

Breathing of the seafloor: Tidal correlations of seismicity at Axial volcano

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ABSTRACT

Tidal effects on seafloor microearthquakes have been postulated, but the search has been hindered by a lack of continuous long-term data sets. Making this observation is further complicated by the need to distinguish between Earth and ocean tidal influences on the seafloor. In the summer of 1994, a small ocean-bottom seismograph array located 402 microseismic events, over a period of two months, on the summit caldera of Axial volcano on the Juan de Fuca Ridge. Harmonic tremor was also observed on all instruments, and Earth and ocean tides were recorded on tiltmeters installed within the seismometer packages. Microearthquakes show a strong correlation with tidal lows, suggesting that faulting is occurring preferentially when ocean loading is at a minimum. The harmonic tremor, interpreted as the movement of superheated fluid in cracks, also has a tidal periodicity.

Keywords: tides, earthquakes, correlations, Axial Seamount.

INTRODUCTION

On land, seismicity at volcanoes has been proposed to correlate with Earth tides (e.g., Mauk and Johnston, 1973; Dzurisin, 1980; Rydelek et al., 1988), and the influence of tides on seismicity in general has been debated for many years (Omori, 1908). In the ocean, tidal effects on seafloor microearthquakes have long been postulated (Glasby and Kasahara, 2001). However, Earth tide signals are strongly influenced by ocean loading, and the direct influence of ocean tides through variations in depth (and hence weight) of the overlying ocean will further influence the local crustal stresses.

During the summer of 1994, an ocean-bottom seismograph (OBS) array was deployed to monitor microseismic activity near Axial volcano (Fig. 1). These instruments contained seismometers and tiltmeters (Tolstoy et al., 1998) and recorded continuously for more than two months. The deployment occurred directly following several days of seismic activity on Axial, as recorded with the SOSUS (Sound Surveillance System) arrays (Dziak and Fox, 1999a). The instrument locations were centered around this area of activity, which appeared to be mostly quiet on SOSUS following the instrument deployment. However, results from the OBS array (Fig. 1) show that activity was ongoing at a lower magnitude level. At the time of the OBS deployment, a water-column attenuation anomaly was observed at the southern end of the area of seismic activity (R.W. Embley, 1994, personal commun.). This anomaly was consistent with the presence of a bacteria bloom, and so it is possible that a small eruption occurred at the end of June 1994, directly prior to the OBS deployment.

EARTHQUAKES

During the course of the two-month deployment, 402 earthquakes were located on Axial volcano within a few kilometers of the array (Fig. 1). Numerous other earthquakes were detected, but were not recorded on a sufficient number of instruments to be located. Seven events were observed on SOSUS at this location during this time (Dziak and Fox, 1999a), making the estimated m_b magnitude for the vast majority of the OBS located events <2.5 . Of the seven events

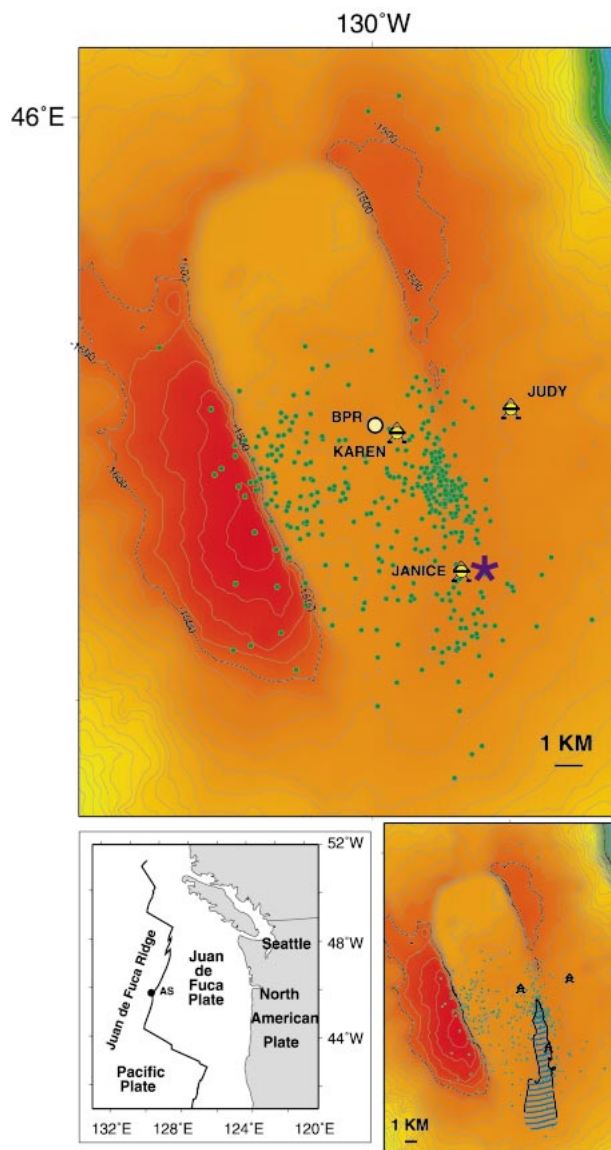


Figure 1. Locations and names of three ocean-bottom seismographs (OBS) used to locate events and NOAA-PMEL's bottom-pressure recorder (BPR). All located earthquakes are shown as green dots. Purple star indicates location of water-column anomaly as recorded during OBS deployments. Lower right figure shows outline of 1998 flow (Embley et al., 1999) compared with location of 1994 seismicity. Lower-left figure shows location of Axial volcano (AS is Axial Seamount) on Juan de Fuca Ridge, off coast of north-western United States.

recorded on SOSUS, none was picked up by land arrays, so none was of m_b magnitude 4.8 or greater (the magnitude of events recorded on land arrays during the 1998 eruption [Dziak and Fox, 1999b]). The activity was at its highest level during the first few weeks of the deployment, consistent with the previously observed SOSUS activity, and dropped during the subsequent three or so weeks and then picked up again toward the end of the deployment (Fig. 2D). There were two main areas of activity. The first was in the center of the array, within the caldera by its southeastern edge. This was the area in which the SOSUS activity was centered and also where fresh lava emerged in the subsequent 1998 eruption (Embley et al., 1999) (Fig. 1). The second area of activity was on the southwestern edge of the caldera, again within the caldera floor near the ASHES hydrothermal field. This area also showed significant activity during the 1998 eruption, including three normal-faulting events large enough to be observed on land (Dziak and Fox, 1999b). Because the data presented here were recorded 4 yr prior to the major eruption, these precursory events may indicate the structure of the primary plumbing system at Axial volcano. A possible interpretation is that magma is stored at depth beneath the southwestern area of the caldera and transported to a shallower reservoir and/or eruption site in the southeastern area of the caldera.

HARMONIC TREMOR

Abundant monochromatic harmonic tremor also was observed throughout the deployment, with a dominant frequency of 6 Hz (Fig. 3). The high frequency of the tremor and lack of signal coherency between instruments imply that this is not tremor caused by movement of magma, but is instead the movement of fluid in cracks, perhaps superheated and behaving in a geyser-like fashion (Talandier and Okal, 1996). The tremor was particularly pronounced on OBS Janice, which was deployed in the area of the water column anomaly. To quantify the amount of tremor activity, the data were assessed visually and a tremor factor (TF) of 0–1 in 0.25 increments was assigned to each hour. In an hour with a TF = 0, there was no obvious tremor within the seismic data, and an hour with a TF = 1 was entirely dominated by tremor.

EARTH AND OCEAN TIDES

As discussed in Tolstoy et al. (1998), the tiltmeters outside of the caldera area were recording extremely subtle ($\sim 10 \mu\text{rad}$) rocking at a tidal frequency, likely due to the movement of currents along the seafloor. However, OBS Karen, located within the caldera and sheltered from the currents, appears to have recorded Earth tides with a maximum amplitude of $\sim 0.6 \mu\text{rad}$ (Fig. 2B). These signals can be attributed to Earth tides because they lack an inertial peak in their spectrum (Anderson et al., 1997), and they lag the recorded ocean tides in this area by ~ 2 h (Fig. 2B, inset). A National Oceanic and Atmospheric Administration–Pacific Marine Environmental Laboratory (NOAA-PMEL) ocean-bottom pressure recorder was also located in the caldera at the time (Fox, 1993), and recorded ocean tides during the deployment as changes in water pressure (Figs. 1 and 2). The tidal signals recorded on this pressure sensor match those recorded on the caldera edge OBSs and also, therefore, precede the tidal signal recorded by OBS Karen by 2 h. A theoretical estimate of Earth tides at Axial volcano implies that the tides recorded by OBS Karen are amplified by a factor of three likely due to ocean loading (Tolstoy et al., 1998), putting their estimated stress amplitude in the 3–12 kPa range (Melchior, 1983). However, these numbers can depend on a number of factors, including depth and crustal properties. By comparison, the variations in ocean tides during this period indicate a maximum stress range of 30.6 kPa. However, the consequences of these different stresses will be very complex and varied with location, and other factors such as the movement of ocean-floor water due to tidal currents may also contribute to tidal correlations.

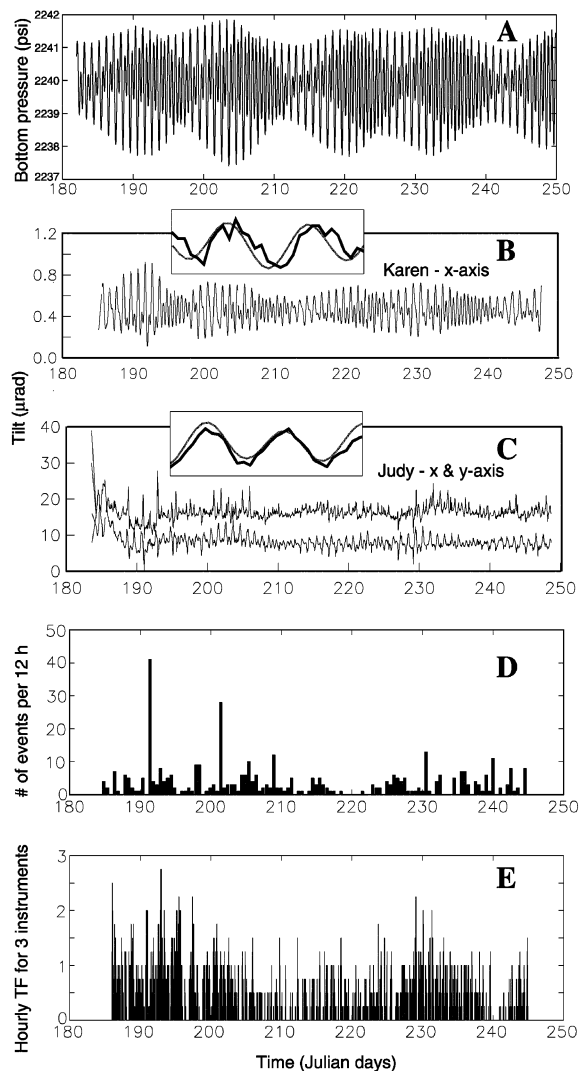


Figure 2. Temporal comparison of tidal signals and earthquake and harmonic tremor signals. **A:** Bottom-pressure recorder (BPR) measurements (Fox, 1993) from Axial volcano showing ocean-tide signal for period of deployment in summer of 1994. **B:** X-axis tilt data from ocean-bottom seismograph (OBS) Karen, bandpass filtered with spline fit removed. OBS Karen, located within caldera and sheltered from tidal currents, likely recorded Earth tides, amplified by ocean loading (Tolstoy et al., 1998). Inset shows comparison of unfiltered OBS Karen tidal signal (thick black line) and BPR tidal signal (thin gray line); note that tidal signal on OBS Karen lags ocean tides by 2 h. **C:** X- and y-axis tilt signal recorded on OBS Judy, with spline fit removed. OBS Judy was located on eastern edge of caldera and tidal signal recorded is coherent with ocean tides recorded on BPR and likely represents very slight rocking of instrument in tidal currents. Other instruments outside caldera showed similar signals. Inset shows comparison of OBS Judy tidal signal (thick black line) and BPR tidal signal (thin gray line). **D:** Histogram of number of located earthquakes per 12 h period. **E:** Combined hourly harmonic tremor factor (TF) for all three OBS instruments (Janice, Judy, and Karen).

TIDAL CORRELATIONS OF EARTHQUAKES

A visual assessment of the occurrence of earthquakes relative to the ocean tides gives a striking indication that earthquakes are occurring preferentially at or near low tide (Fig. 4A). To confirm this visual interpretation, the occurrence of earthquakes relative to the second derivative of the ocean tides was examined, along with a spectrum. The

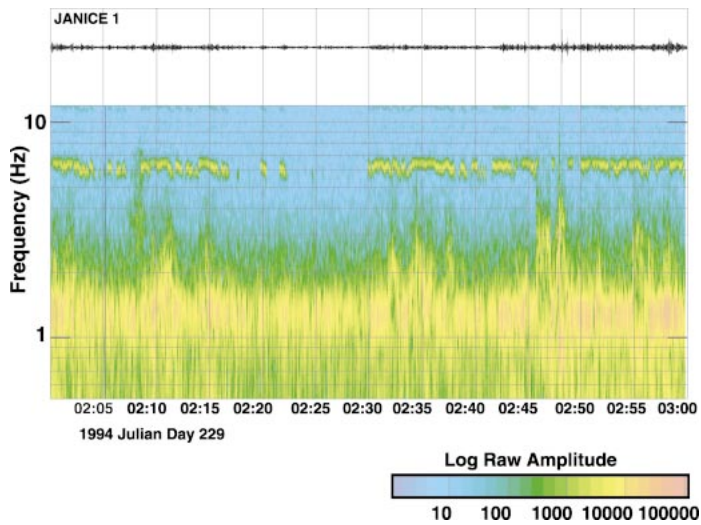


Figure 3. Spectrum of 1 h of data from vertical channel of ocean-bottom seismograph Janice. Note monochromatic harmonic tremor at ~6 Hz that is fairly dominant for this particular hour. This hour was assigned a tremor factor of 0.75.

spectrum shows peaks at semidiurnal and diurnal frequencies (Fig. 4B). The normalized histogram of earthquake occurrence relative to the second derivative (Fig. 4C) indicates a clear systematic bias toward periods of low tide (positive second derivative of tidal signal). A commonly applied statistical test for tidal correlations is the Schuster test, providing a probability that the phase distribution is random (Emter, 1997). For these data, the probability ranged from 1×10^{-7} to 1×10^{-14} , depending on the removal of swarms from the data, yielding a significance level >99.99%. A significance level of >95% is generally accepted as proof of tidal triggering. It is interesting to note that the largest swarm occurring on Julian Day 191 (July 10th) happened at ~2 h past the peak of low ocean tide, which is the time of maximum

low of the Earth tide, although this is obviously not statistically significant. It is also interesting to note that earthquake activity varies broadly on a weekly time scale with the absolute amplitude of the tides (Fig. 2). Furthermore, the largest swarms of activity occur near peaks in the fortnightly tides.

TIDAL CORRELATIONS OF HARMONIC TREMOR

A look at the spectrum of the intensity and timing of harmonic tremor occurrence shows a semidiurnal tidal peak (Fig. 5). This result is consistent with the tremor's being related to the movement of water in cracks and through the hydrothermal circulation system, which is already known to be tidally modulated (Schultz and Elderfield, 1997). There does not appear to be any clear visual correlation with either high or low tide, unlike the seismicity, although the spectrum indicates semidiurnal frequencies. Variations in intensity and duration of tremor on a longer time scale of weeks are also apparent, and seem to follow a weak fortnightly tidal trend (Fig. 2). Absolute tidal amplitudes vary throughout the year on the basis of a variety of complex factors, chiefly including proximity to the Sun and the Moon.

DISCUSSION

The correlation of earthquakes with the low tides is consistent with the dominance of normal faulting in this environment. A study of global earthquakes with magnitudes >6 has shown that normal-faulting events appear to be tidally influenced, whereas other types of faulting do not (Tsuruoka et al., 1995), although not all studies show this (Emter, 1997). The bias toward the events occurring at low tide is possibly explained through the decrease in confining pressure when some of the weight of the ocean is removed at low tide. This change leads to a reduction in normal stress, which causes faults already very close to their failure point to slip. However, there is also likely an influence of the water pressure within the cracks. The decrease in loading may cause the pore pressure within the rocks to increase, leading to an increase in stress and the likelihood of slippage. The tidal correlation of harmonic tremor supports the interpretation that water

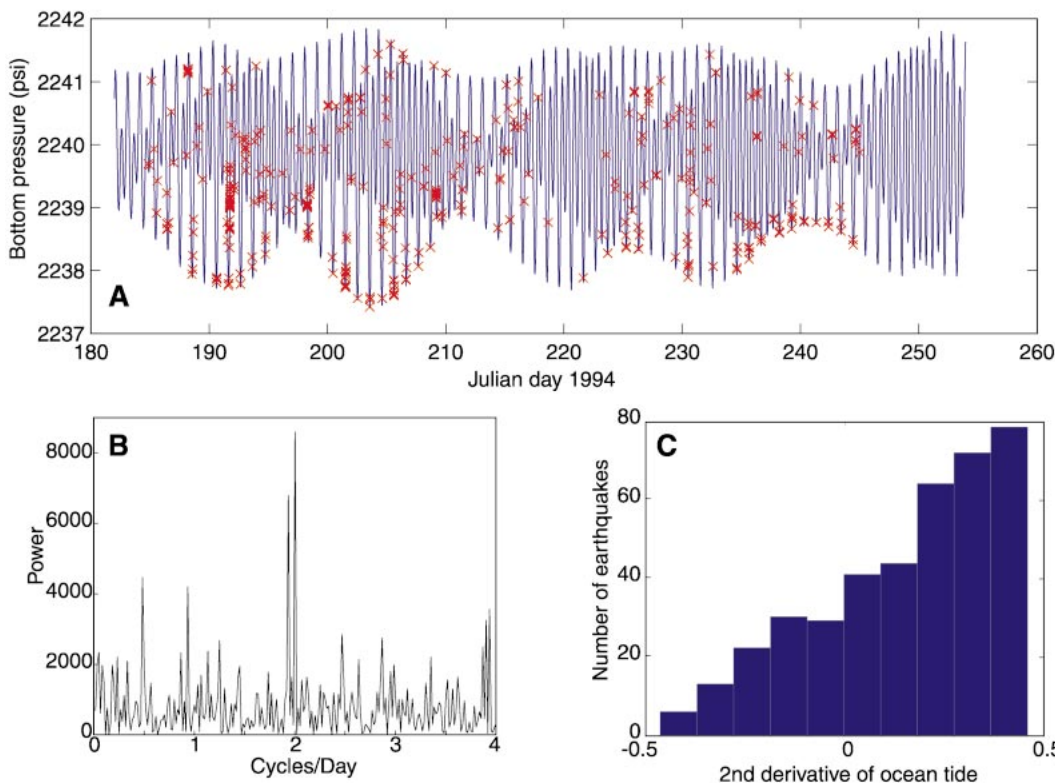


Figure 4. A: Ocean tide signal as recorded by bottom pressure recorder with times of earthquake occurrence shown as red Xs. Note visual bias toward earthquakes occurring near low tide. Also note large swarm on Julian Day 191 that occurred 2 h following low ocean tide, which is precisely at low Earth tide in this region. B: Spectrum of earthquake occurrence throughout deployment, based on number of events per hour. Note peaks at semidiurnal and diurnal frequencies, with both solar and lunar components apparent. C: Histogram of earthquake occurrence relative to second derivative of ocean tides (i.e., rate of change of slope in A) as recorded by NOAA-PMEL pressure gauge. Histogram has been normalized to correct for structure inherent in second derivative of tidal signal. Note strong asymmetry indicating that earthquakes are occurring preferentially near low tide (positive second derivative).

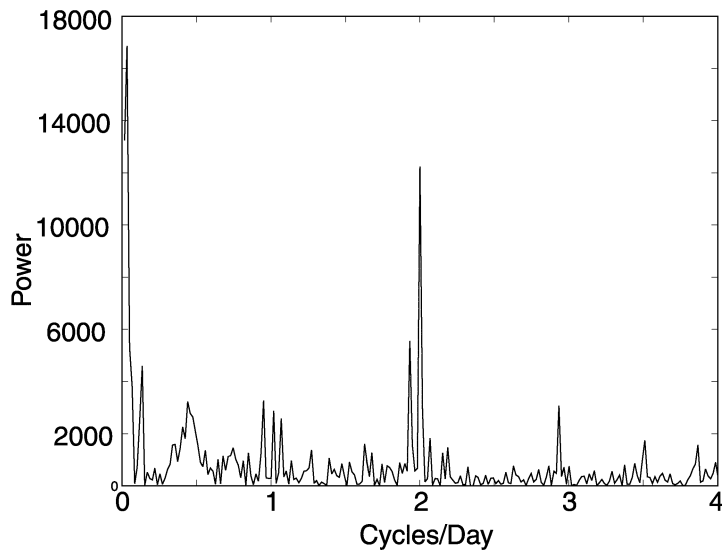


Figure 5. Spectrum of harmonic tremor factor for all three ocean-bottom seismographs combined. Note clear peak at semidiurnal frequencies, consistent with tidal influence, with both solar and lunar components apparent.

movement is being tidally modulated, and this process will presumably further affect the stress regime.

The pressure of the directly overlying water and the possible influence of water in the cracks explain why in this location earthquakes correlate with ocean tides rather than Earth tides. Although Earth tides in the area appear to be amplified, the effects of variations in ocean pressure from directly overhead are apparently a greater influence. Tidal correlations at terrestrial volcanoes are thought to be caused by the effect of Earth tides on a large magma body. A 1999 refraction study in the area (West et al., 2001) showed a substantial magma body centered 2.5–3.0 km beneath the summit caldera. However, because there does not appear to be an obvious correlation between seismicity and Earth tides in this location, despite the presence of a large magma body, the effects of ocean tides on local seismicity appear to be superseding seismicity caused by Earth-tide influence on the magma body. It is also possible that seismicity in this area that is directly influenced by magma movement will correlate with Earth tides, as hinted at by the day 191 swarm that exhibited some volcanic characteristics. However, the majority of the events did not occur in swarms and were more isolated, perhaps being associated with the tectonic or hydrothermal activity of the site rather than the volcanism.

SUMMARY

The mid-ocean ridge location, with fractured, weak material that is permeated with water and overlain by a large water body, creates a system very susceptible to tidal influences. The variations in water pressure due to ocean tides seem the likely cause. At the time this experiment was conducted, it was the longest time period that OBSs had ever recorded continuously on the seafloor, and the 402 events located were the most observed in one deployment. It is probable, therefore, that these ocean tidal influences occur elsewhere on the seafloor and mid-ocean ridge system, as recently observed on the Endeavor segment of the Juan de Fuca Ridge (Wilcock, 2001). It also seems possible that similar to land volcanoes, volcanism on the seafloor may be influenced by Earth tides, although the interaction between ocean-tide variations and other tectonic stresses is likely to be complex. The movement of the fluid through cracks as observed in the tremor and the cracking resulting from earthquakes inherently will influence the hydrothermal systems in these locations. These hydrothermal sys-

tems and possibly the rocks themselves host a myriad of life forms. The increased seismicity at low tides may allow greater access to the nutrients stored in normally sealed cracks. It is possible therefore that life on the seafloor will operate in cycles that are tidally dependent, because the tidal variations in seismicity could control the influx of nutrients into the system. Semidiurnal, diurnal, fortnightly, and annual biological cycles may exist.

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