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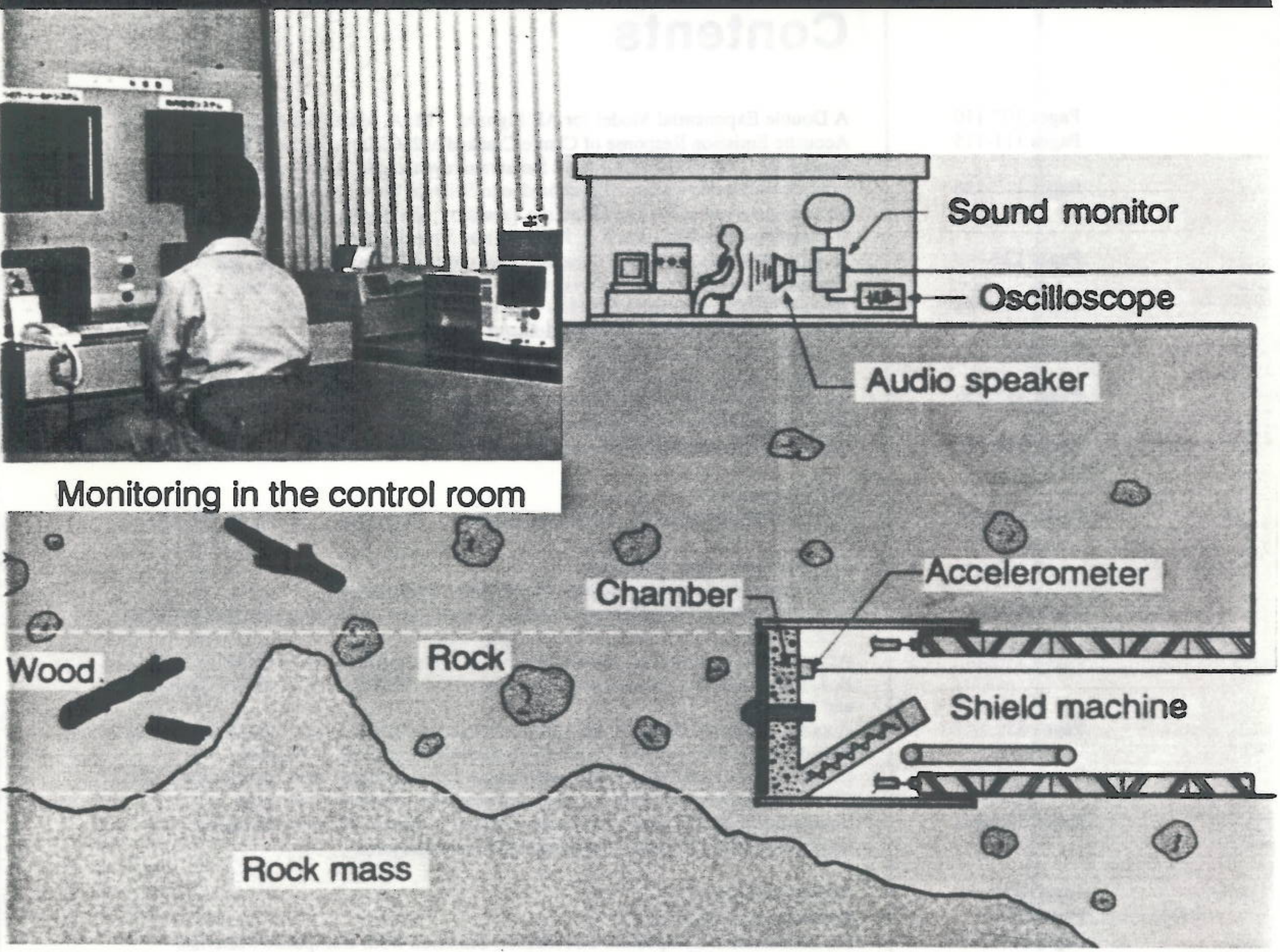

Acoustic Emission Monitoring of Tunnel Excavation at Fujita

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Low Strain Level Acoustic Emission due to Seismic Waves and Tidal/Thermoelastic Strains Observed at the San Francisco Presidio

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Abstract

Acoustic emission (AE) recordings were made at the San Francisco Presidio during the times of the Lake Elsman earthquake and its largest aftershock, the Loma Prieta earthquake aftershocks, and a small earthquake on the Hayward fault. Each earthquake generated abrupt increases in AE production at the time of arrival of the seismic waves that were clearly above the background rates. Sensitivity of AE to tidal strains was checked by comparison of the 30 kHz background AE and the strain recorded by one of the USGS strainmeters. At this site tidal strains are greater than thermoelastic strains at semi-diurnal periods. A weak correlation between the rate of AE production and the observed strain is observed at these near-diurnal and semidiurnal periods. This suggests that AE production occurs at strain levels and strain rates even lower than those estimated to be caused by passage of seismic waves from the 1989 earthquakes.

1. Introduction

The traditional use of acoustic emission (AE) has been in non-destructive testing and study of rock failure (Lockner et al., 1991), and has been limited to relatively high strain levels, typically above 10^{-5}. AE in the range of 1 kHz to 150 kHz is highly attenuated in the earth, with propagation distances of no more than a few 100's m for 1 kHz waves, and a few 10's m for 150 kHz waves. These distances are short compared to the distances traveled by seismic waves. It was suggested that AE may be generated during the strain buildup prior to earthquakes (termed "secondary AE") (Armstrong, 1983). Secondary AE in the range of 20 to 30 Hz is also triggered by seismic waves at substantial distances from the source (Armstrong and Stierman, 1989). Such secondary AE is produced at strain amplitudes and strain rates much lower than those for which AE has generally been studied and observed before.

Received 8 February 1994. B. H. Armstrong and C. M. Valdes-Gonzalez were affiliated with IBM Scientific Center, Palo Alto, CA. M.J.S. Johnston and BHA are with U.S. Geological Survey, 345 Middlefield Road, Menlo Park, Ca 94025, C.M.V-M. is with Instituto de Geofisica, Universidad Nacional Autonoma de Mexico, Ciudad Universitaria, Mexico D.F. and James D. Leaird is with Physical Acoustics Corp., Roseville, CA.

Few observations or experiments have been made of AE at low-strain amplitudes expected to occur in an earthquake-preparation zone. AE triggered in the Lehman Cave National Monument in Nevada by a small earthquake 19 km away was reported by Repsher and Steblay (1985). Hardy and Ersavci (1988) have reported secondary AE in a mine environment; this is further discussed by Hardy et al. (1988), who introduce the concept of a "conversion zone" containing material subject to processes or conditions (e.g., residual stress) that permit the generation of AE by the strain field from a remote source. It seems fair to say, however, that until now there has not been an adequately confirmed identification of secondary AE. Some laboratory observations of AE at strain levels between 10^{-4} and 10^{-6} and over a range of rates down to about 10^{-9} s^{-1} are reviewed by Armstrong and Valdes (1991). The objective of the present work was to determine: [1] whether AE in the range of a few kHz to about 100 kHz is generated by the arrival of seismic waves from local or teleseismic earthquakes and [2] whether AE is generated by earth tides at strain levels below 10^{-7} and at strain rates below 10^{-12} s^{-1}. AE arising from tidal variations could demonstrate the existence of AE at levels of interest in earthquake-preparation zones. Our study is analogous to those of Diakonov et al. (1990) and Galperin et al. (1990). These authors studied the possibility of "seismic emission" of seismic waves due to solid-earth tidal strain and teleseismic waves with strains of the order of 10^{-8} in a range upward from about 30 Hz to a few hundred Hz.

Little energy is required to generate AE signals at 30 kHz. If we assume that a volume several wavelengths on a side is required to produce a well-defined wave, this volume is about 0.5 m^3 or less for 30 kHz but is about 10^9 m^3 for a 30 Hz wave. Thus, for 30 kHz AE excitation, we are dealing with microscopic source sizes, as opposed to the macroscopic source sizes required to produce seismic waves of kilometer wavelengths.

In principle, AE events with stress amplitudes down to at least 10^{-3} Pa can be detected (Lord, 1982). For a material such as concrete or sandstone, the bulk modulus is about 10^{10} Pa. A stress amplitude of 10^{-3} Pa implies a strain of the order of 10^{-13} in such a material. This, as one would expect, is somewhat lower than strains that are resolved by instruments in the traditional seismic regime where localized near-surface strains of 10^{-9} are common. (Strains of

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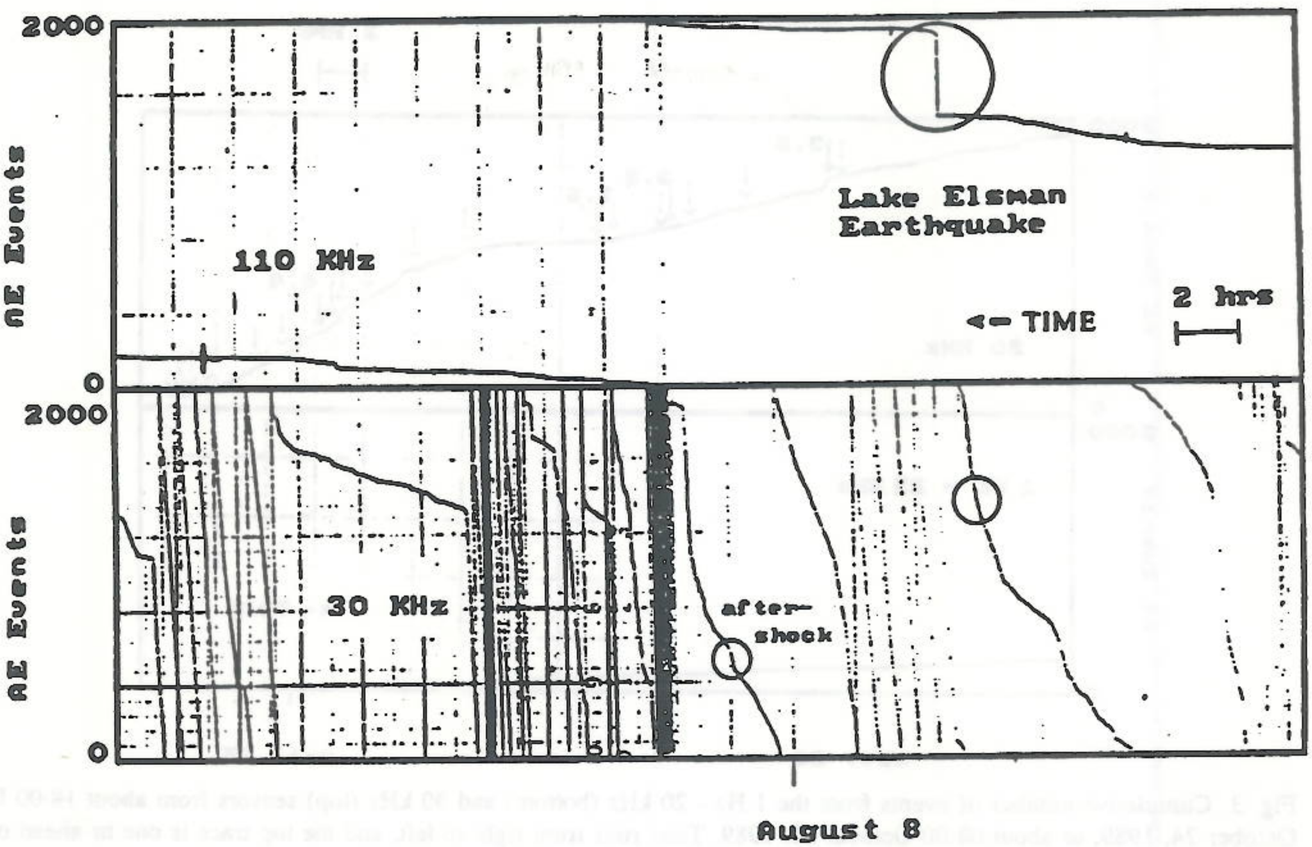

Fig. 2 Cumulative plot of the number of AE events against time for the 30 kHz (bottom) and 110 kHz (top) sensors during the August 8, 1989, Lake Elsman earthquake. Time runs from right to left, and the pen resets at 2000 events. The top trace is offset ahead by 1 hr from the bottom trace. Circles indicate the earthquake and the aftershock.

opening and closing of small cracks, grain boundary movement, and some relative motion at the concrete-sandstone interface cause most of the emissions. Some of the emissions will originate in the sandstone below the concrete floor, which probably has fewer cracks and more grain boundary sliding.

Signal processing, storage and display were performed with the Acoustic Emission Technology Corp. Model 204B AE monitoring system with a total amplification of 98 dB. The output from the system, viz. number of events vs. time, was plotted using a strip-chart recorder. Because the "AE noise level" is not well defined, we measure all events above system and electronic noise.

3. 1989 Lake Elsman and Loma Prieta Earthquake Observations

The M_L = 5.1 Lake Elsman earthquake of August 8, 1989, at 08:13 UTC occurred on the San Andreas fault 85 km south of our San Francisco Presidio location and about 15 km from the hypocenter of the Loma Prieta quake that occurred a few months later. Our 110 kHz sensor registered a 470-event step increase at the time of the Lake Elsman earthquake (within the four-minute time resolution of our strip-chart recorder) upon a fairly regular background rate of about 19 events/hr average for the three hrs preceding the earthquake, and ~8 events/hr afterward (Valdes and Armstrong, 1989). Figure 2 shows this cumulative AE events against time record as the upper part of the figure. As in all the strip-chart figures, time runs from right to left, and the pen resets to 0 when it accumulates 2000 events. The top trace is offset to be one hr ahead of the bottom trace in order to avoid conflict between the marking pens. The signals on the 30 kHz sensor seem well within the noise levels. However, a small step increase of 40 events is visible on the 30 kHz record at the time of a magnitude 4.2 aftershock (encircled on the bottom trace of Fig. 2).

The Loma Prieta M_L = 7.1 earthquake of October 17, 1989 (17:04 local time) occurred about 15 km from the Lake Elsman earthquake. We obtained no useful data during and for 7 days following this event because of the electrical power outage that accompanied the earthquake. On October 25, after our instruments were back in operation, there was a series of many aftershocks, including one of magnitude 4.4 and one of magnitude 3.8. These are marked, along with numerous smaller aftershocks, on the AE response record of Oct. 25 and 26 shown in Fig. 3. The AE event rate for the 30 kHz sensor is variable and at times quite high over this time period, which was a time of high seismic aftershock activity (approximately one aftershock/hr with M_L greater than 2.0). Over the 6-hr periods preceding and following the 4.4 October 25 aftershock, the 30 kHz sensor was registering a background rate exceeding 100 events/hr. No change, however, is observed in the 1 Hz - 20 kHz sensor. Many abrupt steps appear in the 30 kHz AE event rate for the period following the Loma Prieta earthquake that are not coincident with an aftershock but are clearly separated from the normal background. However, the rate at which this background AE activity occurs decreases with time as the Loma Prieta aftershock activity dies out. The total background AE level, continuous plus the steps mentioned above, appeared higher during the aftershock period of the Loma Prieta quake than before the quake, and by February, 1990 and thereafter we observed a generally uniform background marked by only occasional small steps.

On November 4, 1989, at 07:16 UTC there was a M_L = 3.7 event on the Hayward fault with epicenter located 25 km from the Presidio. Figure 5 shows AE jumps of 35 and 420 events for the B & K 4375 and 30 kHz sensors, respectively, at the time of this earthquake. The slope of this cumulative plot shows that the 30 kHz sensor was experiencing an average rate of about 30 events/hr over the four hrs before the quake. This rate dropped to about 5 events/hr afterward. The 4375 sensor showed a uniform background noise rate of about 7 events/hr before and after the earthquake. In both cases, the jumps are clear and unambiguous upon the background.

4. Earthquake Strain and Strain Rate Estimates

Ground-displacement amplitudes were calculated using the magnitudes M_L, for each of the earthquakes in the relation given by Richter (1958) and neglecting resonance effects within the Presidio vault. A sine wave with this amplitude and with a frequency corresponding to the dominant frequency of the wave train was differentiated with respect to displacement and time to obtain the strain and strain rate, respectively. For each of the Lake Elsman earthquake, its aftershock, and the Hayward fault earthquake, this dominant frequency was taken to be 2 Hz while the seismic wave velocity was taken as 3 km/s. Table 1 shows the results of these order-of-magnitude estimates. From this table, we see that the strain level of the seismic wave from the Lake Elsman aftershock is of the same order of magnitude when it reaches the Presidio as that associated with earth tides, although the strain rate is considerably higher.

5. Strain and Acoustic Emission

An important objective of this work was to test whether AE is generated as a result of tidal strains. The primary advantage in selecting the USGS Presidio vault for the experiment is that more then 10 years of strain and

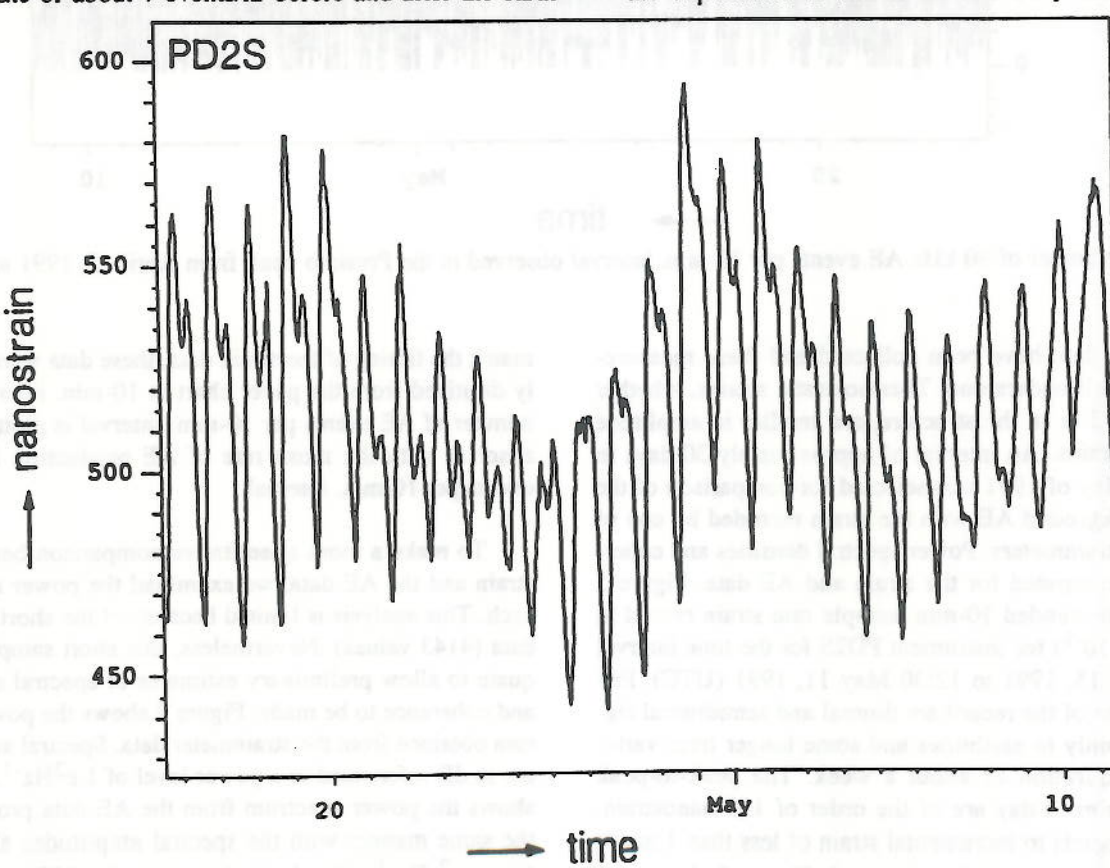

Fig. 5 De-trended strain record in nanostrain from instrument PD2S in the Presidio vault observed from April 15, 1991 to May 11, 1991. The sampling rate is one sample per 10 min.

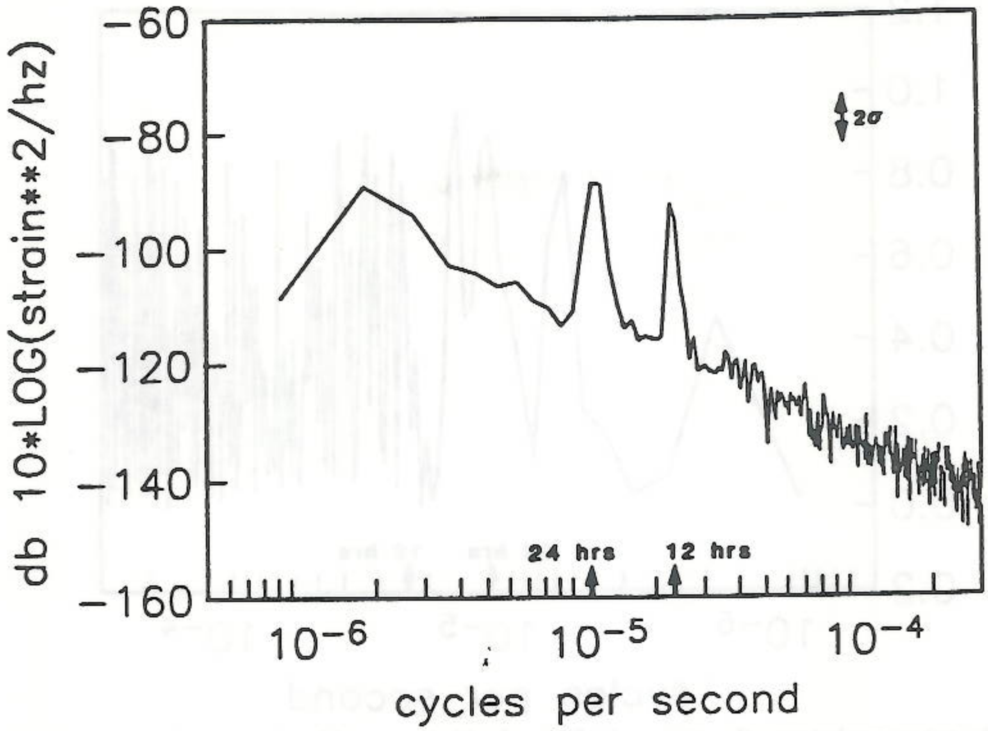

Fig. 7 Power spectral density of the strain record of Fig. 5. The upward arrows mark periods of 24 and 12 hrs.

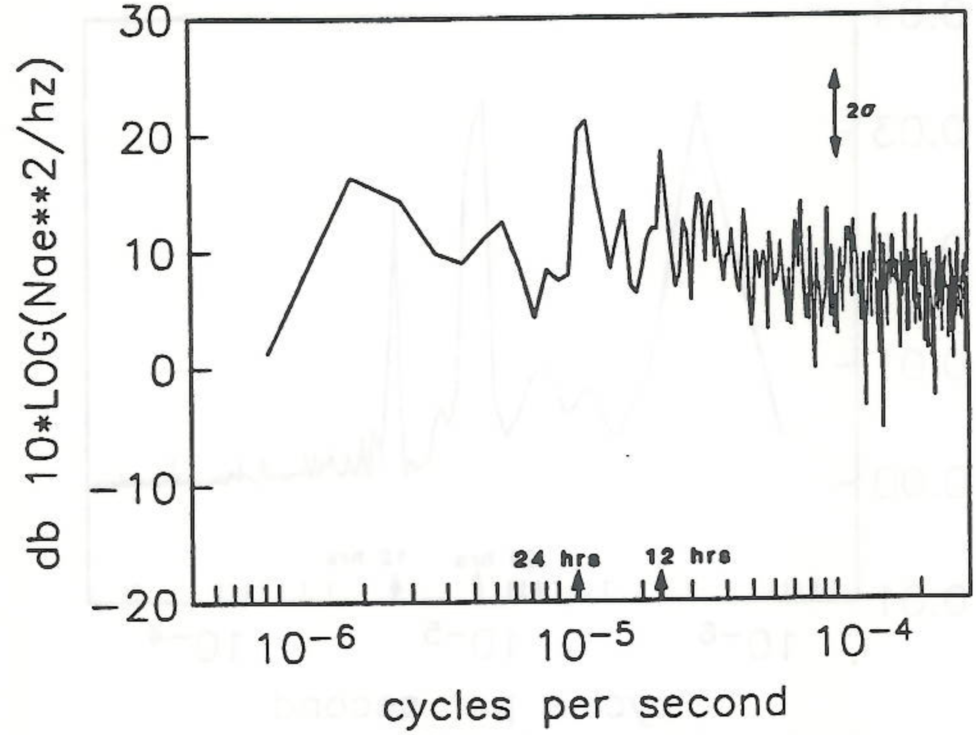

Fig. 8 Power spectral density of the AE data of Fig. 6. The upward arrows mark periods of 24 and 12 hrs.

Dominant spectral peaks significant at the 4σ level are apparent in the strain spectrum at approximately 24 hrs and 12 hrs. The situation is less clear for the spectrum from the AE data. Spectral peaks do occur at approximately 24 and 12 hrs respectively but these are significant only at the 2σ level. Because of the limited data and difficulty in obtaining more data, we cannot analyze these spectral peaks in more detail at this point.

We have examined correlation between the strain and AE data using the methods of cross-spectral analyses (Bendat and Piersol, 1966). These methods should reveal coherence between the two time series as a function of

$$R^2 = \frac{\overline{(C_{12}^2 + C_{21}^2)}}{C_{11}C_{22}}$$

where the bar represents averaging the results from the D time segments. Limits on the accuracy of this estimate are pointed out by Haubrich (1965). The squared coherence between the strain and AE data for 20 degrees of freedom is shown in Fig. 9. After correction for the finite length of the data set the only significant coherence between strain and AE data occurs at a period of 24 hrs. While phase and admittance can also be calculated between the two data sets, we note that these will not have much meaning unless significant coherence exists in a particular frequency band. Figure 10 shows a plot of admittance in units of nanostrain/count between the two data sets. The value of admittance between strain and AE at diurnal periods is 0.03 nanostrain/count.

Two possibilities exist. Either tidal strains or perhaps some thermoelastic strains at diurnal periods are triggering AE. In either case, the strains are 10^{-7} or less. The important issue is not so much the particular source of the strain, but rather that diurnal and semi-diurnal strain changes of about 100 nanostrain are modulating the AE rate at a few counts/10 min. interval. This suggests that AE production occurs at strain rates even lower than those estimated to be caused by passage of seismic waves from various earthquakes. We believe these to be the lowest strain levels and strain rates, for which AE has been observed.

6. Conclusion

Our observations at the Presidio in San Francisco demonstrate existence of AE associated with passage of seismic waves from earthquakes with magnitudes in the range of 4 to 5 and epicenters at distances from about 25 to 85 km away. The seismic waves from these earthquakes are estimated to have strain amplitudes of $\sim 10^{-7}$ and lower. Abrupt AE increases ranging from 35 to 470 events on three different AE sensors were clearly identifiable above the background at the times of the August 8 and November 4, 1989 Lake Elsman and Hayward fault earthquakes, respectively. It is also interesting that a much higher than normal background rate of AE was observed during the aftershock period following the Loma Prieta earthquake of October, 1989.

The background AE is weakly correlated with the tidal/thermoelastic strains in the bunker, and we infer that the former is primarily responsible because the tidal strains dominate the thermoelastic strains at semi-diurnal periods (Fig. 10). The production of AE at such low strain-increment levels and rates independently supports the finding of AE at the higher strain levels and rates associated with passage of seismic waves from the Lake Elsman and Hayward fault earthquakes of 1989.

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