Cascadia Tremor Located Near Plate Interface Constrained by S Minus P Wave Times

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Nonvolcanic tremor is difficult to locate because it does not produce impulsive phases identifiable across a seismic network. An alternative approach to identifying specific phases is to measure the lag between the S and P waves. We cross-correlate vertical and horizontal seismograms to reveal signals common to both, but with the horizontal delayed with respect to the vertical. This lagged correlation represents the time interval between vertical compressional waves and horizontal shear waves. Measurements of this interval, combined with location techniques, resolve the depth of tremor sources within ±2 kilometers. For recent Cascadia tremor, the sources locate near or on the subducting slab interface. Strong correlations and steady S-P time differences imply that tremor consists of radiation from repeating sources.

Deep nonvolcanic tremor (NVT) has been observed in several tectonically active regions. In Cascadia and Japan, a relation with the subduction dynamics is inferred by the contemporaneous occurrence of slow slip detected geodetically (1–3). In these regions, the occurrence of major episodic tremor and slip (ETS) events is surprisingly periodic (2). Minor NVT has been triggered by the stresses imposed by low-frequency seismic waves radiated by major distant earthquakes (4–6), and NVT is modulated by ocean tidal loading (7), indicating that small stress perturbations trigger it. NVT is characterized by low amplitudes, a lack of energy at high frequency, emergent onsets, an absence of clear impulsive phases, and durations from minutes to days. The lack of impulsive phases identifiable across seismic networks in Cascadia hinders accurate source location by conventional techniques.

NVT recorded in Shikoku, Japan, contains identifiable low-frequency earthquakes (LFEs) (8, 9), suggesting that tremor is primarily made up of many back-to-back LFEs. On individual seismograms, S waves are sometimes identified. Stacking seismograms of repeating events recorded at a given station after aligning them on the S waves produces a clear P wave. The S minus P times allow an accurate depth to be determined. Such Japanese tremor locations are found to be near the subduction plate interface (8, 10). Individual LFEs have not yet been reported in tremor recorded in Cascadia.

Tremor episodes that continue for several days are accompanied by geodetically observed slow slip in both Cascadia and Shikoku, leading to the widely accepted interpretation for Japan that tremor and slow slip are manifestations of the same process. In contrast, attempts to locate tremor in Cascadia have resulted in a broad, 40-km- thick, distribution in depth, leading to the interpretation that much of the tremor is related to fluids throughout a large volume above the plate interface (11, 12). Three different location techniques for tremor in Cascadia produce depth estimates over a range of 40 km. One technique uses the arrival times of seismic signal envelopes (12–14) and conventional location techniques based on an S-wave velocity model. A second technique, the Source Scanning Algorithm (15), stacks seismograms such that theoretical S-wave time delays correspond to a grid of possible source locations. Formal uncertainties are as small as 5 km but still show a wide depth

range (11, 16). A third technique uses small- aperture arrays to compute slowness vectors for seismic wavefronts and back projects those for a common source (17). In all of these cases, common signal shapes are processed under the assumption that they are direct S phases.

Cascadia tremor depth estimates likely have a greater uncertainty than the reported formal errors of 10 km in epicenter and more in depth. We tested this assumption by using two of the techniques to locate earthquakes in the same region as the tremor. The differences between the more accurately determined catalog earthquake depths and those we computed are much greater than the formal errors, sometimes tens of kilometers different (14, 17). In the case of back projection of slowness vectors, unmodeled lateral velocity variations may bend the wave fronts sufficiently to explain these large errors in estimated tremor depths. Errors in depth determined from arrival times of seismogram envelopes are caused largely by unmodeled variations in S-wave coda duration. Here, we apply a new location procedure that greatly improves the depth resolution of the tremor sources.

Our data come from low-noise stations of the Pacific Northwest Seismograph Network and from three dense arrays composed of six three-component short-period seismic stations that were deployed specifically to record the July 2004 ETS event in Cascadia (18) (Fig. 1). Tremor periods with depths from 20 to 60 km have been reported (12, 16, 17). Polarization analysis of array data indicates that most of the signal has S-wave polarization (13) with apparent velocity higher than 5 km/s, as expected for shear waves from a deep source (17). P-wave polarization is observed in some of the tremor signals (18).

To improve the signal-to-noise ratio, we first stacked the seismograms over all the stations for each component of each array. Such stacks emphasize signals arriving with a steep incidence angle, i.e., from sources directly below an array. Then we computed the cross-correlations between the vertical and each horizontal stacked trace by using 300-s windows bandpass-filtered from 2 to 8 Hz. On many traces, the cross-correlogram envelopes show a distinct and persistent peak at positive lag times of 3.5 to 6.0 s, and no such peaks at negative lag times (Fig. 2). Positive lags correspond to the vertical component leading the horizontal component. These are particularly evident at the Sequim and Sooke arrays, where they were observed in many 5-min windows every day from 9 to 18 July. At the Lopez array, similar lags were visible only sporadically on 9 and 10 July, when tremor was nearest the array.

The distinct peaks at positive lags are consistent with the arrival of first vertical P waves and then horizontal S waves. The sequential correlations are characterized by tens of minutes with almost constant S minus P times (t_{s-p}). In several cases, when these peaks are most evident, visual inspection of the stacked seismograms revealed many subtle individual P- and S-wave arrival pairs with the same t_{s-p} (Fig. 3). This pattern implies that at least some Cascadia tremor is made up of individual LFEs from a single source region occurring rapidly one after another in a sporadic sequence such as observed in Japan (9).

Figure 2 shows lag times of 5.2 s at Sequim and of 3.7 s at Sooke. At Sequim, there were no intervals during the entire tremor period with t_{s-p} less than 4.5 s. The low horizontal slowness measured at this array during times corresponding to t_{s-p} near 4.5 s, indicate that the sources were directly beneath the array. In contrast, higher slowness and back-azimuths to the north systematically correspond to t_{s-p} = 5.0 to 5.4 s. At the Sooke array, all S-P times were between 3.7 and 4.4 s. The smallest value of t_{s-p} = 3.7 s (Fig. 2) is consistent with sources located almost directly beneath the array. At the Lopez array, there were only a few periods of tremor with clear crosscorrelation peaks, and those had t_{s-p} = 5.5 s.

Combining the t_{s-p} -determined distances with slowness determined by array analysis allows an accurate estimate of the source depth. Based on a standard layered Earth model (19), tremor below the Sequim array (t_{s-p} = 4.5 s) was located at a depth of 39 ± 2 km, whereas it was 31 ± 2 km below the Sooke array (t_{s-p} = 3.7 s). To better compare the range of depths determined with and without the t_{s-p} constraints, we applied an envelope cross-correlation tremor location method (14) to

the same periods of time for which good S-P cross-correlation times are available. We located these tremor bursts both with and without the constraints of distance based on array measurements of t_{s-p} and show the resulting epicenters in Fig. 1 and cross-section in Fig. 4. We kept all observations for which the theoretical ray angles at the arrays were less than 15° from the vertical. Depths are shown relative to the plate interface depth as determined from slab-Moho reflections (20). The depth range for locations determined with just envelope crosscorrelations is large (small circles) as compared with those of the same tremor located with the additional t_{s-p} constraints (large circles). At Lopez and Sequim, the refined depths are close to the plate interface. On average, the tremor beneath Sooke appears to be farther above the slab interface than that beneath Sequim and Lopez. This is likely an artifact of unmodeled high wave speeds associated with the Crescent Basalts beneath Sooke (21). Taken together, out of 128 observations, the mean source distance above the plate interface is 3 km and the standard deviation is ±5 km.

The clear correlations and stable t_{s-p} in the signals suggest that, as was the case in Shikoku, where individual low-frequency events are found in the tremor and precisely located (8), at least some of the deep tremor in Cascadia consists of highly repetitive, continuous sequences of individual events, which radiate both P- and S-wave energy from a volume small enough to give almost constant t_{s-p} over periods tens of minutes or more. We cannot locate all tremor with this 5 method for two reasons. First, the stable determination of t_{s-p} depends on tremor over an extended period coming from only one place, which is not always the case. Second, our technique is most sensitive to tremor beneath each array where the P and S waves are clearly separated into vertical and horizontal components. There are many periods of time, particularly at the Lopez array, in which tremor was located some distance from an array. In these cases, there was likely too much S-wave energy on the vertical component and P energy on the horizontal to get a strong cross-correlation. Although we cannot determine the depth of all observed tremor, the tremor under each array occurred near the subduction zone interface, and we see no evidence for shallow tremor, in contrast to other studies (11, 12, 16, 17). Our method is ideally suited to find shallow tremor if it existed beneath an array.

If our results are representative of most NVT in Cascadia, then the contemporaneous occurrence of Global Positioning System–detected slow slip (22) indicates that deep tremor and slow slip are two manifestations of the same source process in Cascadia, as has been inferred for Japan (8, 10, 23). This hypothesis is further supported by the polarization characteristics of tremor signals, which are in good agreement with the expected polarization of signals produced by fault slip along the subduction megathrust (13).

References and notes
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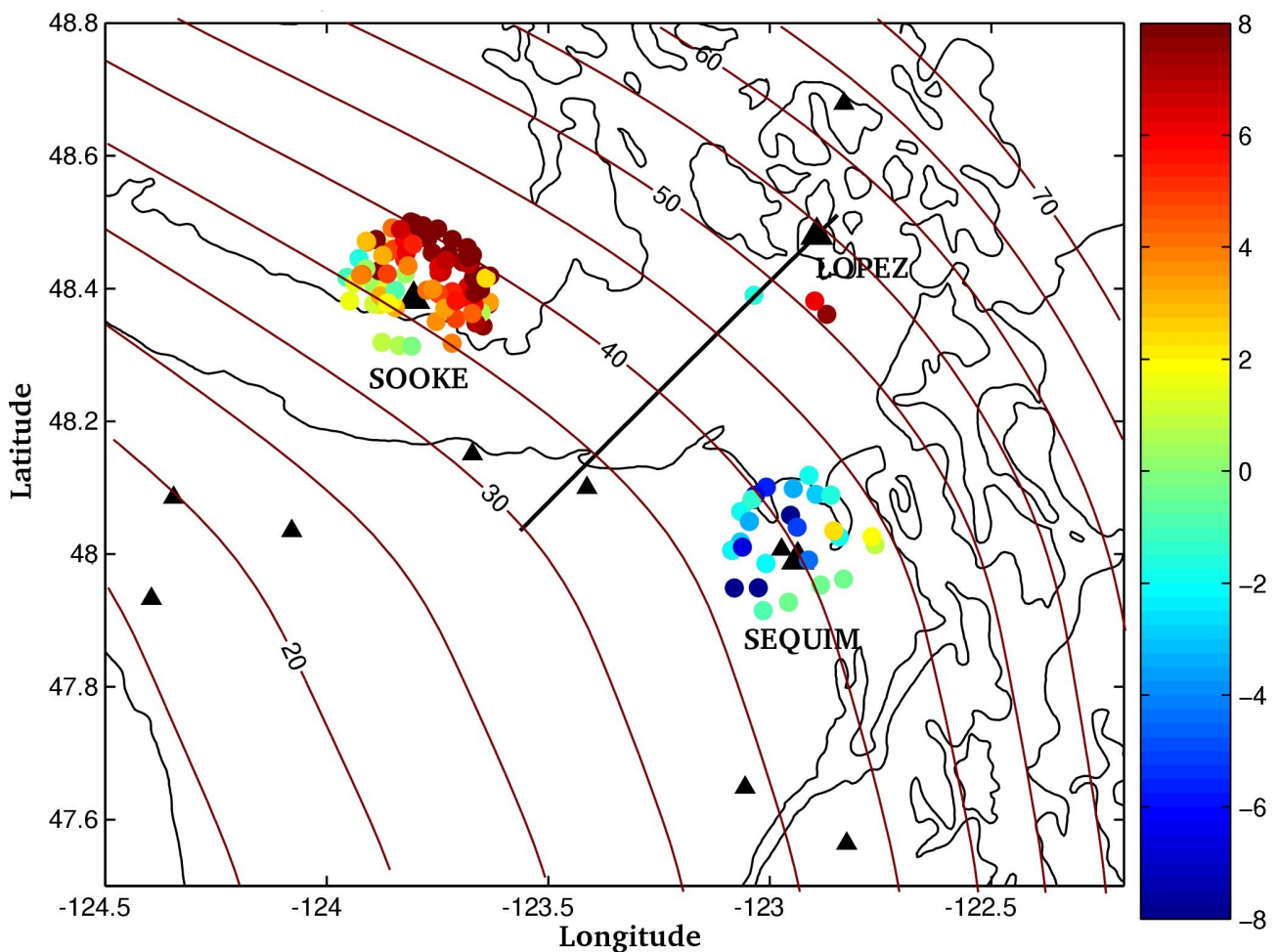
Fig. 1. Map showing locations of the three seismic arrays (large triangles), other stations used for location (small triangles), depth (km) to the plate interface [assumed to be 7 km above the slab Moho (20)], and location of cross section on Fig. 4 (black line) and tremor epicenters (dots), colorcoded by distance above (red) and below (blue) the plate interface. Tremor epicenters are determined from cross-correlations of seismogram envelopes, and depths come from additional t_{s-p} constraints. Theoretical ray incident angles at the arrays are restricted to be less than 15°.
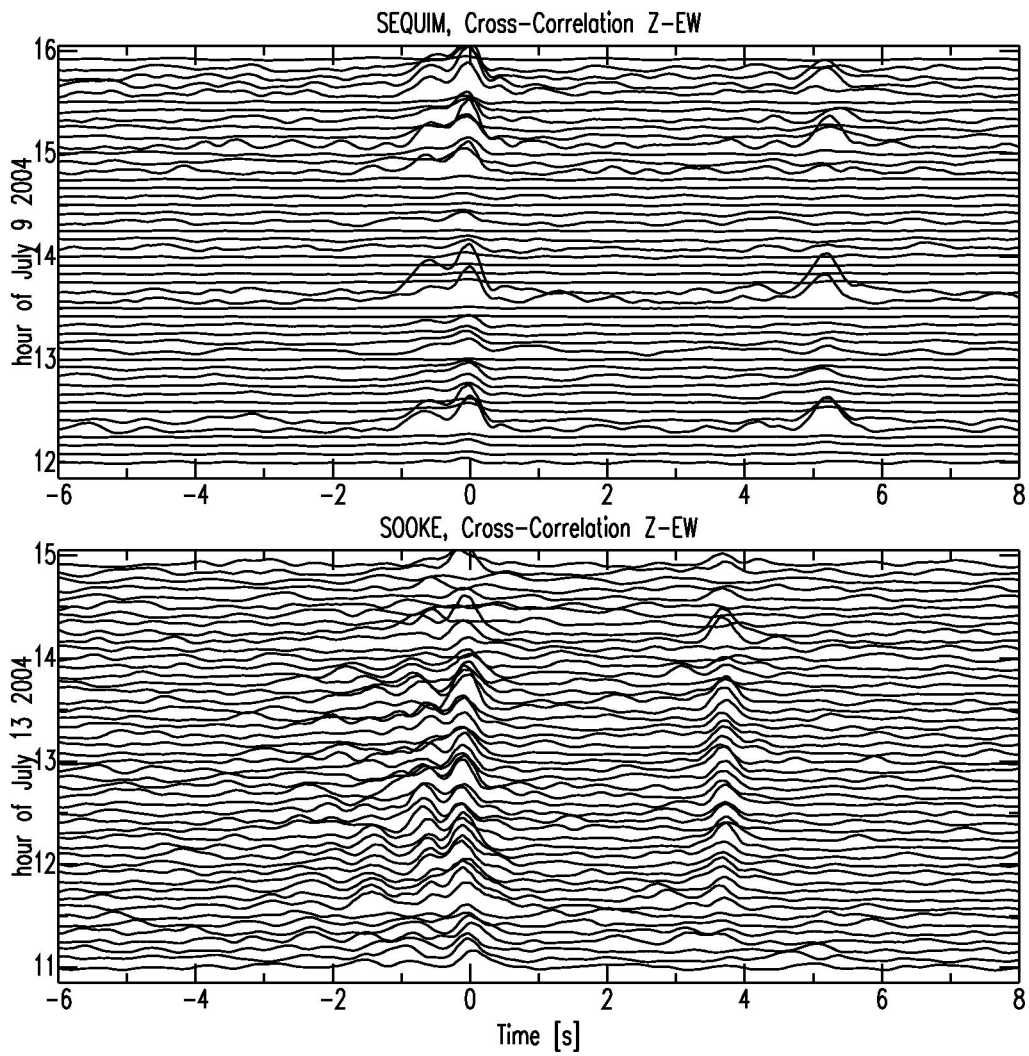
Fig. 2. Envelopes of the cross-correlations between vertical and east components for 5-min windows recorded at Sequim array (top) and Sooke array (bottom).
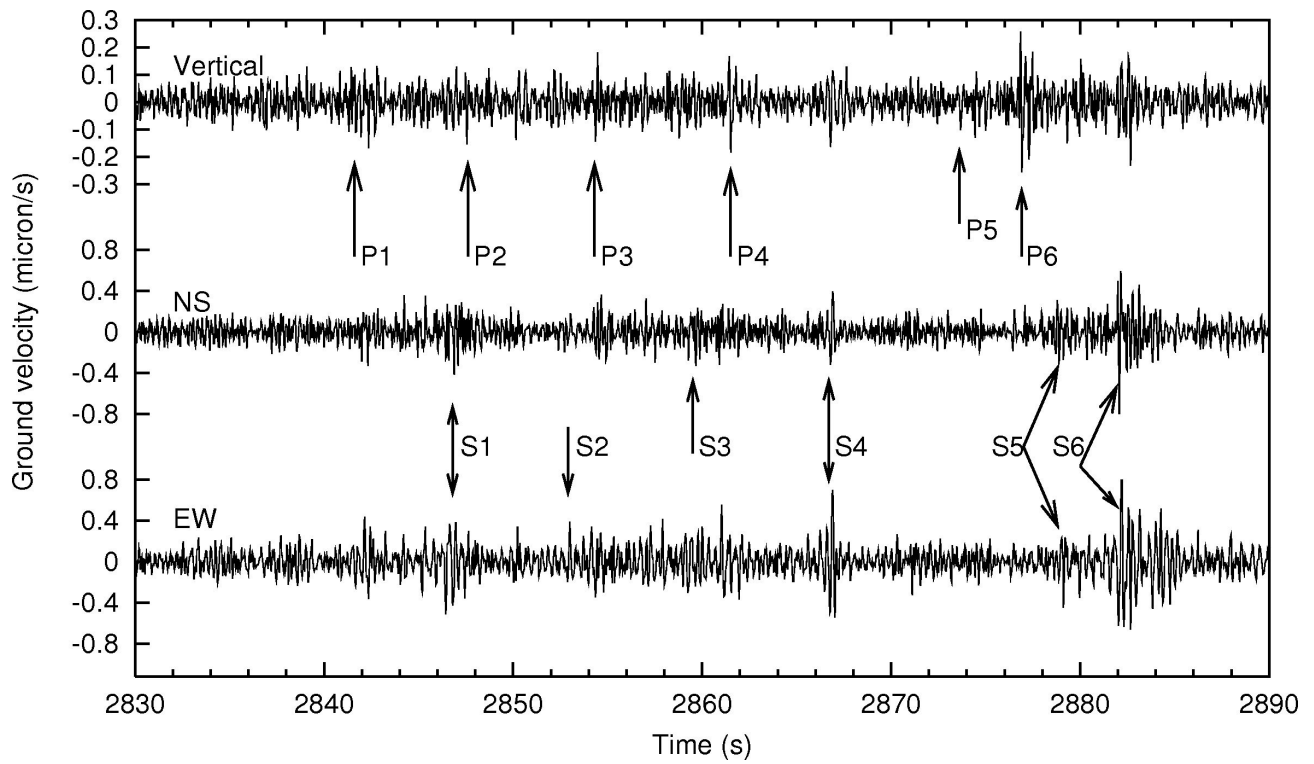
Fig. 3. Three-component seismograms in which several P-waves, marked by arrows on the vertical component, are followed by S-waves 5.1 ± 0.2 s later, as marked by arrows on the horizontal components. Seismograms are the stacked signals of Sequim array bandpass filtered between 2 and 10 Hz. The reference time is 15:00 GMT of 9 July 2004.
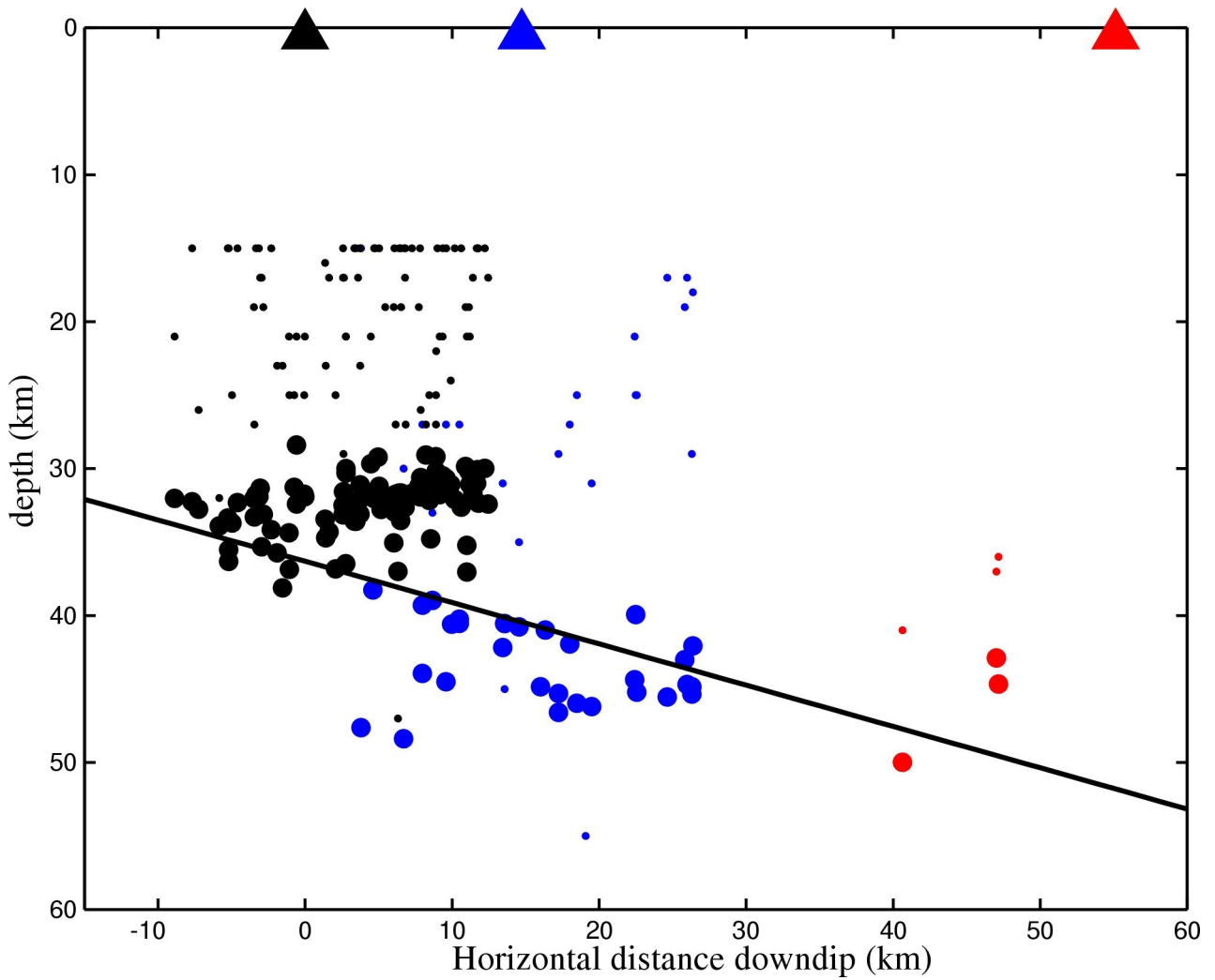
Fig. 4. Cross-section of tremors shown in Fig. 1 along southwest-northeast profile. Small dots show hypocenters determined solely from envelope cross correlations. Large dots are hypocenters of the identical set of tremor periods, but with their depths shifted to satisfy the additional t_{s-p} constraints from the Sooke (black), Sequim (blue), and Lopez (red) arrays.