offered many helpful comments.

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Circadian Clock in Culture: *N*-Acetyltransferase Activity of Chick Pineal Glands Oscillates in vitro

Abstract. N-*Acetyltransferase activity was measured in organ-cultured chick pineal glands. A circadian rhythm of enzyme activity persisted in cultured glands for up to 4 days. The phase of the rhythm in vitro closely approximates its phase in vivo. These observations demonstrate that the pineal gland of chicks contains (or is) a self-sustained circadian oscillator.*

The pineal glands of birds and mammals exhibit circadian rhythms in the production of the hormone melatonin. Not only levels of melatonin but also the activity of *N*-acetyltransferase (NAT), the enzyme primarily responsible for its rhythmic production, are significantly higher during the night than during the day (*1, 2*) and the rhythm in NAT activity persists in constant darkness with a period of approximately 24 hours (*1, 3, 4*).

In rats, the circadian rhythm of pineal NAT is generated by rhythmic release of norepinephrine from the sympathetic fibers of the superior cervical ganglia (*5*). The circadian rhythm in sympathetic nerve activity may be generated in turn by an oscillator located in, or transmitting through, the suprachiasmatic nucleus of the hypothalamus (*6*). In contrast, the rhythm of NAT activity in the pineal gland of the chicken does not appear to be generated by the superior cervical ganglia or by any other noradrenergic input. Denervation of the pineal gland does not abolish diurnal rhythms of NAT in the chicken as it does in the rat (*7*). Furthermore, administration of either norepinephrine or isoproterenol to the chick pineal gland in vivo or in vitro does not elicit the increase in NAT activity observed in similar preparations of rat pineal glands (*8*). In the chick, examination of the timing of the spontaneous decline of NAT activity in vitro has revealed a short-term timekeeping ability of the isolated pineal gland (*9*). In the house sparrow (*Passer domesticus*), the pineal gland functions as a biological clock regulating the rhythm of locomotor activity (*10-13*); and melatonin may be involved in this process (*14*). These facts led us to the hypothesis that melatonin synthesis in the avian pineal is controlled by a circadian oscillator located within

