HYDROACOUSTIC EVENT LOCATION USING T-PHASES

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ABSTRACT

In this study, we examine the use of T-wave arrivals in pinpointing earthquake locations for sources with epicenters in the ocean basins. Our database consists of a set of events listed in the IDC's Reviewed Event Bulletin (REB), for which arrivals were recorded at the Wake Island and Pt. Sur hydrophones. Most of these events had accurate epicentral location estimates; the given event mislocations were 30km or less. Misfits between the T-phase picks and the predicted arrival times were as large as 120sec, far larger than could be accounted for given the size of the epicentral error ellipse. Since T-phase generation occurs over a broad region of the seafloor, the T-phase onset time is usually not associated with excitation at the epicenter. Hence the accuracy of source location depends on both the method used for picking T-phase onset times, as well as the velocity model. We find that the seasonal variability in the phase velocities is on the order of 4 mm/sec - too small to account for the observed time residuals. Comparing predicted T-phase arrival times with observed T-phase arrivals, we demonstrate that by picking the T-phases in a high frequency band (8-32Hz) improved estimates of source location may be obtained.

We also examine whether waveform matching can be used to improve hypocentral estimates. We show that for arrivals with multiple peaks, the time separation between peaks depends on the distance between T-phase source regions. For well-located series of events east of Honshu, Japan, we determined that a seismic velocity of between 2.2km/sec-3.9km/sec would yield waveforms with peaks showing approximately the correct delay time. Our preliminary interpretation is that the S-wave is coupling into T-phase energy.

Key word: hydroacoustics

OBJECTIVE

Hypothetically, the slow phase velocity (less than 1.5km/sec) and low attenuation characteristics of the T-phase should allow for highly precise estimates of event location. In practice, T-phase source location is often not coincident with earthquake epicentral location, since the efficiency of seismic to acoustic coupling is dependent on water depth(de Groot-Hedlin and Orcutt, 1999), therefore T-phase source locations are often biased toward bathymetric promontories in the vicinity of the hypocenter (Walker, 1992). Moreoever, acoustic velocities are seasonally variant which may yield mis-estimates of predicted T-phase travel times. In this study, we compute seasonal variation s in the acoustic velocitiy for deep ocean paths. We compare results of picking T-phase arrivals in different frequency bands and examine whether waveform fitting can aid in event location estimates.

RESEARCH ACCOMPLISHED

T-phase residuals for Pacific events

Figure 1 shows a map of events that had identifiable T-phases at at least three hydrophones. The locations of the hydrophones at Pt. Sur and the two near Wake Island (WK30 AND WK31) are marked by asterisks. The T-phases are auxiliary phases, that is, they are not used in estimating event locations. The size of the major axes of the error ellipses ranges from 10 to 38 km, that is, the events are located quite accurately by the seismic phases. The size of the circles is proportional to the size of the error ellipse.computed as the square root of the product of the minor and major axes. Since the events are well located this set can serve as a good test set to determine the accuracy needed in both the velocity model, and the most accurate way to pick the T-phase arrival.

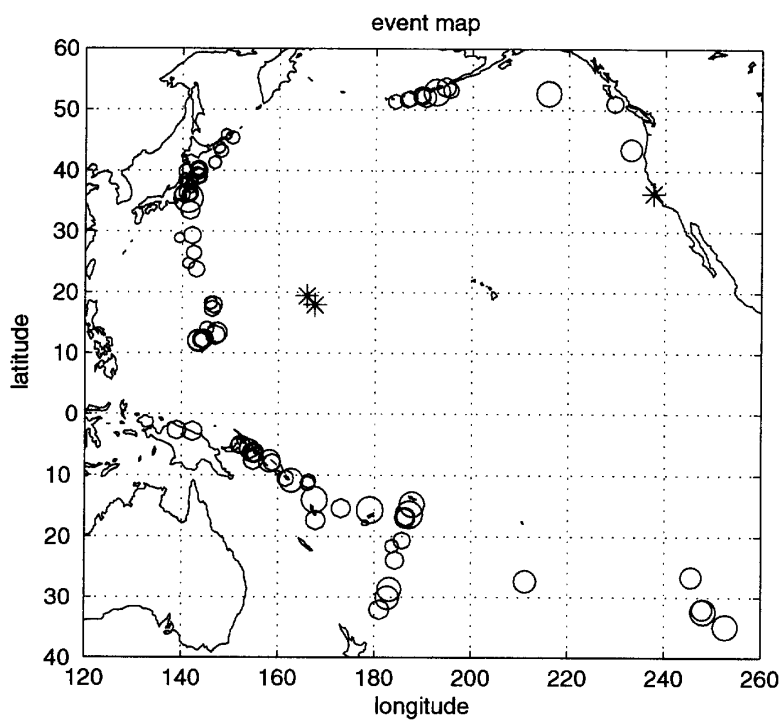

Figure 1: Map of events which had identifiable T-phases at WK30, WK31, and Pt Sur. The size of the circles increases with the size of the location error ellipse.

A comparison of the size of the error ellipse vs. the absolute time difference between the T-phase pick in the REB and the expected T-phase arrival is shown in figure 2. The predicted T-phase arrival times are based on modal velocities

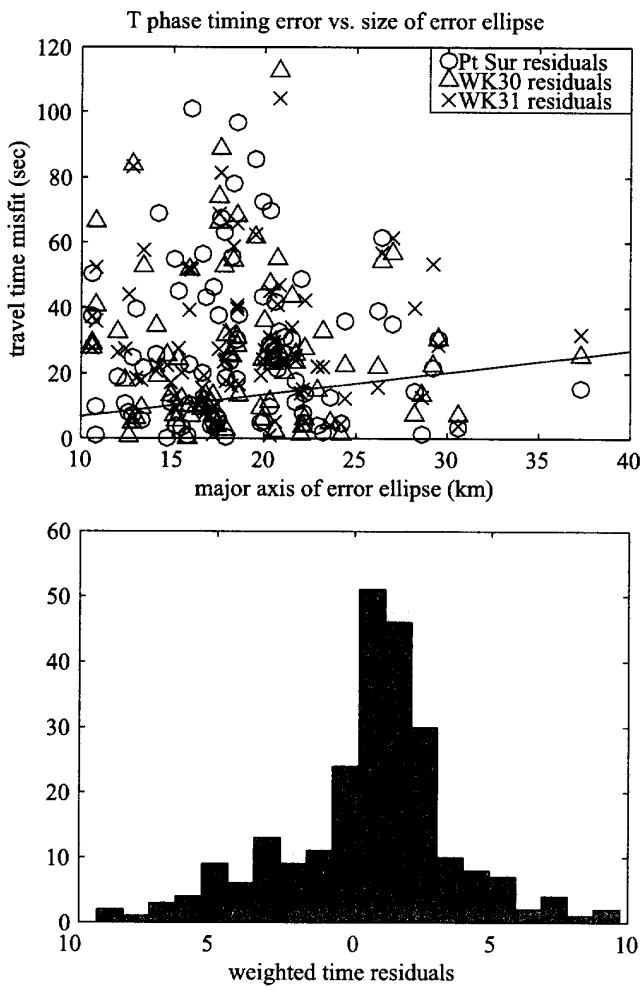

Figure 2 : top - size of T-phase time residuals vs. size of error ellipse. bottom - histogram of weighted time residuals.

computed along geodesic travel paths from source to receiver. T-phase arrivals are based on a "probability weighted time" (Hanson et.al, 1999) and are picked in the frequency band with the highest signal level. The probability weighted time is a weighted sum of the peak time and the mean energy time. For a location error ellipse oriented with its major axis parallel to the direction of propagation, the maximum expected timing residual is given by the length of the major axis divided by the T-phase velocity (about 1.5km/sec). The solid line in this figure represents the maximum expected timing misfit. As indicated, a large number of points fall well above this line, suggesting a problem either with the velocity model used, or with the method of picking T-phase arrivals. We define the weighted time residual as the time residual supplied in the REB, divided by the travel time across the major axis of the error ellipse.A histogram of the weighted time residuals is shown in the bottom panel. The time residuals have a net positive bias, with a mean weighted error of 0.57sec. The time residuals are randomly distributed geographically.

Seasonal variations in T-phase velocity

Since we don't have direct velocity measurements we use a nine term formula (Mackenzie,1981) relating salinity, temperature, and depth to sound velocity. Temperatures and salinity profiles are derived from the WOA database (Levitus and Boyer, 1994). Surface temperatures, and to a lesser extent, salinities, vary over the year thus the acoustic velocity model is a function of time. In figure 3, we examine acoustic velocity profiles and group velocities for each month at 50N, 180E. As shown in the top left panel both the SOFAR channel velocity and depth vary over the year. Below approximately 500m, velocities are constant. Mode shapes, shown in the top right panel of figure 3, are nearly constant over the year. Ocean-borne sound energy propagates at the modal group velocities (Heaney et.al., 1991), plotted for the first few modes for f=5Hz, left, and f=10Hz, right. Velocity variations over the year are only on the order of nearly 4mm/sec, which translates to a time difference of 9 sec over a 5000km path. Thus seasonal variations in travel time are small, and not a significant source of location error. Note that the above computations were done for a deep water at a nearly polar latitude. Velocity variations at equatorial latitudes are less severe, due to less severe variations in surface temperature. On the other hand, seasonal velocity variations in shallow water are slightly greater, since the modal propagation is confined to the upper, more variable part of the ocean column.

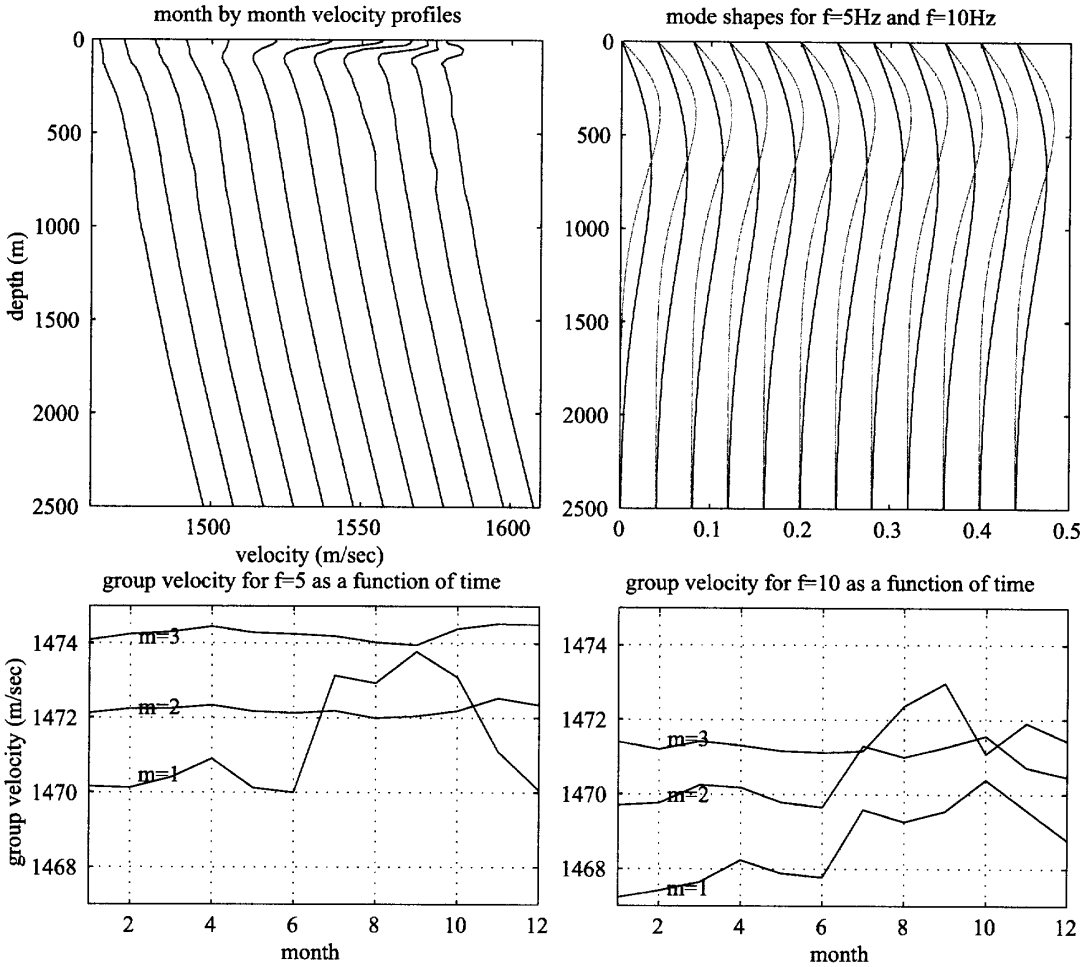

Figure 3: top left - velocity profiles for each month, offset by 10m/sec. top right - mode 1 shapes for f=5 Hz (dark line and f=10Hz (light line). bottom left - variations in group velocities over a year at f=5Hz for the first 3 modes. bottom right - variations in group velocity for f=10Hz.

Accuracy of T-phase picks

For some events, large T-phase time residuals may be attributed arrivals with low signal to noise ratios. However, in many cases, the T-wave recordings consist of a number of distinct peaks, and the large residual is due to the ambiguity in picking one of these as the arrival corresponding to the epicentral location. In figure 4, we show sonograms and waveforms for an event with high signal to noise ratios at all three hydrophones, which nevertheless had timing residuals of 80-90 seconds. The epicenter was located east of Honshu, Japan at 40N, 143E, about 100km east of the coastline where the water depth is nearly 2km, that is, far below the SOFAR velocity minimum. There are two distinct arrivals at WK30 and WK31, the first with travel times corresponding to excitation at the epicenter, and the second with travel times suggesting excitation near the coastline. The latter peak, generated about 100km from the epicenter, has a higher signal to noise ratios and was picked as the T-phase arrival by the automatic picking routine at the IDC, yielding the large time residuals. We identify the latter peak as a slope phase, usually characterized by a high amplitude phase with peak frequency at 5Hz; the first arrival is an abyssal T-phase, usually characterized by lower amplitudes which peak at

For T-phase arrivals with two or more distinct peaks, the arrival time chosen by an automated picking routine often depends on the frequency band used in picking. To examine the frequency dependence of the T-phase picks, we bandpass T-wave recordings at WK30 and WK31 for a series of events off Honshu, Japan. Earthquake epicentral locations, plotted on a bathymetry map as shown in figure 5, are mainly offshore so that at least two peaks are evident in the T-phase recordings of the events. Waveforms bandpassed from 2-8 Hz and 8-16Hz are shown in Figure 6 for most of these events. As indicated, the relative amplitude of each arrival is dependent upon the frequency band, with the amplitude of the abyssal phase dominating the high frequency band. Since abyssal phases are associated with excitation at the epicentral location, T-phase picks made in a high frequency band will likely yield more accurate location estimates. However, this method fails if high frequencies are absent or very weak at frequencies greater than about 8Hz (as in the T-phase recording at Pt Sur shown in figure 4).

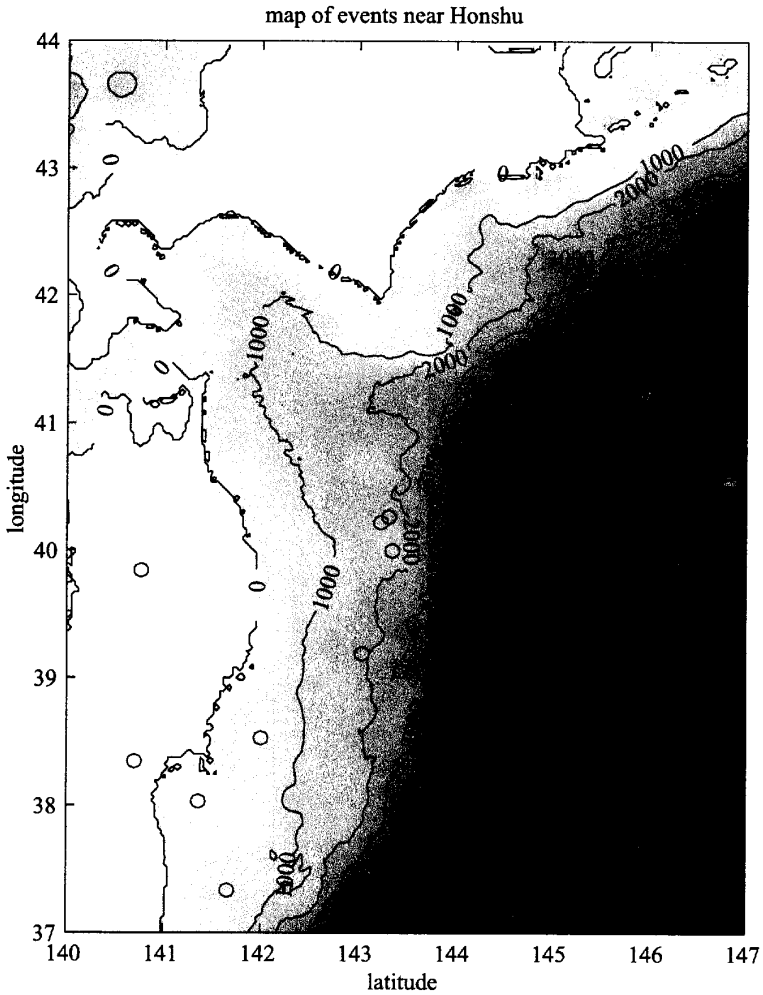

Figure5: Event locations and bathymetry east of Honshu, Japan

Finally, we note that the shape of the T-waveform is dependent on source location, with clustered events all having similar amplitude, duration, and frequency characteristics. This suggests that waveform fitting may aid in event location. For events with both an abyssal phase and a slope phase, the time separation of these phases depends on the distance between the epicenter and nearby bathymetric highs where seismic energy can be scattered energy into the ocean column (deGroot-Hedlin and Orcutt, 1999). As shown in figure 6, the time separation between the two types of

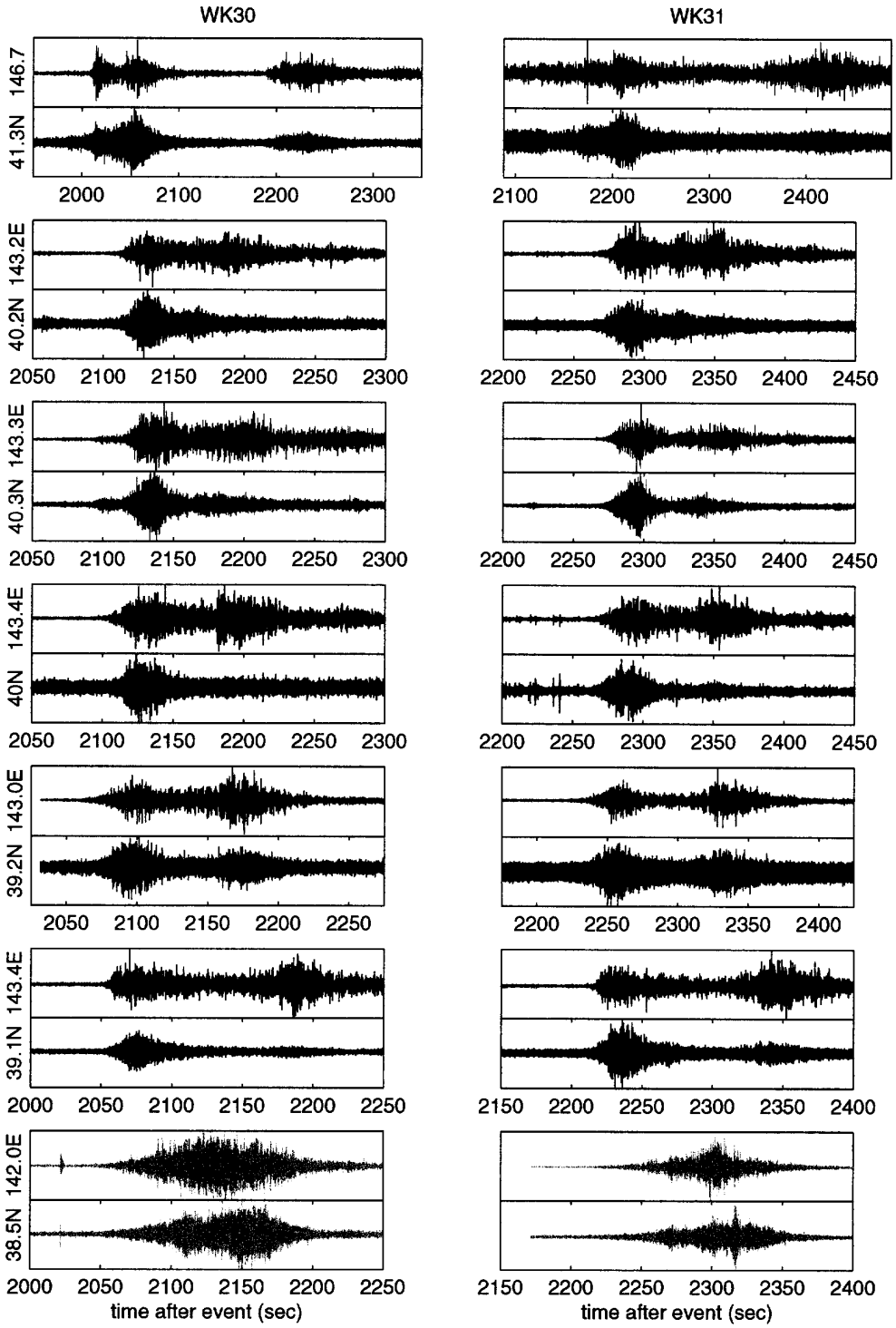

Figure 6: Bandpasses T-wave recordings for a series of events off Honshu, Japan. WK30 recordings are shown at left; WK31 recordings at right. For each recording pairs of waveforms bandpassed from 2-8Hz (top) and from 8-32Hz (bottom) are shown. Note that the first event is on a different time scale.

frequencies of 10-20Hz.. In this case the differences in the frequency content and amplitude of these two arrivals is relatively insignificant at Pt Sur. At WK30 and WK31, there is a greater falloff with increasing frequency for the second arrivals (the "slope" phase), than for the first (the abyssal phase).

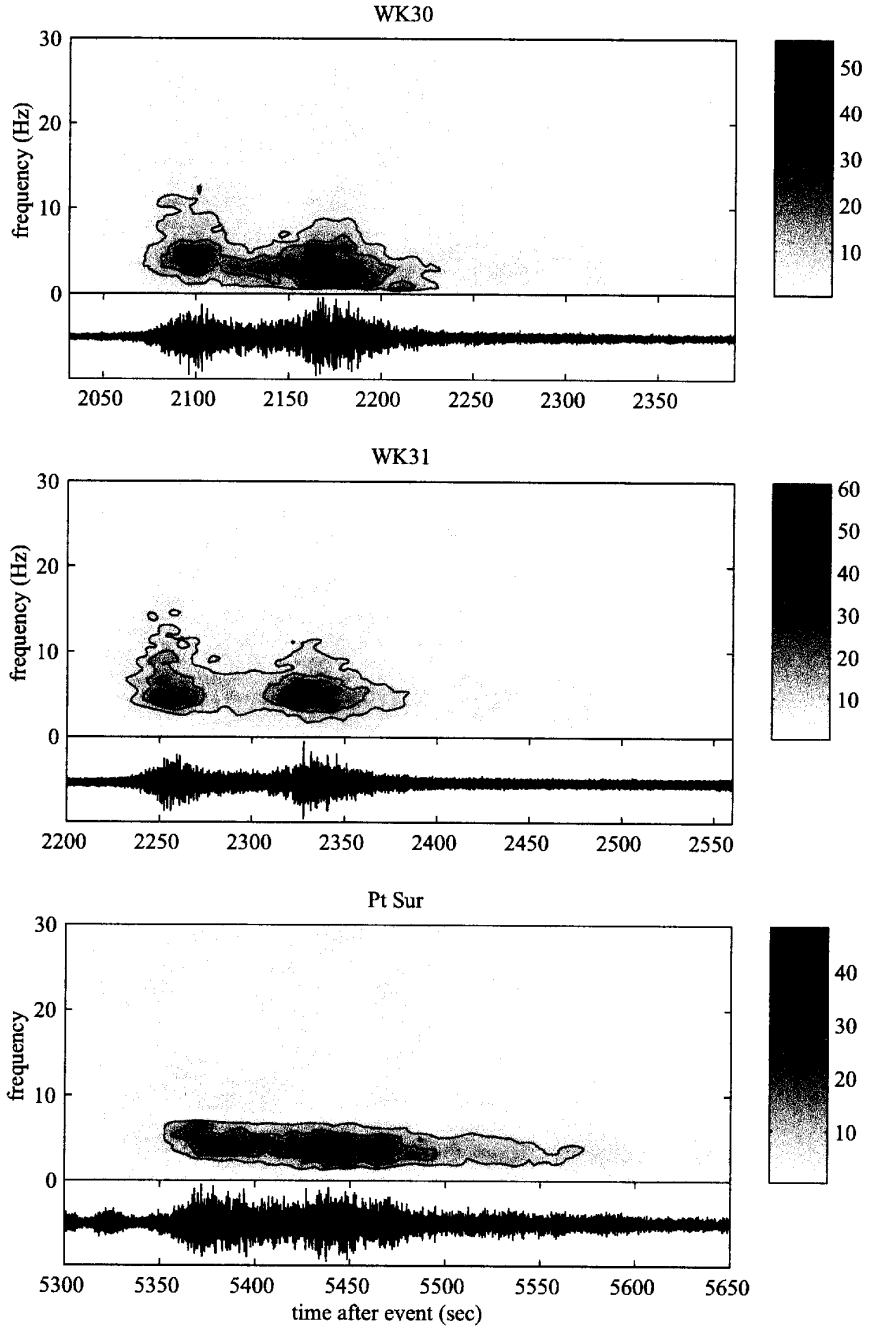

Figure 4 Waveforms and spectral ratio sonograms for an event at 40N, 143E, formed by dividing sonograms for each time slice by average noise powers computed for quiet intervals before the T-phase arrivals, for hydrophones located in the Pacific Ocean. The waveforms are bandpassed from 1-30Hz for WK30 and WK31; from 1-10Hz at Pt Sur.

T-phase increases with increasing distance from the shore. We estimated the crustal velocity for each event of figure 5 by finding the distance from the epicenter to the shallow region where the slope phase is generated, and determining the difference in the crustal portion of the traveltime. The crustal portion of the travel time is given by

$$dt_{crust} = dt_{meas} - dt_{ocean}$$

where dt_{meas} is the observed travel time difference between the slope and the abyssal phase, and dt_{ocean} is the difference in the computed travel paths through the ocean from epicenter to reciever and from the shallow region to the receiver. We found that crustal velocities ranged from 2km/sec to 3.9km/sec. We attribute the large variation in the crustal velocities to the difficulty of picking a precise travel time for each arrival, and to the fact that all but one of the events was within 100km of the coastline, so that high precision in the picks was required. However, we can state that the seismic velocities are low, suggesting that S-wave energy, not P-wave energy converts to acoustic energy at the slope. Thus, given the arrival times of both the high and low frequency T-phase arrivals (which correspond to the abyssal and slope phases, respectively), a reasonably accurate epicentral source location estimate may be made.

CONCLUSIONS

Seasonal velocity variations yield variations in travel times on the order of less than 10 seconds, which correlates to a hypocentral misestimate of about 15km. The major difficulty in using T-phases to estimate epicentral location is that many arrivals are excited at bathymetric peaks in the vicinity of the epicentre, rather than at the epicenter itself. We found that picking T-phase arrivals in a high frequency passband (8-32Hz) yielded travel times corresponding to exciation at the epicenter. We also found that the velocity of the seismic phase which couples into T-phases is on the order of 2.2-3.9km/sec, corresponding to the velocity of a shear wave. Given this approximately known seismic velocity, and the accurately known acoustic velocities, T-phases with multiple peaks may be correlated with bathymetric highs to give an estimate of epicentral location.

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