COMPARISON OF T-PHASE OBSERVATIONS AT NORTHERN CALIFORNIA SEISMIC STATIONS AND THE PT SUR HYDROPHONE

Catherine deGroot-Hedlin and John Orcutt
Scripps Institution of Oceanography, La Jolla CA 92093-0225

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ABSTRACT

Plans for a hydroacoustic network intended to monitor compliance with the CTBT call for the inclusion of five T-phase stations situated at optimal locations for the detection of seismic phases converted from ocean-borne T-phases. We examine factors affecting the sensitivity of land-based stations to the seismic T-phase. The acoustic to seismic coupling phenomenon is modeled as upslope propagation of an acoustic ray impinging at a sloping elastic wedge. We examine acoustic to seismic coupling characteristics for two cases; the first in which the shear velocity of the bottom is greater than the compressional velocity of the fluid (i.e. $v_p>v_s>v_w$), the second is a weakly elastic solid in which $v_s<<v_w<v_p$. The former is representative of velocities in solid rock, which might be encountered at volcanic islands; the latter is representative of marine sediments. For the case where $v_s>v_w$, we show that acoustic energy couples primarily to shear wave energy, except at very high slope angles. We show that the weakly elastic solid (i.e. $v_s<<v_w$) behaves nearly like a fluid bottom, with acoustic energy coupling to both P- and S-waves even at low slope angles.

We examined converted T-wave arrivals at northern California seismic stations for a series of earthquakes near the Hawaiian islands. The characteristics of the T-phase arrivals varied between stations but were consistent from event to event within the event cluster. The seismic T-phases consisted of both P- and S-wave arrivals, consistent with the conversion of acoustic to seismic energy at a gently sloping sediment-covered seafloor. hi general, the amplitudes of the seismic T-phases were highest for stations nearest the continental slope, where seafloor slopes are greatest, however noise levels decrease rapidly with increasing distance from the coastline, so that T-wave arrivals were observable at distances up to several hundred kilometres from the coast. Signal to noise levels at the seismic stations are lower over the entire frequency spectrum than at the Pt Sur hydrophone nearby, and decreased more rapidly with increasing frequency, particularly for stations furthest from the coast.

Key word: hydroacoustics

OBJECTIVE

The planned hydroacoustic network designed to monitor compliance with the Comprehensive Test Ban Treaty (CTBT) will eventually consist of four hydrophones and five T-phase stations located on ocean islands. The plan is to located T-phase stations, each consisting of a single vertical component seismometer, at optimal sites for detecting seismic phases generated by the coupling of acoustic T-phases into compressional (P) or shear (S) waves. Since seismic phases are much more severely attenuated than ocean-borne acoustic energy, the T-phase stations are expected to be less sensitive to T-phases acoustic energy excited by nuclear tests and low atmospheric explosions than hydrophones are. However, their anticipated lower cost makes their use desirable. The rationale behind locating T-phase sensors close to a shoreline is that T-waves are expected to undergo less attenuation, particularly at high frequencies, at these locations. The ability to detect T-waves over a broad frequency band is an essential feature of a T-phase station, as naturally-occurring events often have different spectral characteristics than explosions.

In this paper, we examine factors affecting the sensitivity of land-based stations to the seismic T-phase. In the next section, we examine the physics of acoustic to seismic coupling at a sloping wedge for an acoustic bottom and for two types of elastic bottoms; a Poisson solid with a shear velocity (v_s) that is higher than the acoustic velocity (v_w) of the fluid above, and a semi-elastic solid with a shear velocity much lower than v_w. In the following section, we examine T-phase arrivals at seismic stations in northern California for two event clusters. The first is a series of shallow events that occurred near the Hawaiian islands in July 1996; the second is a series of nuclear tests conducted by the French in the Tuamoto archipelago from September 1995 to January 1996. Both types of events generated T-waves that were recorded at a Pt Sur hydrophone as high amplitude, short duration (15-20 see), broadband arrivals. However, each type of event yielded characteristic T-phase recordings at the seismic stations that were repeatable within each, but distinct between clusters.

RESEARCH ACCOMPLISHED

T-phase coupling at an elastic bottom

Long range acoustic propagation in the SOFAR channel can be described in terms of adiabatic normal mode theory (*eg.* Heaney *et. al*., 1991). At any given frequency, a mode may be represented by an equivalent pair of upgoing and downgoing rays that propagate at an angle or phase velocity giving rise to constructive interference (Officer, 1958). The propagation angle is constant for a range-independent ocean, with higher modes propagating at steeper angles than low modes. As the acoustic wavefield approaches a sufficiently shallow, upward sloping seafloor, a ray trapped in the SOFAR channel becomes bottom interacting, and steepens by twice the seafloor inclination at each cycle of bottom and surface reflections. As the angle becomes steeper than the critical angle, part of the energy is transmitted into the seafloor at each successive bottom bounce. Parabolic equation modeling indicates that, for a fluid over a fluid wedge, acoustic energy is radiated into the bottom in discrete beams at approximately the depths predicted by normal-mode theory, (Jensen and Kuperman, 1980). Thus, for a fluid bottom, the acoustic T-phase would couple into P energy at discrete segments along the slope, defined by the cutoff depths.

The mode cutoff depth is dependent on both mode number and frequency. At any given frequency low modes have the shallowest cutoff depth; for any given mode, the highest frequencies have the shallowest cutoff depth. The lowest modes and highest frequencies are therefore predicted to have the longest oceanic travel path and to couple into seismic energy nearest to the shore. The depth dependence of the acoustic to seismic coupling thus translates to a time separation between coupling points. However, separate T-wave arrivals corresponding to individual mode cutoffs are expected only for highly impulsive sources. In general, for shallow slopes, we predict seismic T-phases with much longer duration than the incident acoustic phase due to the greater lateral separation between the mode cutoff depths. For steeper slopes, mode cutoff depths are more closely spaced, so the seismic T-phase would be expected to have a much more impulsive arrival, yielding T-phases with greater SNR than for shallow slopes.

So far we have discussed only the fluid over fluid case, where the S-wave velocity in the bottom is assumed to be zero. If instead we consider an elastic bottom, with non-zero shear velocity, the coupling problem is

modified by the fact that there are now two critical angles, $Ø_s$, corresponding to the critical angle for transmission of shear waves into the bottom, and $Ø_p$ corresponding to transmission of compressional waves. Since P velocities are always greater than S velocities by at least a factor of √2, the critical angle for S waves is less steep than that for P waves. Therefore, ray theory predicts that supercritical incidence is reached first for the S-wave, then for the P-wave after several more bottom reflections.

The partitioning of energy into P and S-waves in strongly dependent upon both the slope and the velocity structure of the elastic bottom. Energy flux densities for transmission and reflection of an acoustic wave incident on an elastic solid, computed using equations (4.2.24 - 4.2.36) of Brekhovskikh and Godin (1990), are shown in Figure 1 at a range of incident angles for three elastic wedge models. The velocities and densities, listed in the figure caption, are typical for solid rock near the Earth's surface. For a ray incident on a shallow elastic wedge, the propagation angle with respect to the vertical decreases by twice the slope inclination at each bottom bounce until it falls below critical incidence for the shear wave in the bottom. A portion of the acoustic energy then couples into S-wave energy in the solid at each bottom bounce until the critical angle for the P-wave is reached. Any remaining acoustic energy then couples into both the P- and S-wave as the angle of incidence continues to decrease. Overall, the introduction of a non-zero shear velocity "softens" the boundary, that is, the total impedance of the solid is less than that of a equivalent liquid with identical velocity and density values, thus the reflection coefficient in the liquid is reduced (Brekhovskikh and Lysanov, 1991). This is indicated by the grey lines in the left panel of Figure 1, which show reflection and transmission coefficients for a liquid with identical density and compressional velocities as those for the solid. For $Ø < Ø_p$, the reflection and transmission coefficients vary more with angle of incidence than for the equivalent solid.

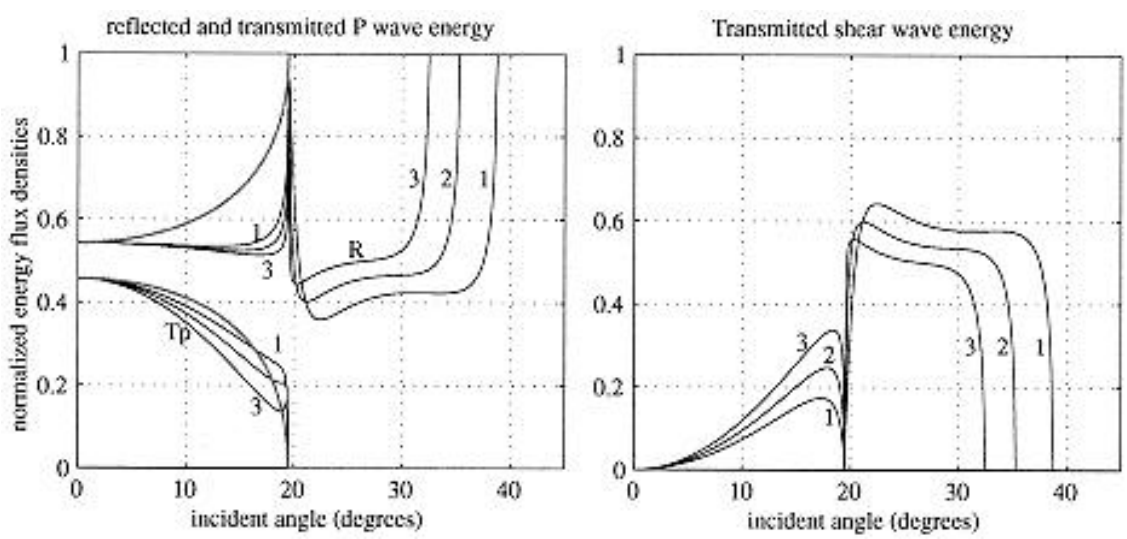

Figure 1: Energy flux densities for transmission and reflection of an acoustic ray incident on an elastic solid. The ratio of compressional velocities from solid to fluid is 3: 1, corresponding to a P-wave velocity of 4.5km/sec and a water velocity of 1.5km/sec. The density contrast from solid to liquid is 2.2. Curves were computed for three values of S-wave velocity: (1) 2.4km/sec, (2) 2.6km/sec (corresponding to a Poisson solid), and (3) 2.8km/sec. In the left panel, the curves labelled R are the reflected energy fluxes in the fluid; those labelled Tp are the transmitted P-wave energies. Transmitted S-wave energy flux densities are shown in the right panel. Velocities and densities for the elastic solid are typical for those of solid rock. Grey lines indicate corresponding values for an equivalent liquid, i.e. one with identical compressional velocity and density

For a slope with inclination ß, a ray goes through approximately $(Ø_s - Ø_p)2ß$ bottom bounces between reaching the critical angles for S- and P-waves. Part of the acoustic energy is transformed into shear wave energy in the bottom at each bounce, thus a shallower slope results in more bounces during which acoustic energy can be transformed to shear waves. This may account for the observations of Talandier and Okal (1998) that for Polynesian shield islands (*i.e.* regions where the seafloor is composed of recent volcanics or

coral reefs) T->P waves are the dominant arrivals only at very steep slopes (*i.e.* slopes greater than 50º), and that the energy couples instead to shear waves at 20º slopes.

Also, parabolic equation modeling confirms that acoustic energy couples into S-wave energy for shallow slopes (Collins, 1993), for the case where the bottom shear velocity is greater than the water velocity. As indicated in Figure 1, the transmission factor for the S-waves increases as shear velocity decreases (for constant P velocity), and conversely, the amount of energy reflected at each bounce decreases. Furthermore, $Ø_s – Ø_p$ increases for decreasing shear velocity so that the range of incident angles over which acoustic energy is transmitted into S-waves increases. Thus, for this range of velocities and densities, the percent of energy coupling into S-waves increases with decreasing shear velocities and decreasing slope.

For typical marine sediments, the shear velocity of the elastic bottom is less than the compressional velocity of the fluid above (Hamilton, 1980), so that an incident T-phase is post-critical with respect to the bottom S-waves at all angles. Thus T->S conversion takes place whenever the seafloor intersects the SOFAR velocity channel. Energy flux densities for transmission and reflection of an acoustic wave incident on an elastic solid with velocities and densities corresponding to those of marine sediments are shown in Figure 2. As shown, for angles of incidence $Ø_p$ such that $Ø < 0 < Ø_P$ the transmission factors for S-waves increase with increasing shear velocity, with most of the energy reflected at each bottom bounce. Once $Ø_p$ is reached, most of the energy is transmitted into P-waves thus, in this case, the percentage of energy coupling into S-waves increases with increasing shear velocity. Again, we predict that the relative partitioning of energy between P- and S-waves will depend on the slope, with coupling into shear waves increasing with decreasing slope. For a shear velocity of zero, the problem reduces to acoustic transmission only and the acoustic energy couples into P-waves in the bottom.

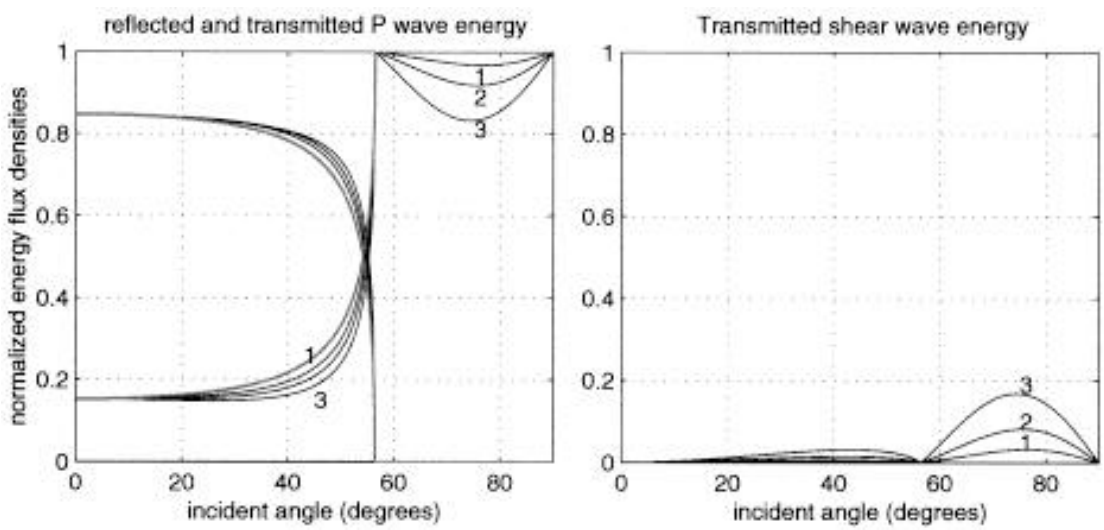

Figure 2: As for Figure 1, but for an elastic solid with velocities and densities corresponding to those of marine sediments. The P-wave velocity of the solid is 1.8km/sec, the density contrast from solid to liquid is 1.9. Curves were computed for three values of S-wave velocity: (1) 0.3km/sec, (2) 0.4km/sec, and (3) 0.5km/sec. The grey lines represent values for an equivalent fluid.

Transmission and reflection coefficients for an equivalent liquid bottom are shown by the grey lines in Figure 2. As indicated, the reflection and transmission coefficients for $Ø < Ø_P$ are almost identical to those of the typical marine sediments, thus for low angles of incidence, the physics of T->P coupling are almost identical to that of the fluid over fluid wedge. As shown by Jensen and Kuperman (1980), for a fluid over fluid wedge with low velocity contrast, the water-borne energy is radiated into downward-going P-waves in the bottom. This suggests that there may be a shadow zone for T->P coupling, with the extent of the shadow zone being dependent on the P velocity gradient. Since shear velocities in the bottom are much lower than the water velocity, acoustic energy coupled into shear energy will also be refracted downward

into the bottom, creating a T->S shadow zone. Hence T->S or T->P phases may be absent for stations located near the coast.

Comparison of acoustic and seismic T-phase recordings

A map of the seismic stations used in this study is shown in Figure 3, along with the off-shore bathymetry in the region. The seismic stations on land, which form part of the Berkeley seismic array, are equipped with three-component accelerometers with a 20Hz sampling rate. The hydrophone at Pt Sur measures pressures at a 200Hz sampling rate. The continental slope in this region is fairly gradual, with average slopes of about 5º between 200m and 3.2km depth. The seafloor off California consists of enormous coalescing fans (the Delgada Fan and the Monterey Fan) that cover the continental shelf and slope, and transgress over the abyssal hills province (Seibold and Berger, 1996). Reflection profiles and drill logs recovered at DSDP sites 32 (McManus et.al, 1970), and 33 (McManus *et. al*., 1970) in central California, and 467 (Yeats *et. al*., 1981) in southern California, indicate that the sediment column is several hundreds of metres thick in the deep water of the continental rise but is well over 1km thick on the continental slope. Compressional velocities in these marine sediments range from 1.5-1.6km/sec in the top 500m, increasing to 3km/sec at a depth of 1km, and densities grade from 1600kg/m^3 to 2300kg/m^3. Waveform fitting of interface waves indicates that shear velocities range from 30m/sec at the surface to 450m/sec at a depth of 150m(Nolet and Dorman, 1996).

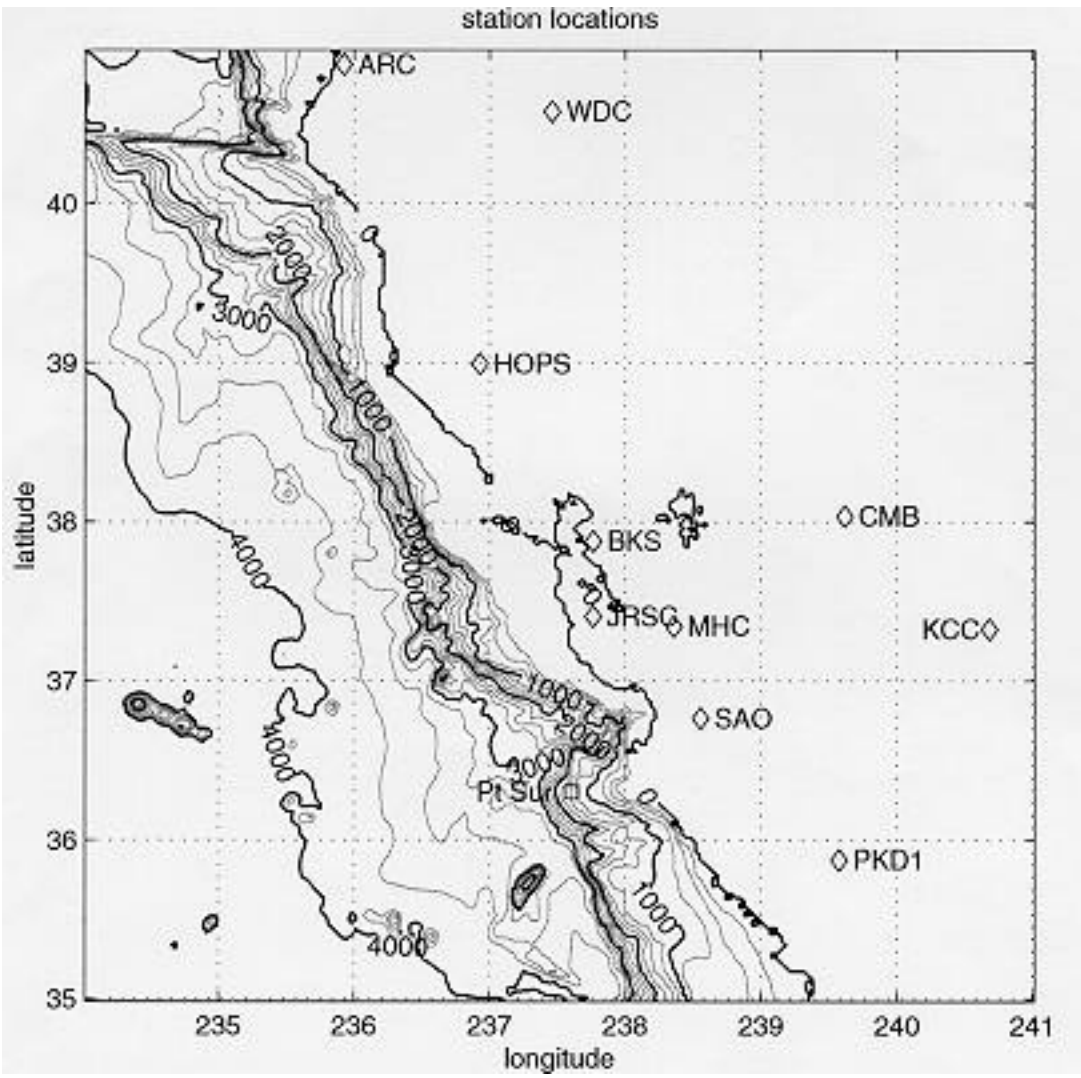

Figure 3: Map of stations used in this study. The locations of the seismic stations, which form part of the Berkeley seismic array, are indicated by diamonds; the location of the Pt. Sur hydrophone is marked by a

square. Contour lines show the bathymetry (from Smith and Sandwell, 1997) near the shoreline. The heavy lines show contours every I km from 0 to 4km depth; the thinner grey lines show contours every 250m.

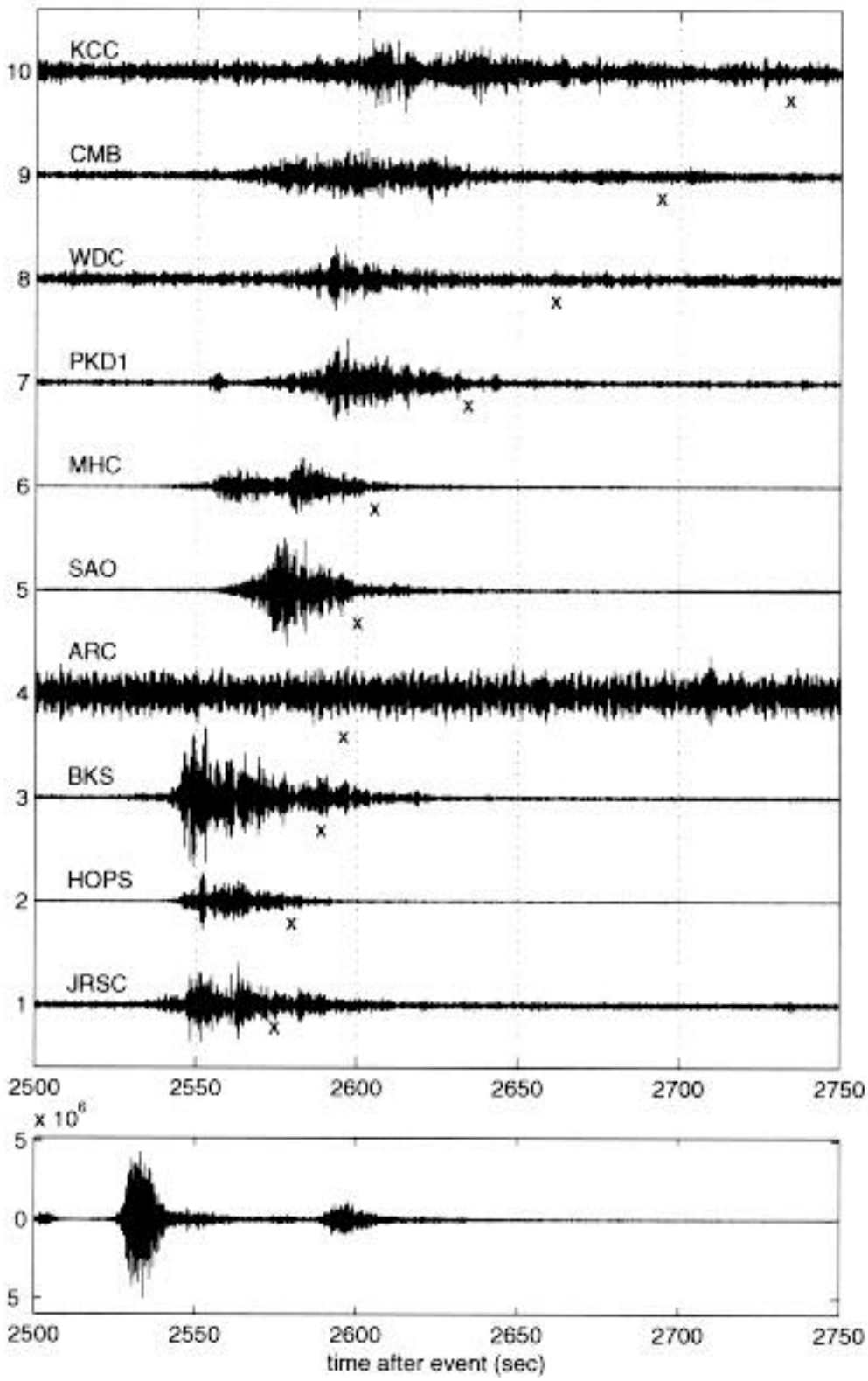

Figure 4: Top - vertical records from the Berkeley array, high-pass filtered over 2Hz, for an mb 5.0 event at 18.83, 155.32W. The 'x'es denote the travel time for purely oceanic propagation. The first 7 records are

shown at a uniform scale; the top 3 records, for stations furthest inland, are shown magnified 10x with respect to the others. Bottom pressure data from Pt Sur, bandpassed from 2-10Hz.

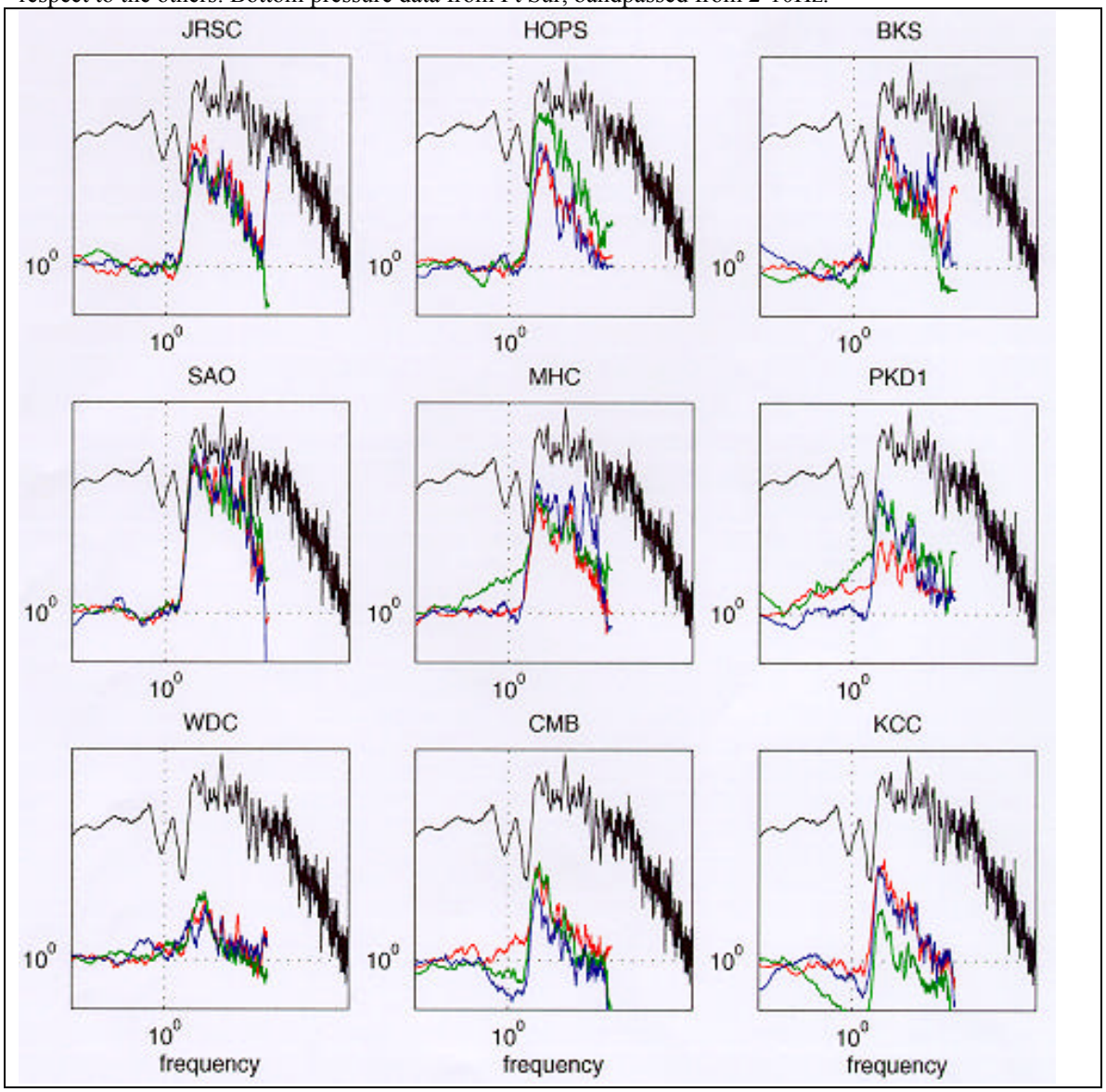

Figure 5: Signal to noise power ratios (SNRs) computed for each station over the entire T-wave arrival. SNRs for the East-West (red), North-South (green), and vertical components (blue) are shown compared to the SNR at Pt Sur (black).

Vertical component recordings of the seismic T-waves, high pass filtered above 2Hz, are shown in the top panel of Figure 4 for a magnitude Mb 5.0 event, one of the largest of the Hawaiian event clusters of July-August 1996. The characteristics at each station, *i.e.* duration, frequency content, and relative amplitudes, are nearly uniform for events within the cluster. The first seven recordings are shown on a uniform physical scale, with the top three recordings, from stations further inland (WDC, CMB, and KCC), shown magnified 10 times with respect to the others. The Pt Sur recording is shown for comparison in the bottom panel. Two stations, JRSC and MHC show two distinct arrivals, whereas signals at other stations appear to consist of several overlapping arrivals. The arrivals at MHC and JRSC have velocities of 4.8-5.7km/sec for the first arrival, and 2.1-2.4km/sec for the second arrival, consistent with crustal P-wave and S-wave velocities, respectively. For stations further inland, amplitudes decrease with distance from the coast. In general, noise levels also decrease with distance inland, so that arrivals are observable as far inland as CMB and KCC.

Spectral ratios were computed over the entire T-wave arrival for each component at each seismic station, and compared to those at Pt Sur as shown in Figure 5. All seismic recordings show lower signal to noise than for the hydrophone at all frequencies. T-phases recorded at Pt Sur for the Hawaii cluster peak at 2-4 Hz, and drop off gradually to background levels at 50Hz. The T-waves at the seismic stations peak at about 2Hz, then drop off more rapidly with increasing frequency. Since the sampling rate at the seismic stations is only 20Hz, compared to 200Hz at Pt Sur, high frequencies cannot be examined but for most stations the spectral ratios suggest that the seismic T-phases decrease to background levels at 9Hz. SAO is a notable exception, with a relatively slow decrease in power with increasing frequency. As expected, recordings at stations located over 100km inland (WDC, CMB, and KCC) are much more attenuated than for stations close to the coast, and the dropoff in signal level with increasing frequency is greater. However, stations closest to the coast (JRSC, BKS, ARC) do not exhibit the highest signal-to-noise, suggesting that there is a tradeoff between noise levels and T-phase amplitudes for stations within several tens of kilometres from the coast.

DISCUSSION AND CONCLUSIONS

Current plans call for several T-phase stations to be located on volcanic shield islands and for one at the edge of a continental margin (on Queen Charlotte Island, Canada). Seafloor slopes at volcanic islands are quite steep (12º-20º), and velocities are high, such that $v_s > v_w$ (*eg*. Piserchia *et.al*., 1998). At continental margins, the sediment-covered seafloor is characterized by very gentle inclinations (3º-6º) at the continental slope. Reflection and transmission energy flux densities computed for $v_s > v_w$ indicate that most acoustic energy will couple into S-waves at volcanic islands, except at very steep slopes. This is consistent with the observations of Hanson (1998) at Ascension Island, of Koyanagi *et.al.* (1995) at Hawaii, and of Talandier and Okal (1998) at Polynesian shield islands. At the edge of a continental margin, T-waves convert to both P and S-waves as observed in this study, and by Shapira (1981), and Cansi and Bethoux (1985).

A marine sediment-covered seafloor has similar acoustic properties to that of an equivalent fluid, i.e. one with identical density and compressional velocity. Thus coupling is expected to occur at distinct cutoff depths corresponding to modal cutoff depths. In this study, we do not discern distinct arrivals corresponding to each mode coupling point, and would not expect to, as the incident T-phases have durations of 15-20 seconds, which is greater than the travel time between mode coupling points. The largest amplitude arrivals occur at stations with propagation paths crossing steep portions of the continental slope near the station, where delay times between cutoff points are minimal and the propagation through land is minimal. The largest arrivals thus likely correspond to the nearly simultaneous arrival of several converted modes. Therefore information in the acoustic wavefield is lost in coupling to seismic energy. Variations in the duration of the seismic T-phase arrivals between stations thus can be attributed to variations in the bathymetry nearest each station.

Noise levels generally decrease with increasing distance from the coast so that seismic T-phases can be detected as far as several hundred kilometres inland. Comparison of T-phase signal to noise ratios over a 0.1-10Hz band at the Berkeley array to those observed at Pt Sur indicate that the seismic T-phase signal is lower at all frequencies than the acoustic T-phase arrival. Furthermore, signal strengths decrease more rapidly with increasing frequency, especially at stations located several hundreds of kilometres from the coast. The relatively high SNR at SAO, compared to the other seismic stations, may be attributed to the fact that the continental shelf is unusually narrow at this point, thus the low mode coupling points lie closer to SAO than at the other sites. This implies that optimal sites for T-phase stations will be at locations where the continental slope lies close to the coastline. For slopes covered by marine sediments, acoustic to seismic coupling is efficient for slopes as low as 5º.

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