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Monochromatic body waves excited by great subduction zone earthquakes

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Abstract. Large quasi-monochromatic body waves were excited by the 1995 Chile M_W=8.1 and by the 1994 Kurile M_W=8.3 events. They are observed on vertical/radial component seismograms following the direct P and P_{diff} arrivals, at all azimuths. We devise a slant stack algorithm to characterize the source of the oscillations. This technique aims at locating near-source isotropic scatterers using broadband data from global networks. For both events, we find that the oscillations emanate from the trench. We show that these monochromatic waves are due to localized oscillations of the water column. Their period corresponds to the gravest 1D mode of a water layer for vertically traveling compressional waves. We suggest that these monochromatic body waves may yield additional constraints on the source process of great subduction zone earthquakes.

Introduction

For a shallow focus source, the intervals between P and PP (for $30° < \Delta < 100°$) and that between P_{diff} and PP or PKP (for $100° < \Delta < 140°$) is usually, in a 1D earth model, free of any significant teleseismic phases. However, large arrivals or oscillations often fill these "clean gaps", and as of yet have been largely underused in seismic studies. Figure 1 shows such oscillations on vertical component broadband seismograms from two great subduction zone events. These nearly monochromatic waves, observed at all teleseismic distances and azimuths, follow the direct arrivals, and have significant amplitudes. Teleseismic signals from large earthquakes normally contain a broad range of frequencies. Band-limited signals are not unusual, however. They often represent energy trapped by wave guides, such as crustal surface waves or acoustic T-waves in the oceanic SOFAR channel. Almost monochromatic atmospheric waves can be excited by volcanic eruption [*Widmer & Zürn*, 1992; *Kanamori et al.*, 1994]. Harmonic signals from volcanic tremors have been the object of extended research, but their origin remains uncertain [*Chouet*, 1988; *Schlindwein et al.*, 1995]. Similarly, sedimentary basins resonate at discrete frequencies when excited by an incident wave [*Bard & Bouchon*, 1985]. Ward [1979] and Wiens [1989] describe observations of ringing P wave excited in the water column by submarine faulting, similar to those of Figure 1. Using broadband data from global networks, we confirm the nearly monochromatic character of these oscillations. We devise a slant stack technique to locate them, and we demonstrate that they are caused by spatially limited oscillations of the trench's water column.

Methodology

We use a simple slant stack technique to extract the location of scatterers with respect to the hypocenter of the earthquake. Seismograms are aligned on the P-wave onset, and a 3D grid of points is set up around the hypocenter. The slant stack $s(x_k, y_k, z_k, t)$ at the k-th node of the grid is defined as the weighted average of appropriately shifted seismograms $u_n(t)$ observed at the n-th station,

$$s(x_k, y_k, z_k, t) = \frac{1}{N} \sum_{n=1}^{N} u_n(t + \tau_{nk}) / w_n \quad . \tag{1}$$

The weights w_n are computed from the root mean square of the part of the seismogram under interest. Delay-times τ_{nk} are calculated for each station from the differential travel-time between the hypocenter and the grid points, using the iasp91 earth model and software [*Kennett*, 1991]. The use of differential travel-times is advantageous because it makes the technique relatively insensitive to the velocity structure near the source. Little bias in position of scatterers is expected, even in the case of imperfect azimuthal coverage. The hypothesis underlying the stacking technique is that seismograms can be added without sign change, i.e. coherent energy is emitted isotropically toward the stations. In this preliminary study, the stack is searched for the global absolute maximum. One can however easily envision a technique that aims at extracting more information from the stack, such as additional maxima or minima. Also, a waveform matching procedure may be used to iteratively strip the stack of its coherent energy.

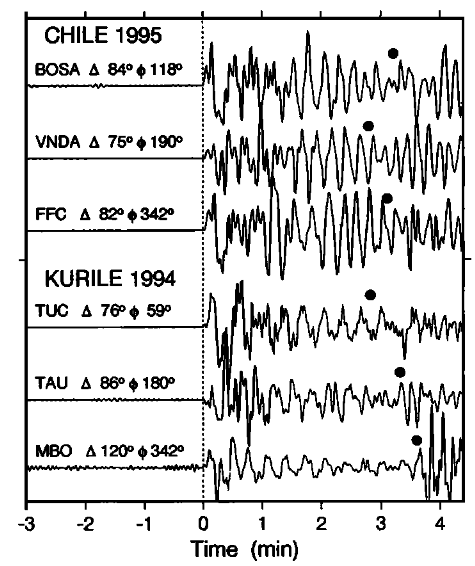

Figure 1. Broad-band velocity seismograms of the M_W=8.1 Chile 95/07/30 event (top traces), and of the M_W=8.3 Kurile 94/10/04 event (lower traces). Records are aligned on the P-wave onset (or P_{diff} depending on distance). The predicted PP (or PKP) arrival is marked with a solid circle. Each trace is normalized to its absolute largest amplitude. Epicentral distance and station azimuth are indicated. Strong quasi-monochromatic oscillations follow the end of the direct arrival (starting at ~80 s and ~60 s after onset for the Chile and the Kurile events, respectively).

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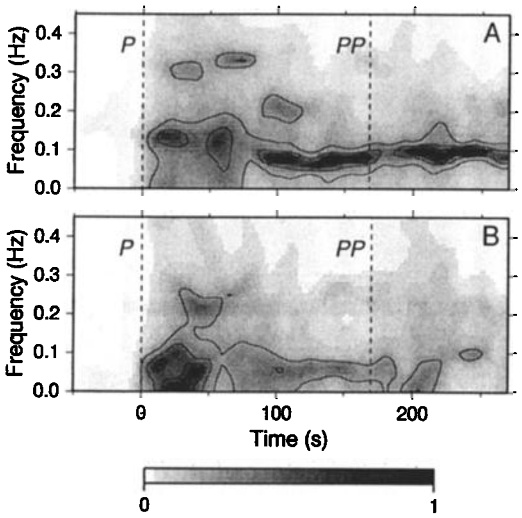

Figure 2. (A) Chile 1995 event. Spectrogram of the vertical component broadband velocity record at station VNDA (see Figure 1). (B) Kurile 1994 event. Spectrogram at station TUC (see Figure 1). Spectrograms are estimated from 40 s long sliding windows using the maximum entropy spectral method. They are normalized to their maximum amplitude. *P* and *PP* onsets are marked with the dashed lines. In the case of the Chilean event, note the strong change in spectral content after the direct *P* wave.

The 1995 Chile M_W=8.1 event

Figure 1 shows vertical component broad-band *P* waves of the M_W=8.1 Chile 95/07/30 event. This shallow focus thrust earthquake occurred at the interface between the Nazca and South American plates. It had a source duration of about 65 s, and a southward unilateral source process with rupture velocity around 3.0 km/s [*Ruegg et al.*, 1996; *Ihmlé*, unpublished data]. 4 to 6 oscillations follow the direct *P*-wave arrivals, and are observed at all azimuths. With a nearly constant period of ~14 s, they mark a sharp contrast with respect to the broad spectral content of the direct wave (Figure 2). These quasi-monochromatic waves are polarized like the *P* wave, and are thus of probable near-source origin, but they are not observed after the *SH* arrival on transverse component seismograms.

We apply the slant stack procedure to 10 vertical component displacement records chosen to provide a nearly uniform azimuthal coverage. To ensure a large gap between the end of the *P* wave and the *PP* arrival, epicentral distances between 70°-90° are favored. Seismograms are aligned on the *P* onset. A 6 s running mean filter is used to slightly smooth the waveforms. A 100 s window is extracted starting 90 s after onset, and, after light tapering, used in the stacking procedure. A 10 km x 10 km horizontal grid is defined around the hypocenter located at 23.43° S, 70.48° W, h =36 km [*Ruegg et al.*, 1996]. Figure 3 shows a contour plot of slant stack amplitudes at the time of the global absolute maximum of the stack. Because of steep take-off angles, the maximum stack amplitude and optimal location have little depth sensitivity. Slightly better stack values are nevertheless obtained for shallow grids with depth around 5-15 km. The contour plot on Figure 3 indicates that the source of the oscillations is located near the end of the rupture, slightly west of the middle of the Chile trench, 184 km to the SSW of the epicenter at 24.59° S, 71.77° W, h = 5 km, and 121 s after the earthquake's onset.

Figure 4 displays the stacked trace together with the seismograms appropriately shifted using delay-times computed for the optimum location. The maximum delay-time τ_{nk} at this location is 10.8 s for station PAB, and cycle skipping problems cannot be excluded. We examine the maximum stack value and location as a function of time in the interval 90-140 s after onset. All extrema of the stack function indicate nearly the same location suggesting that cycle skipping does not occur. The period varies from 15 s at the beginning to 13 s at the end of the wavegroup. Slight move-out between peaks and troughs of the oscillations implies some variability in the resonance. The resonance seems to grow after the end of the *P* wave (Figure 1 and 2), but it is likely that the *P* wave is affected by such oscillations. Indeed, water reverberations are

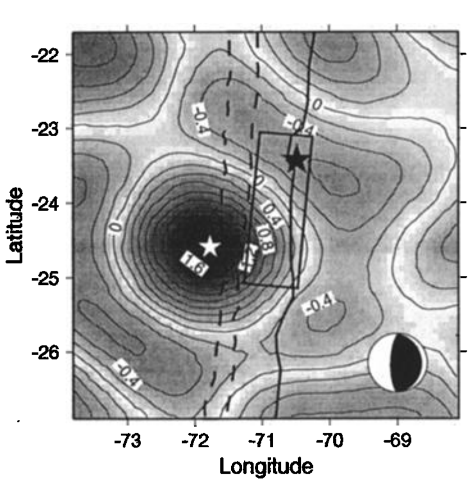

Figure 3. Location of the oscillations excited by the 1995 Chile event. Contours show stack amplitudes at the time of the global maximum of the slant stack. The optimum location for the oscillations (white star), and the event's epicenter (black star) are indicated. The box gives the approximate rupture extent [*Ruegg et al.*, 1996]. The continuous thick line marks the coast of Chile. The dashed lines delineate the -6000 m isobath. The focal mechanism of the event, as determined by the Harvard CMT, is shown at the lower right.

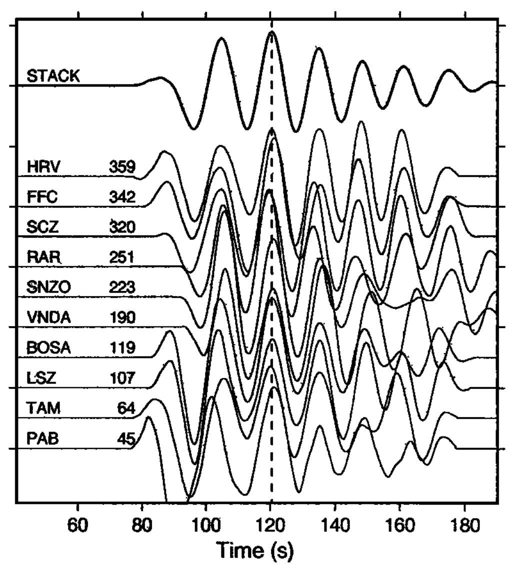

Figure 4. Displacement records of the Chile 1995 event shifted with the delay times computed for the optimal stack location (see Figure 3). Each trace is normalized by its root mean square amplitude. Station names and azimuths are given. Top trace is the stack. The dashed line marks the time (relative to onset time) of the optimum stack value.

known to contaminate P waves in broad-band source inversions [e.g., *Wiens*, 1989].

We measured the RMS amplitude of the resonance on all available broad-band records at epicentral distances from 30° to 90°, and corrected the data for geometrical spreading and bulk attenuation. No azimuthal pattern was apparent in the data, and we found that the hypothesis of isotropic scattering was satisfied, at least for the narrow range of take-off angles (14°-27°) under consideration.

The 1994 Kurile Islands M_W=8.3 event

Figure 1 also shows vertical component broad-band P waves of the Kurile Islands 94/10/04 event. This M_W=8.3 earthquake is thought to be an intraplate event, that ruptured a nearly vertical fault, parallel to the strike of the trench axis [*Kikuchi & Kanamori*, 1995]. Using broadband body waves, Kikuchi & Kanamori [1995] inferred a predominantly unilateral rupture toward the southwest, propagating at ~ 2.5 km/s, and a source duration of 42 s. They determined a centroid depth of 56 km and a location for the initial break at 43.48° N, 147.40° E. Figure 5 indicates the approximate source extent of the event. On Figure 1, 4-6 oscillations with period ~ 18 s are visible on the seismograms, but the change in spectral content is not as marked as that of the Chile 1995 event (Figure 2). The oscillations have the same polarization as the direct arrival. Like in the Chilean case, these waves are not observed after the first SH arrival.

We apply the slant stack procedure to 10 vertical displacement records, which are processed in the same way as before. Figure 5 shows a contour plot of slant stack amplitudes at the time of the global extremum of the stack. The source of the oscillations is located slightly southeast of the middle of the Kurile trench, 136 km to the SE of the epicenter at 42.40° N, 148.19° E, h = 5 km, and 94 s after the onset of the rupture. The source of scattered energy is located near the trench at the level of the middle of the rupture zone. Figure 6 displays the stack together with the seismograms shifted using the delay-times computed for the optimum location. Again, we search the stack for evidence of cycle skipping, but all well defined extrema of the stack function indicate nearly the same position.

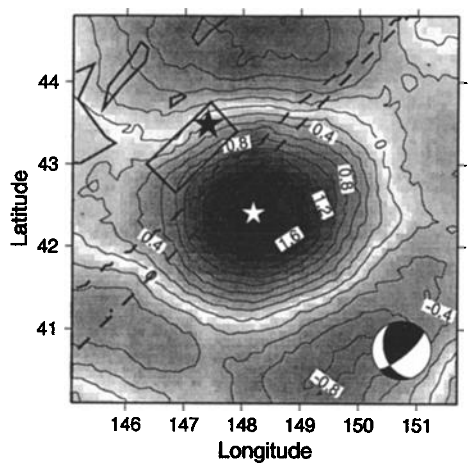

Figure 5. Location of the oscillations excited by the 1994 Kurile event. Contours show stack amplitudes at the time of the global maximum of the slant stack. The optimum location for the oscillations (white star), and the event's epicenter (black star) are indicated. The box shows the approximate rupture extent [*Kikuchi & Kanamori*, 1995]. The continuous thick lines indicate land. The dashed lines delineate the -6000 m isobath. The CMT focal mechanism of the event is shown at the lower right.

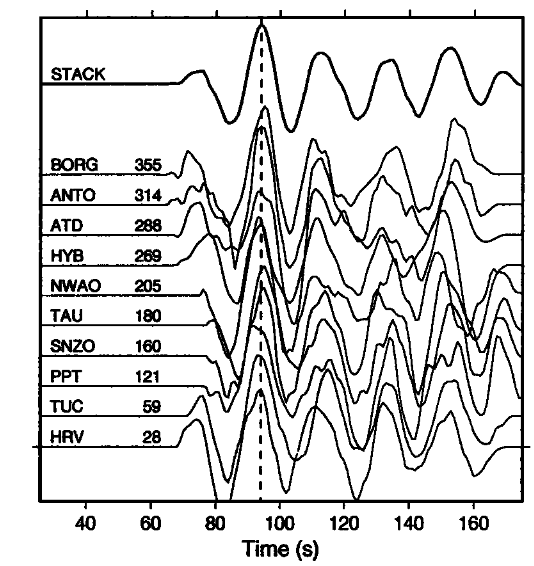

Figure 6. Displacement records of the Kurile 1994 event shifted with the delay times computed for the optimal stack location (see Figure 5). Each trace is normalized by its root mean square amplitude. Station names and azimuths are given. Top trace is the stack. The dashed line marks the time (relative to onset time) of the optimum stack value.

Discussion

Our slant stack method demonstrates that the quasi-monochromatic waves of Figure 1 originate near the trench. The oscillations are characterized by 1) their absence after the SH arrival, 2) their wavelength in the water which corresponds to 4 times the water depth (see below), 3) their lack of radiation pattern, 4) their amplitudes which are commensurate with that of the direct P arrival.

These observations strongly suggest that these monochromatic waves are due to localized oscillations of a water layer. Energy appears to be fed by the rupture into the water column, and is radiated back at teleseismic distances mainly as P waves, as the water reverberations have essentially vertical incidence on the nearly horizontal water-solid interface at the bottom of the ocean. Assuming an origin in the water (compressional velocity of 1.5 km/s), the wavelength of the oscillations is ~ 20 km, and ~ 27 km in the Chile and Kurile cases, respectively. These wavelengths correspond to about 4 times the water depth at the optimum location of scattered energy. In a simple 1D model of a layer of water over a half-space, the periods of resonance T_n for vertically traveling waves are given by [*Haskell*, 1960, and reference therein]:

$$T_n = \frac{4h}{\alpha_0(2n+1)} \tag{2}$$

where h is the water depth, α_0 the compressional velocity, and n the mode index. The observed periods agree well with the fundamental frequency ($n=0$) of resonance. Higher modes of resonance, such as $T_1 = \frac{1}{3}T_0 = 7-9$ s, and $T_2 = \frac{1}{5}T_0 = 4-5$ s, are not readily observed. This is likely due to the spectral content of the source time function of the events, to the trench geometry, or to contamination with other sources of signal generated noise. A number of questions remain to be explained. Why is the resonance well behaved and locatable ? How can the large oscillations in the case of the Chile 1995 event be accounted ?

Wiens [1989] showed that the deeper the water layer overlying the seismic source, the stronger the reverberation amplitudes. He demonstrated also that a dip of a few degrees of the water-solid interface strongly enhances the oscillation amplitudes compared to the strictly 1D case. Okamoto [1993] showed that the sedimentary structure and the actual trench bathymetry contribute significantly to the waveforms. Updip rupture propagation appears also to play a role in augmenting their amplitudes [*Ward*, 1979]. In the case of the Chile 1995 event, the source of resonance is located close to the trench axis near the end of the rupture (Figure 3). Interestingly, that is where the rupture appeared to move closest to the trench axis [*Ihmlé*, unpublished data], and hence moved under a deeper water column . The rupture probably did not reach the bottom of the ocean, since only a small tsunami was excited by the Chile 1995 event [*Ruegg et al.*, 1996]. Numerical modeling of the resonance may help address the question of the rupture extent in the shallowest region of the subduction zone. The event rupture velocity (~ 3 km/s) is supersonic with respect to the compressional velocity in water (1.5 km/s). The southward propagation parallel to the trench axis may have generated a shock wave in the water of the trench, accounting perhaps for the unusual characters of the Chilean oscillations. In the case of the Kurile Islands 1994 event, the source of resonance is located across the trench of the point of largest moment release in Kikuchi & Kanamori's [1995] body wave model (Figure 5). There is some debate on which focal plane was the fault plane of the event [*Kikuchi & Kanamori*, 1995; *Tanioka et al.*, 1995], with important implications for the seismic gap hypothesis, and the large scale tectonics of the region. The characteristics of the resonance may possibly help discriminate among models of the rupture process.

Conclusion

In this study, we develop a simple slant stack technique in order to locate near-source isotropic scatterers. The origin of monochromatic body waves following direct arrivals from great subduction zone earthquakes is easily located and characterized using this algorithm. The oscillations, excited by the event's source process, originate in the water column of the trench. Their period corresponds well with the 1D fundamental period of the water column. The 2D trench geometry may be locally well approximated by a horizontally layered medium, suggesting that the oscillating water column is of limited lateral extent. In fact, the reverberation acts as an oscillating point source for all localization purposes. The earthquake geometry, and spectral content, which is a function of earthquake size, are likely to play a role in the excitation of such waves, whereas trench and fault geometry contribute probably additional factors. Body waves scattered by near source structures are ubiquitous in broadband seismograms. They are potentially interesting for characterizing the near-source region and the source process itself.

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