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Upper Boundary of the Pacific Plate Subducting Beneath Hokkaido, Japan, Estimated from *ScSp* Phase

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Abstract

Three-dimensional geometry of the upper boundary of the Pacific plate subducting beneath Hokkaido, Japan, was obtained using the *ScSp* phase: the phase converted from *ScS* (S wave reflected at the core-mantle boundary) to P wave at the plate boundary. Taking the advantage of a dense seismic network, "Hi-net", recently deployed across the Japanese islands, we applied several seismic array analyses to the recorded waveform data for a large nearby deep earthquake, in order to enhance very weak *ScSp* signals in the original records. At first, we set up five blocks for the region in plate dip directions. After aligning the travel times of *ScS* and stacking seismograms among stations in a given sub-block perpendicular to each dip direction, we searched for the optimal plate model (i.e., two-dimensional geometry of the upper boundary) for each block. The model was parameterized by seven depth grids, and seismograms were stacked based on the travel time of *ScSp* as a time lag of each sub-block, so that the optimal model would yield the

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maximum spectral energy of *ScSp* after stacking. This model parameter search was conducted, using ray tracings of *ScSp* with a reference velocity model and a non-linear inversion scheme (Neighbourhood Algorithm). The optimal model of each block was combined each other by cubic spline interpolation, in order to construct an overall three-dimensional geometry of the upper boundary of the plate. Next, we performed the frequency-wavenumber (f - k) spectral analysis to refine the above result. Assuming each station as a reference point, we made beam output from records of its adjacent stations as a function of wavenumber vector (k_x, k_y) and frequency. The peak of its power spectrum was considered to represent the wavenumber vector of *ScSp*, that is, azimuth of arrival and slowness, so that we can estimate the position and depth of the corresponding *ScS-ScSp* conversion. In the frequency range from 0.5 to 1.5 Hz, we could estimate the conversion points for 21 stations or hypothetical arrays, and revised the geometry of the upper boundary obtained by the non-linear stacking approach in the previous step. The final plate model was compared with the distribution of intraplate earthquakes in the Pacific plate. This comparison clearly reveals that the upper seismic zone merges with the lower from 150 to 200 km in depth, deviating systematically away from the upper boundary where the boundary is slightly bumped in a convex manner.

Key words: *ScSp* phase; subducting slab; Pacific plate; upper boundary; array processing

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1. Introduction

Regions around subducting plates or slabs are recognized to be highly anomalous in the propagation of seismic waves for a long time. Tomographic studies have been widely conducted in subduction zones over the world to determine large-scale spatial distribution of P and/or S-wave velocities (e.g., Fukao et al., 2001). These studies with travel-time data are, however, not suitable to retrieve sharp discontinuities or boundaries in velocity. There are several seismic approaches appropriate to structural boundaries like upper boundary of a subducting plate. The upper boundary is an important, sharp discontinuity of the earth's interior, due to its dominant role over various geodynamic activities in a subduction zone. It has been studied extensively using focal mechanisms in slab, reflected and/or refracted waves for local or artificial events, and receiver function analysis for teleseismic events. Nevertheless, one of the most straightforward and effective seismic approaches to focus on the profile of the upper plate boundary is the use of *ScSp* phase.

ScSp is the wave observed as a precursor of *ScS* that is reflected from the core-mantle boundary (CMB) and then propagates upwards nearly vertically. It is converted from S (*ScS*) to P wave at the upper boundary. In comparison with *ScS*, the measurement of *ScSp* eliminates all the complicated effects such as source, station site and lateral heterogeneities other than the upper plate boundary, so that the value of boundary depth can be estimated directly with good precision. Okada (1979) was the first attempt to profile a subducting plate with the *ScSp* phase observed in Hokkaido, Japan. Several researches on *ScSp* phases have been followed in other parts of the world (e.g. Snoke et al, 1977; Helffrich et al., 1989; Helffrich and Stein, 1993; Helffrich, 1996;

26 Bourne and Stuart, 2002).

27 In Japan, *ScSp* phases are observed clearly in some areas, and have been
28 used to estimate the depth profile of upper plate boundaries even before
29 the deployment of the high-density seismic network, Hi-net, in late 1990s:
30 for example, in the Chugoku-Shikoku region by Nakanishi (1980) and in the
31 Kanto region by Iidaka and Obara (1993). Thanks to the recent deployment
32 of high-density seismic networks over the world resembling the Hi-net system
33 in Japan (Obara, 2003), it is possible to obtain a detail trajectory in depth of
34 the upper boundary of a subducting plate. Umino et al. (2002) obtained the
35 overall depth distribution of subducting plates in and around Japan, using
36 the Hi-net data.

37 In contrast, the *ScSp* phase has not been observed clearly in the Hokkaido
38 region, except for some limited areas close to the trench axis (e.g., the sta-
39 tion KMU located at Cape Erimo, as observed by Okada (1979)). Compared
40 with other regions in Japan, reliable estimation of the spatial distribution of
41 the upper boundary of the Pacific plate subducting there has been a difficult
42 issue. For example, while receiver function analyses have imaged various
43 boundaries clearly in other parts of Japan (e.g. Shiomi et al., 2004; Tone-
44 gawa et al., 2006; Kawakatsu and Watada, 2007; Shiomi et al., 2008), such
45 images in the Hokkaido region have never been obtained except for a depth
46 range shallower than 100 km (Hirahara et al., 2005). This difference may be
47 related to some specific features in this region, for example, (1) the trench
48 axis of the Pacific Ocean is farther from the coast of the island arc than the
49 other areas in Japan, so that the upper boundary beneath stations on land
50 is relatively deep, resulting in very weak *ScSp* signals, (2) the majority of

Hokkaido is covered with soft and relatively thick surface layers, generating high levels of background noise that prevent the detection of weak *ScSp* signals, and (3) the upper boundary of the Pacific plate beneath in the Hokkaido region seems to be not as sharp as that beneath the other regions of Japan, making the amplitude of *ScSp* phases relatively small. For similar reasons, the seismicity related to the Pacific plate subducting in the Hokkaido region has also been investigated the least in Japan, in spite of dense seismic networks. Katsumata et al. (2003) was the first systematic search to obtain a reliable three-dimensional distribution of earthquakes associated with the Pacific plate in the Hokkaido region, utilizing the temporary deployment of many new stations in addition to Hi-net stations.

This study aims to estimate three-dimensional geometry of the upper plate boundary (or a suite of two-dimensional depth distribution) with *ScSp* phases recorded with Hi-net stations in Hokkaido. Since individual *ScSp* phases recorded in this region are very weak, we enhance their signals with several array processing techniques such as slant stacking, non-linear inversion with ray tracing, and frequency-wavenumber spectral analysis, to estimate the *ScS* to *P* conversion depth at a given small area. We shall compare our results with the seismic event distribution obtained by Katsumata et al. (2003), and discuss the spatial seismic pattern and its related stress field in the Pacific plate subducting in the Hokkaido region.

2. Data and Pre-processing

We collected the seismograms recorded at the total of 112 stations in Hokkaido as a part of the seismic network, Hi-net, deployed over the Japanese

75 islands (Obara, 2003). It is desirable that an impulsive *ScS* wave of large
76 amplitude is incident to the upper plate boundary upwards as vertically as
77 possible for our purpose. After the establishment of Hi-net, the largest deep
78 event in this region occurred on 17 November 2002 in the south of the Sea
79 of Okhotsk at the focal depth of 476.8 km with $Mw = 7.3$. We used seismic
80 records from this event. The distribution of the stations used in this study
81 is shown in Figure 1. The focal mechanism in this figure is taken from the
82 Global CMT catalog (Ekström et al., 2005).

83 In preprocessing of the present data, we removed instrumental response
84 of the observed three-component velocity waveform records, and transformed
85 them into displacement data. The obtained horizontal two-component data
86 were rotated into radial and transverse components, followed by their band-
87 pass filtering between 0.1 and 0.5 Hz for the stacking analysis presented in
88 the next section and between 0.5 and 1.5 Hz for the following f - k spectral
89 analysis. As explained later, the spatial extent of stations for the stacking
90 analysis is much larger than that of the f - k spectral analysis, resulting in a
91 lower frequency filter in the former case. *ScS* phases are clearly identified at
92 this stage for all the seismograms.

93 Since these *ScS* waves were radiated from the source in a very limited
94 range of azimuth, we can ignore all the complicated source effects, path
95 effects between the source and the upper plate boundary and site effects by
96 shifting all the *ScS* phases to be aligned in time. The *ScS* phase at the
97 station SMPH is the clearest of all, setting it as the reference station. We
98 take its cross-correlations with other *ScS* waveforms, shifting seismograms
99 in time to achieve the maximum correlations. In other words, we arrange

100 seismograms as if the *ScS* phase arrives simultaneously at each station. In
 101 order to avoid any possible anisotropic effects, we utilized radial-component
 102 *ScS* phases because we shall focus on the converted *ScSp* phases in the vertical
 103 component in the subsequent analyses. After the above shift of seismograms
 104 in time, we use vertical seismograms in which the amplitudes of *ScSp* are the
 105 largest.

106 **3. Stacking analysis and reconstruction of slab geometry**

107 *3.1. Slant stack analysis*

108 Very weak *ScSp* signals recorded in this region prevent us from any stan-
 109 dard analyses and inversion schemes to estimate the image of the plate bound-
 110 ary. Since the overall geometry of the subducting Pacific plate is known in
 111 this region, we first divide the studied region into several rectangular blocks
 112 in the plate dip direction. Then, we attempt to obtain the 2-D geometry
 113 of the upper plate boundary in each block, using the slant-stack technique
 114 of seismograms at stations located in a given block. Figure 2 shows an ex-
 115 ample of the present analysis. Along the dip direction of the Pacific plate,
 116 we take a block of 90 km wide, dividing it into sub-blocks perpendicular to
 117 the original block (i.e., along the trench axis) of 20 km wide. Assuming that
 118 the conversion points from *ScS* to *P* wave at the upper plate boundary share
 119 a common depth, the *ScSp* phase arrives simultaneously at all the stations
 120 within a given sub-block. We simply stack all the time-domain waveforms in
 121 a sub-block to enhance *ScSp* signal, resulting in a representative *ScSp* wave-
 122 form at each sub-block, as shown in Figure 2b. The resulted *ScSp* phase is
 123 indeed slightly clearer than that in original waveforms.

124 We then apply the slant stack technique to the already stacked waveforms
 125 in each sub-block. In a given block, a plane *ScSp* wave is assumed to arrive
 126 at a fictitious station in the center of each sub-block. Then, the *ScSp* signal
 127 should be represented by the stack of these seismograms with a constant
 128 slowness p , or with a time lag proportional to the distance from a reference
 129 point. We shift a seismogram of the j -th sub-block with the distance D_j from
 130 the reference point by $\tau_j = D_j \cdot p$. We stack seismograms in the slowness
 131 range between -12 s/km and zero (e.g., Kawakatsu and Niu, 1994). In this
 132 study, we employ N th-root stacking (Kanasewich, 1973) in order to enhance
 133 weak *ScSp* signals as much as possible. The stacked value $y_i(p)$ at time i is
 134 defined by

$$y_i(p) = R_i(p) | R_i(p) |^{N-1} \quad (1)$$

135 where

$$R_i(p) = \frac{1}{K} \sum_{j=1}^K \text{sgn}(w_j(i + \tau_j)) | w_j(i + \tau_j) |^{1/N} \quad (2)$$

136 $w_j(i)$ is the amplitude of the waveform of the j -th sub-block at time i , K is the
 137 number of sub-blocks in the given block, and sgn represents the sign of a value
 138 (i.e., +1 for a positive value, -1 for a negative value and 0 for zero). The above
 139 result in the case of $N=1$ is reduced to a simple linear stack. The optimal
 140 value of N that enhances signals relative to noise depends on the quality of
 141 data, particularly how much coherent components are contaminated in noise.
 142 After several tests with various values of N , we found that *ScSp* is the most
 143 prominent with our present data set in the case of $N=2$.

144 Stacking seismograms with various values of slowness p as explained above
 145 (Figure 2b), we obtain a diagram of the stacked waveforms in the time-
 146 slowness domain. We plot their envelopes in this diagram, using the Hilbert

147 transform of the stacked waveforms (Figure 2c). The maximum in this figure
 148 should correspond to the travel-time and slowness of the *ScSp* phase in the
 149 given block. In this example, we obtain $t=-25.0$ sec and $p=-7.25$ km/deg.
 150 We thus estimate the arrival time and slowness of the *ScSp* phase relative to
 151 the *ScS* phase in each block, assuming that the angle of the corresponding
 152 part of the subducting plate is constant. With reasonable depth distributions
 153 of P and S waves above the upper plate boundary, we can pinpoint the depth
 154 and horizontal location of the conversion point from *ScS* to *P* phase. These
 155 results for five blocks in the studied region are summarized in Figure 3.
 156 All the maxima in the time-slowness diagram are quite clearly identified,
 157 so that we confirm that the present waveforms contain sufficient energy of
 158 the *ScSp* phase although we cannot find such signals clearly in the original
 159 seismograms.

160 3.2. *Non-linear parameter search for slab geometry*

161 The slant-stack approach assumes that a plane *ScSp* wave is incident at
 162 stations in each block. This assumption may be too brave because station
 163 locations in a given block are spread over 200 km along its dip direction. We
 164 therefore introduce a new approach to determine 2-D geometry of the upper
 165 boundary in each block, by stacking seismograms with *ScSp* with dip angle
 166 of the boundary to vary freely. We search for the optimal 2-D geometry
 167 of the upper boundary by stacking *ScSp* signals based on this flexible slab
 168 geometry. The shape of each 2-D upper plate boundary is expressed by
 169 cubic spline functions with discrete grid points along the plate (Figure 4a).
 170 We trace rays of *ScSp* phase with the assumed plate geometry to compute
 171 ray-theoretical travel time at the reference point of each sub-block. Strictly

172 speaking, it is the time lag from *ScS* phase. Based on the computed time lags,
 173 we stack all the seismograms (i.e., already pre-stacked within each sub-block)
 174 in a given block, searching for the maximum of the stacked seismograms
 175 that should correspond to the optimal plate geometry. This procedure is
 176 highly non-linear so that we estimate the optimal model parameters with
 177 the Neighbourhood Algorithm, called NA hereafter (Sambirdge, 1999).

178 For each profile of the upper boundary along the dip of the Pacific plate
 179 (i.e., beneath each block of Figure 3), we assign seven points of 100, 200,
 180 300, 400, 500, 600 and 800 km in depth away from the trench axis as model
 181 parameters, which forms the 2-D geometry of the upper boundary by a cubic
 182 spline function (Figure 4a). For an assigned geometry (called a plate model
 183 hereafter), we trace rays of *ScSp* for a plane *ScS* wave incident from below
 184 vertically. As shown in Figure 1, epicentral distances in this study are less
 185 than eight degrees. Even though *ScS* is radiated from a point-like source,
 186 the above assumption (i.e., vertical plane-wave incidence) is sufficiently valid,
 187 because the slowness of *ScS* at each station is as small as 1 sec/deg.

188 The velocity model ak135 (Kennett et al., 1995) in Figure 4b is used,
 189 by adding a velocity discontinuity of 10 % at the plate boundary. The un-
 190 certainty of this velocity jump should affects the amplitude of *ScSp* or the
 191 conversion rate from *ScS* to *P* but not their travel time difference, which is
 192 essential in this study. With the dip angle of 30 degrees, for example, the
 193 amplitude ratio of *ScSp/ScS* is changed from 0.07 to 0.12 for velocity con-
 194 trast at the boundary from 5 to 10 % while the travel time difference by less
 195 than 1 sec. With a steeper dip angle, the amplitude ratio changes a little,
 196 so as the travel time difference. Since the dip angle of the Pacific plate in

197 the Hokkaido region is about 30 degrees, our study to retrieve the depth
 198 profile of the upper boundary, based on not amplitude ratio but difference
 199 in travel time, should not be affected by the choice of the velocity contrast.
 200 (See a rather critical case in contrast with a nearly horizontal dip angle in
 201 the Shikoku-Chugoku, Japan, region in Nakanishi (1980)). We employed a
 202 standard ray-tracing scheme for a 1-D velocity structure with one discon-
 203 tinuous boundary (i.e., the upper plate boundary). Based on the computed
 204 travel times of the *ScSp* phase incident to sub-blocks of each block, we stack
 205 all the seismograms in the block, similar to the slant stack in the previous
 206 section.

207 For the optimal plate model, the stacked *ScSp* phase should have the
 208 maximum amplitude in the model space. The amplitude may vary in a
 209 complicated or non-linear manner with parameters of the plate model, so
 210 that we adopt the neighbourhood algorithm (NA). A highly non-linear problem
 211 may be difficult to solve because we must combine two conflicting factors:
 212 random sampling of possible model parameters and efficient iterative scheme
 213 to converge into the optimal model. The criterion to balance these two factors
 214 may tend to be subjective or a priori, including the present NA method. The
 215 main parameters for such a criterion in NA are the following two numbers: (1)
 216 N , the number of models generated in each iteration step of model parameter
 217 search and (2) M , the number of optimal models that lead to new N models
 218 in the subsequent iteration step. After several tests with various values of
 219 these two tunable parameters, we found that the case with $N=30$ and $M=10$
 220 yielded good results in our present data set and modeling.

221 Figure 5 shows an example of the results of the NA inversion, for block

222 2 in Figure 3. The top of Figure 5 shows the total of 6,500 plate models
 223 generated during the model parameter search with the NA. For each plate
 224 model, we computed the travel time difference between ScS and $ScSp$ phases
 225 at each sub-block, then stacked all the waveforms by each time difference, as
 226 shown in the bottom of Figure 5. We selected the best M models from N
 227 models for the subsequent iteration step, using a criterion with the spectral
 228 energy of the stacked seismograms in the time window of a possible $ScSp$
 229 arrival. After such iteration steps, the plate model to give the maximum
 230 $ScSp$ energy was judged to be the best. Figure 6 shows the best plate models
 231 for the five blocks in Figure 3, together with rays of $ScSp$ phases. Compared
 232 with the preliminary results of the slant-stack analysis with the plate model
 233 of constant dip angles in the previous section, irregular undulations at plate
 234 boundaries are apparent with these models, implying the necessity of a de-
 235 tailed 2-D geometry for each block along the dip direction, to explain our
 236 present $ScSp$ data. We combine the plate models for the five blocks with a
 237 cubic spline function in horizontal directions along the trench axis, resulting
 238 in the 3-D plate model shown in Figure 7. This figure includes ray paths of
 239 $ScSp$ for block 4.

240 4. f - k Spectral Analysis

241 The stacking analysis in the previous section may be appropriate to ob-
 242 tain the overall geometry of the upper plate boundary in this region, because
 243 the number of stations is still not sufficient to identify its detailed irregular-
 244 ity, particularly we needed to stack waveforms at several stations of a given
 245 sub-block into one data set to be inverted. We also introduced five 2-D plate

246 models along dip directions. Station pairs are apart more than 200 km in
 247 some cases for which good cross-correlation may not be expected due to com-
 248 plex subsurface structure of this region (Katsumata et al., 2003). Since we
 249 can only estimate a 2-D profile of conversion points (i.e., depth and location)
 250 in each case, more accurate and reliable results on the upper boundary may
 251 be obtained in the use of an additional type of array-type approaches. Here,
 252 we apply the frequency-wavenumber spectral analysis (called f - k analysis),
 253 assuming a seismic array consisting of a given station and its adjacent sta-
 254 tions (e.g., Capon, 1973; Aki and Richards, 1980). As schematically shown in
 255 Figure 8, we set one reference station and its adjacent stations, assuming that
 256 a plane wave is incident locally with wavenumber vector (k_x, k_y) and angu-
 257 lar frequency ω . Changing the values of wavenumber vector components, we
 258 search for the maximum power spectrum by taking their cross-correlations at
 259 each frequency. The spatial extent of each array is about 50 km, so that the
 260 assumption of a constant slowness within an array is valid, while we allow
 261 slowness to vary from array to array, depending on the 3-D geometry of the
 262 upper boundary.

263 With the travel time t_0 of a specific wave ($ScSp$ phase in this case) at the
 264 reference station of (x_0, y_0) , the time shift t_i for the record at the i -th station
 265 located at (x_i, y_i) at frequency ω may become

$$t_i = t_0 + \frac{k_x}{\omega}(x_i - x_0) + \frac{k_y}{\omega}(y_i - y_0). \quad (3)$$

266 By summing the total of N records $w_i(t)$ at the i -th station by the time shift
 267 t_i in equation (3), we get the following beam output:

$$b(k_x/\omega, k_y/\omega, t) = \frac{1}{N} \sum_{i=1}^N w_i(t + t_i). \quad (4)$$

268 The f - k power spectrum is the Fourier transform of the auto-correlation
 269 (denoted by $\langle \rangle$) of beam outputs:

$$P(k_x, k_y, \omega) = \int_{-\infty}^{\infty} d\tau \cdot \exp(i\omega\tau) \langle b(k_x/\omega, k_y/\omega, t) \cdot b(k_x/\omega, k_y/\omega, t + \tau) \rangle. \quad (5)$$

270 At a given frequency ω , the maximum of these power spectra in the wavenum-
 271 ber domain gives the slowness and back-azimuth of the arriving phase as
 272 follows:

$$p = \frac{\sqrt{k_x^2 + k_y^2}}{\omega} \quad \text{and} \quad \theta = \tan^{-1}(k_x/k_y). \quad (6)$$

273 In this study, we assume each of all the 112 stations as a reference station
 274 with its adjacent stations in the radius of 50 km. The average number of
 275 stations for each array is about seven. Figure 9 shows the results of the f - k
 276 spectral analysis for seven example reference stations in the frequency range
 277 from 0.5 to 1.5 Hz. The peak of power spectra in the (k_x, k_y) domain should
 278 correspond to the $ScSp$ phase arriving at each array, and we can estimate
 279 its slowness and back-azimuth from its wavenumber vector by equation (6).
 280 The dotted lines in the right of Figure 9 represent the arrival times of the
 281 maximum beam output, which should correspond to $ScSp$ phases.

282 Although we attempted to identify the spectral peaks for all the 112
 283 stations in a wide range of frequencies, we could obtain the limited number
 284 of successful cases. Correlations among waveforms within each array are poor
 285 in most of cases, probably because the signals of $ScSp$ phases in this area are
 286 indeed very weak and the average radius of arrays (about 50 km) is relatively
 287 large, that is, the spatial density is still not sufficient even for the present
 288 distribution of Hi-net stations. Correlations at low frequency are relatively
 289 high, as shown in Figure 9, but the signals of $ScSp$ are weak, while low

290 correlations even with apparent large signals at high frequency. As a result,
 291 we could identify clear spectral peaks (i.e., *ScSp* phase) for 21 stations in the
 292 frequency range of Figure 9, that is, from 0.5 to 1.5 Hz. In these successful
 293 cases, we projected the ray path from a given station backwards, using the
 294 estimated wavenumber vector (k_x, k_y) or p and θ with the velocity model
 295 ak135, similar to the stacking analysis. By the travel-time difference from
 296 that of the *ScS* phase, we estimated the depth and location of the conversion
 297 point of the *ScSp* phase (i.e., the upper plate boundary) for each station or
 298 array.

299 Since the number of the estimated depths and locations of the upper plate
 300 boundary is limited with our present data set, we could not make a complete
 301 3-D map of the boundary in a similar manner to the standard seismic tomog-
 302 raphy. Since we already obtained a plate model by the stacking-NA approach
 303 in the previous section, we used the results of the f - k analysis to revise this
 304 plate model. The left of Figure 10 shows the contours of the depth distribu-
 305 tion of the plate model derived from the NA inversion in the previous section
 306 with the 21 conversion points (i.e., the upper plate boundary) estimated by
 307 the f - k analysis. While the previous stacking analysis provides the overall
 308 geometry of the plate model, the present f - k analysis gives more accurate
 309 estimation of its depths and locations although we can only obtain such val-
 310 ues at the limited number of points. In other words, these two results are
 311 complimentary, so that we obtain a reliable and accurate final plate model in
 312 this region from the combination of the two independent analyses. The right
 313 of Figure 10 shows the cross section of the final upper plate boundary in the
 314 rectangular section of the left, together with its event locations (Katsumata

315 et al., 2003).

316 The present final result does not differ significantly from previous works
317 such as Umino et al. (2002). Nevertheless, it may be the first opportunity
318 that we can compare the plate model (i.e., the upper boundary) with the
319 associated seismicity for the Pacific plate in the Hokkaido region where both
320 plate structure and seismicity have been least investigated in Japan, due to
321 the difficult factors mentioned in the Introduction. Katsumata et al. (2003)
322 revealed a double seismic zone in the plate down to the depth of about 150
323 km, then the two zones appear to be converged below this depth. The right
324 of Figure 10 clearly supports that the upper seismic zone shifts into the lower
325 zone systematically, departing from the upper plate boundary in this depth
326 range. The upper boundary at the depth of about 200 km is slightly bumped
327 upwards in a convex manner. One may claim velocity anomaly overlying this
328 part of the slab to be responsible for the above apparent localized bump in
329 plate geometry. If it were the case, a part of extremely negative anomaly
330 in V_s/V_p would be required, because of the present use of the travel time
331 difference between $ScSp$ and ScS . Such an anomaly might be possible at
332 a very localized part of mantle wedge. Nevertheless, tomographic study
333 by Katsumata et al. (2006) did not detect any large anomalies in terms of
334 V_s/V_p that would affect the local depth profile of the slab, as we obtained in
335 this study. Complex flexure of a slab has been reported in several areas, for
336 example, the Philippines Sea plate in southwest Japan, as studied in detail by
337 Shiomi et al. (2004, 2008); Tonegawa et al. (2009). Implying its structural
338 effect on the variation of event locations shown in Figure 10, relationship
339 between stress state and possible factors to generate deep seismic events

340 should be extremely important in this not-well investigated subduction zone.

341 5. Conclusions

342 Applying several array processing techniques to the Hi-net data with a
343 very large deep adjacent event, we obtained the 3-D geometry or the 2-D
344 distribution of the upper boundary of the Pacific plate subducting beneath
345 Hokkaido, Japan. We attempted to enhance the signals of *ScSp* phase con-
346 verted from *ScS* phase at the upper boundary although original *ScSp* phases
347 in record are too weak to be identified.

348 We first confirmed the existence of *ScSp* signals in our data set by simple
349 slant-stacking analysis for blocks in dip directions, assuming a constant dip
350 angle in each block. Introducing general 2-D profiles of the upper boundary,
351 we calculated ray paths of *ScSp* phases for vertically upgoing plane *ScS* waves.
352 The travel time (i.e., time lag) was computed for *ScSp* relative to *ScS* at
353 each sub-block with these rays, and records were stacked with the time lag.
354 The optimal 2-D profile of the upper boundary was then inverted for each
355 block, using the Neighbourhood Algorithm (NA) for this highly non-linear
356 problem. Combining the results of all the blocks, we established the overall 3-
357 D geometry of the upper plate boundary in this region. In order to utilize the
358 advantage of the dense Hi-net data as seismic arrays, we further conducted *f*-
359 *k* spectral analysis for arrays composed of a reference station and its adjacent
360 stations. We searched for the maximum of beam output in the wavenumber
361 domain for the slowness and back azimuth of the arriving *ScSp* phase at
362 each array. In spite of difficult observational conditions in this region, we
363 could identify *ScSp* signals for 21 stations or arrays in the frequency range

364 from 0.5 to 1.5 Hz. Tracing a ray backwards with the estimated slowness
 365 and back azimuth at each array and using the time lag of each *ScSp* phase,
 366 we estimated the depth and location of the *ScS-ScSp* conversion point, that
 367 is, the upper plate boundary. This procedure revised the 3-D geometry of
 368 the plate model obtained in the previous step. In a cross section across the
 369 center of Hokkaido, we found close relationship between the seismicity in the
 370 double seismic zone and the irregularity of the upper plate boundary from
 371 150 to 200 km depth.

372 The Hi-net in Japan is still one of the best local seismic arrays over the
 373 world for their quality, density, aperture and uniformity in data (Obara,
 374 2003). The subducting plates have been investigated in detail by a num-
 375 ber of recent researches, including seismic tomography (Zhao et al., 1994;
 376 Nakajima et al., 2001) and receiver-function analysis (Shiomi et al., 2004;
 377 Tonegawa et al., 2006; Kawakatsu and Watada, 2007). Although these stud-
 378 ies proposed many interesting features of slab dynamics in and around Japan,
 379 investigations of the structure associated with the Pacific plate subducting
 380 in the Hokkaido region have not been successful yet (Hirahara et al., 2005).
 381 Array analyses such as those presented in this study are essential to obtain
 382 the image of the upper plate boundary, the strongest structural boundary, in
 383 this specific subduction zone of Japan, which should be also useful to many
 384 subduction zones in the world.

385 Even with the present Hi-net data, we could utilize cross-correlations
 386 among the observed seismograms only in a relatively low frequency range,
 387 say, lower than 1 Hz. We cannot therefore expect good spatial resolution of
 388 the image of the plate boundary with *ScSp* phases. Since the present signal

level was not sufficient for *ScSp* phases even after stacking, we could only use their time lags but not other kinds of *ScSp* information, such as the amplitude ratio of *ScSp/ScS* and its frequency dependency, which would lead us to quantitative estimations of physical properties of the upper plate boundary. For example, if data from several deep adjacent events are available, we may stack records of not only neighbouring stations but also all the events in order to obtain large *ScSp* signals. Collecting data for more deep large adjacent events in this region and introducing more effective array processing methods, we may enhance *ScSp* signals to retrieve any additional pieces of information on the physical states of the upper plate boundary in this seismically active and tectonically important region in the future.

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Figure 1: Location of Hi-net stations in Hokkaido, Japan, represented by solid circles, and the epicenter of the used event on 17 November 2002 of 476.8 km in depth. Focal mechanism from the Global CMT catalog is also shown.

Figure 2: (a) Example of blocks and sub-blocks for stacking analysis. The star represents the location of the reference point for stacking, (b) pre-stacked waveforms in each sub-block aligned with the arrival time of ScS phase in red, and (c) amplitude contours of their slant stacking with the maximum signal corresponding to the dotted line in (b).

Figure 3: Maps of five blocks, and their amplitude contours of each block derived from the slant stack: blocks 1 and 2 in the left and blocks 3, 4 and 5 in the right.

Figure 4: (a) Seven parameters for the plate model, and (b) reference velocity model of ak135.

Figure 5: Total of the 6,500 plate models and the optimal model (thick blue line) derived from the model parameter search with the Neighbourhood Algorithm, together with waveforms to be stacked for block 2. All the plate models are ranked in order of the smaller misfit, and are plotted with colors varying from green (larger misfit) to yellow (smaller misfit). For the optimal model, waveforms are stacked along the dotted line.

Figure 6: Optimal plate models and ray paths of $ScSp$ phases for blocks 1, 2, and 3 in the left, and blocks 4 and 5 in the right.

Figure 7: Three-dimensional view of the inverted upper boundary of the Pacific plate estimated from the 2-D five plate models in Figure 6 with a cubic spline function, and ray paths of $ScSp$ for block 4.

Figure 8: Schematic view of f - k spectral analysis. A plane-wave is incident to the reference station located at (x_0, y_0) with adjacent stations at (x_i, y_i) , and an example of beam outputs with the corresponding $ScSp$ phase represented by the dashed line.

Figure 9: Examples of f - k spectral analysis. The reference and adjacent stations in the left, contours of power spectra in the wavenumber domain in the center, and corresponding beam outputs in the right with the dotted lines as the estimated $ScSp$ arrivals.

Figure 10: (a) Comparison of the contours for depths of the upper plate boundary derived from the NA algorithm with the conversion depths of $ScSp$ phase estimated by the $f-k$ spectral analysis, and (b) plate geometry in the region represented by the block of (a) with revision of the conversion depths derived from the $f-k$ spectral analysis, together with its earthquake locations obtained by Katsumata et al. (2003).