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Citation	Physics of the Earth and Planetary Interiors, 183(1-2), 63-72 <a href="https://doi.org/10.1016/j.pepi.2010.06.006">https://doi.org/10.1016/j.pepi.2010.06.006</a>
Issue Date	2010-11
Doc URL	<a href="http://hdl.handle.net/2115/44908">http://hdl.handle.net/2115/44908</a>
Type	article (author version)
File Information	PEPI183-1-2_63-72.pdf



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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 **1. Introduction**

2       Regions around subducting plates or slabs are recognized to be highly  
3 anomalous in the propagation of seismic waves for a long time. Tomographic  
4 studies have been widely conducted in subduction zones over the world to  
5 determine large-scale spatial distribution of P and/or S-wave velocities (e.g.,  
6 Fukao et al., 2001). These studies with travel-time data are, however, not  
7 suitable to retrieve sharp discontinuities or boundaries in velocity. There are  
8 several seismic approaches appropriate to structural boundaries like upper  
9 boundary of a subducting plate. The upper boundary is an important, sharp  
10 discontinuity of the earth's interior, due to its dominant role over various  
11 geodynamic activities in a subduction zone. It has been studied extensively  
12 using focal mechanisms in slab, reflected and/or refracted waves for local or  
13 artificial events, and receiver function analysis for teleseismic events. Never-  
14 theless, one of the most straightforward and effective seismic approaches to  
15 focus on the profile of the upper plate boundary is the use of *ScSp* phase.

16       *ScSp* is the wave observed as a precursor of *ScS* that is reflected from the  
17 core-mantle boundary (CMB) and then propagates upwards nearly vertically.  
18 It is converted from S (*ScS*) to P wave at the upper boundary. In comparison  
19 with *ScS*, the measurement of *ScSp* eliminates all the complicated effects such  
20 as source, station site and lateral heterogeneities other than the upper plate  
21 boundary, so that the value of boundary depth can be estimated directly with  
22 good precision. Okada (1979) was the first attempt to profile a subducting  
23 plate with the *ScSp* phase observed in Hokkaido, Japan. Several researches  
24 on *ScSp* phases have been followed in other parts of the world (e.g. Snoke  
25 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

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

62 This study aims to estimate three-dimensional geometry of the upper  
63 plate boundary (or a suite of two-dimensional depth distribution) with *ScSp*  
64 phases recorded with Hi-net stations in Hokkaido. Since individual *ScSp*  
65 phases recorded in this region are very weak, we enhance their signals with  
66 several array processing techniques such as slant stacking, non-linear inver-  
67 sion with ray tracing, and frequency-wavenumber spectral analysis, to esti-  
68 mate the *ScS* to *P* conversion depth at a given small area. We shall compare  
69 our results with the seismic event distribution obtained by Katsumata et al.  
70 (2003), and discuss the spatial seismic pattern and its related stress field in  
71 the Pacific plate subducting in the Hokkaido region.

## 72 **2. Data and Pre-processing**

73 We collected the seismograms recorded at the total of 112 stations in  
74 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  $\text{sgn}$  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  $\omega$ . 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  $\omega$  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  $\omega$ , 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  $\theta$  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

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

#### 400 **Acknowledgments**

401 The waveform data used in this study were provided by the Institute of  
402 Seismology and Volcanology (Hokkaido University) and Japan Meteorological  
403 Agency. Part of the data was downloaded from the website of Hi-net operated  
404 by the National Research Institute for Earth Science and Disaster Prevention  
405 of Japan. We thank Malcolm Sambridge for the provision of the NA code,  
406 as well as Dr. G. Helffrich and an anonymous reviewer for their many useful  
407 comments. This study was partly supported by Grant-in-Aid for Scientific  
408 Research (No. 16075201) from the Ministry of Education, Culture, Sports,  
409 Science and Technology of Japan. Maps and diagrams were generated using  
410 the Generic Mapping Tools (Wessel and Smith, 1998),

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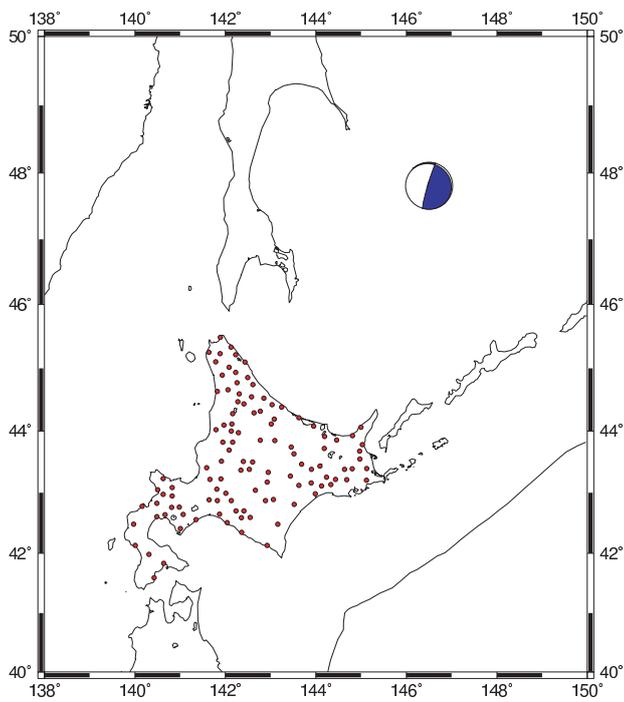


Figure 1: Location of Hi-net stations in Hokkaido, Japan, represented by solid circles, and the epicenter of the used event on 17 November 2002 of 476.8 km in depth. Focal mechanism from the Global CMT catalog is also shown.

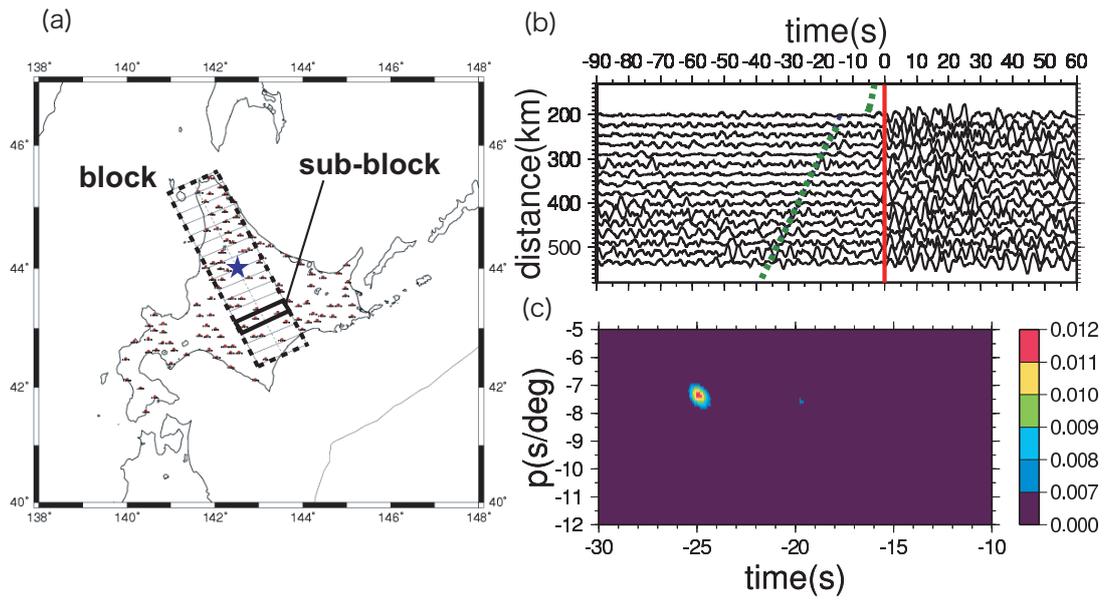


Figure 2: (a) Example of blocks and sub-blocks for stacking analysis. The star represents the location of the reference point for stacking, (b) pre-stacked waveforms in each sub-block aligned with the arrival time of *ScS* phase in red, and (c) amplitude contours of their slant stacking with the maximum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

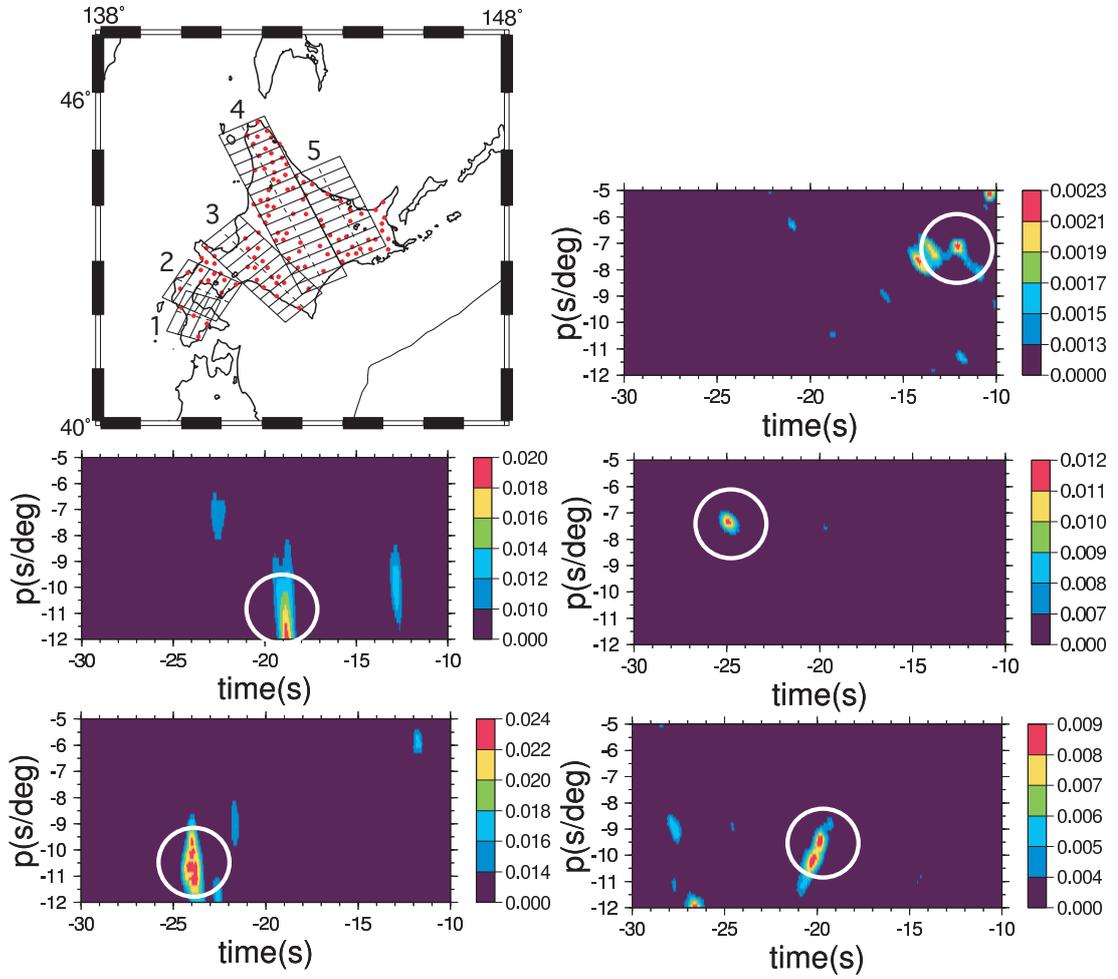


Figure 3: Maps of five blocks, and their amplitude contours of each block derived from the slant stack: blocks 1 and 2 in the left and blocks 3, 4 and 5 in the right.

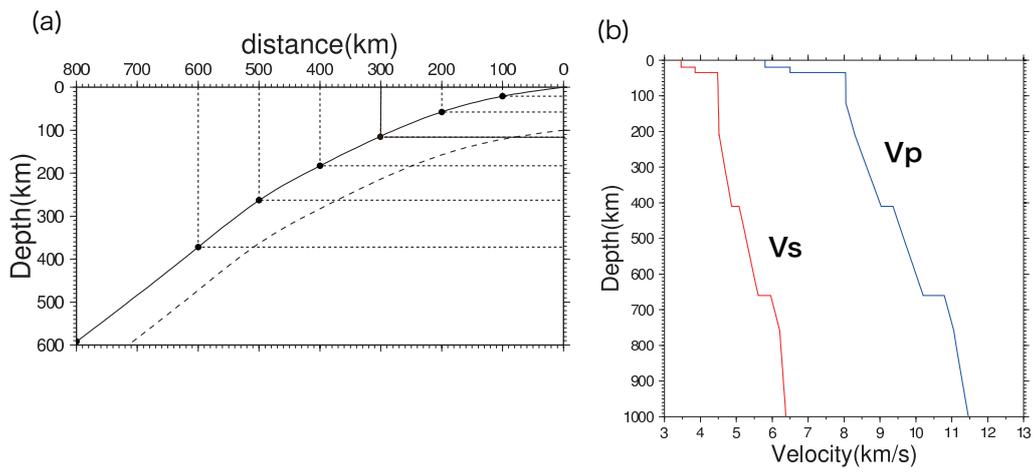


Figure 4: (a) Seven parameters for the plate model, and (b) reference velocity model of ak135.

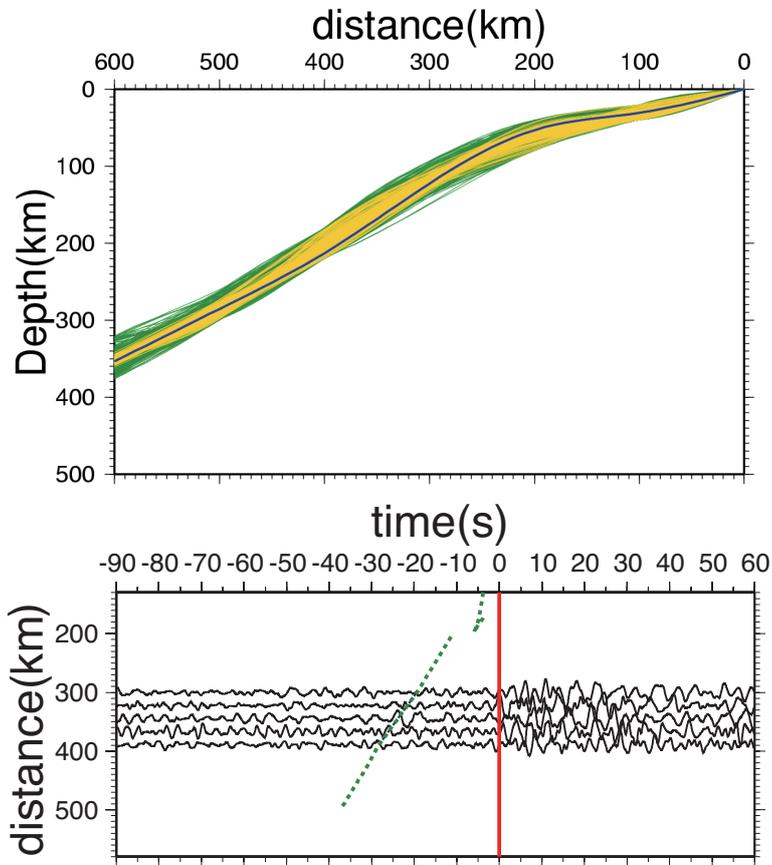


Figure 5: Total of the 6,500 plate models and the optimal model (thick blue line) derived from the model parameter search with the Neighbourhood Algorithm, together with waveforms to be stacked for block 2. All the plate models are ranked in order of the smaller misfit, and are plotted with colors varying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

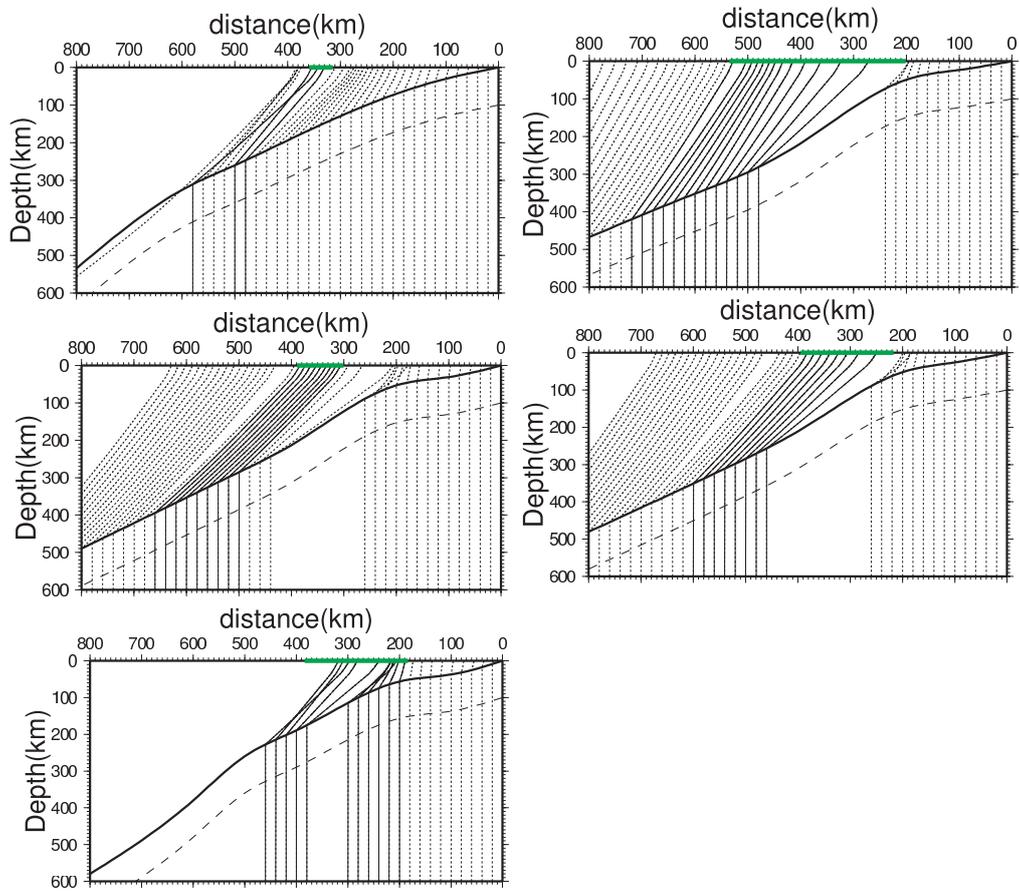


Figure 6: Optimal plate models and ray paths of  $ScSp$  phases for blocks 1, 2, and 3 in the left, and blocks 4 and 5 in the right.

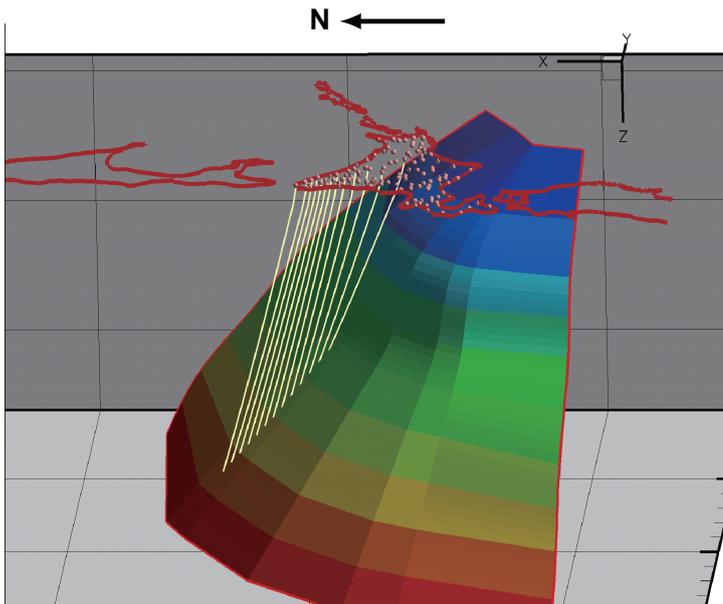


Figure 7: Three-dimensional view of the inverted upper boundary of the Pacific plate estimated from the 2-D five plate models in Figure 6 with a cubic spline function, and ray paths of  $ScSp$  for block 4.

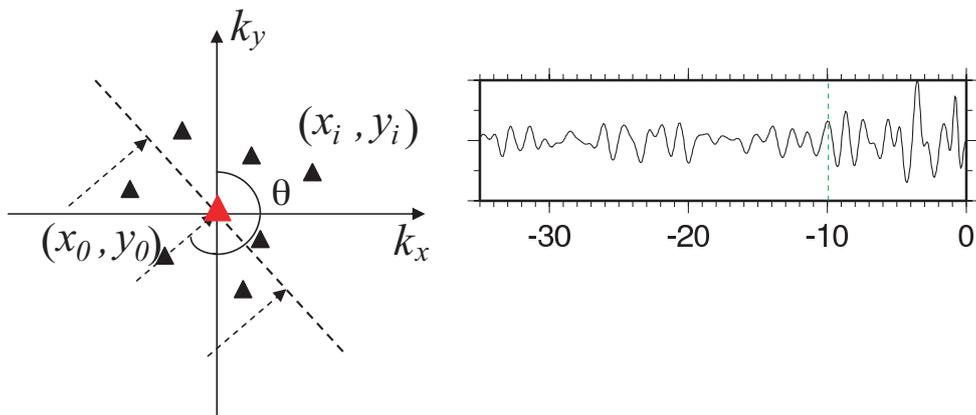


Figure 8: Schematic view of  $f-k$  spectral analysis. A plane-wave is incident to the reference station located at  $(x_0, y_0)$  with adjacent stations at  $(x_i, y_i)$ , and an example of beam outputs with the corresponding  $ScSp$  phase represented by the dashed line.

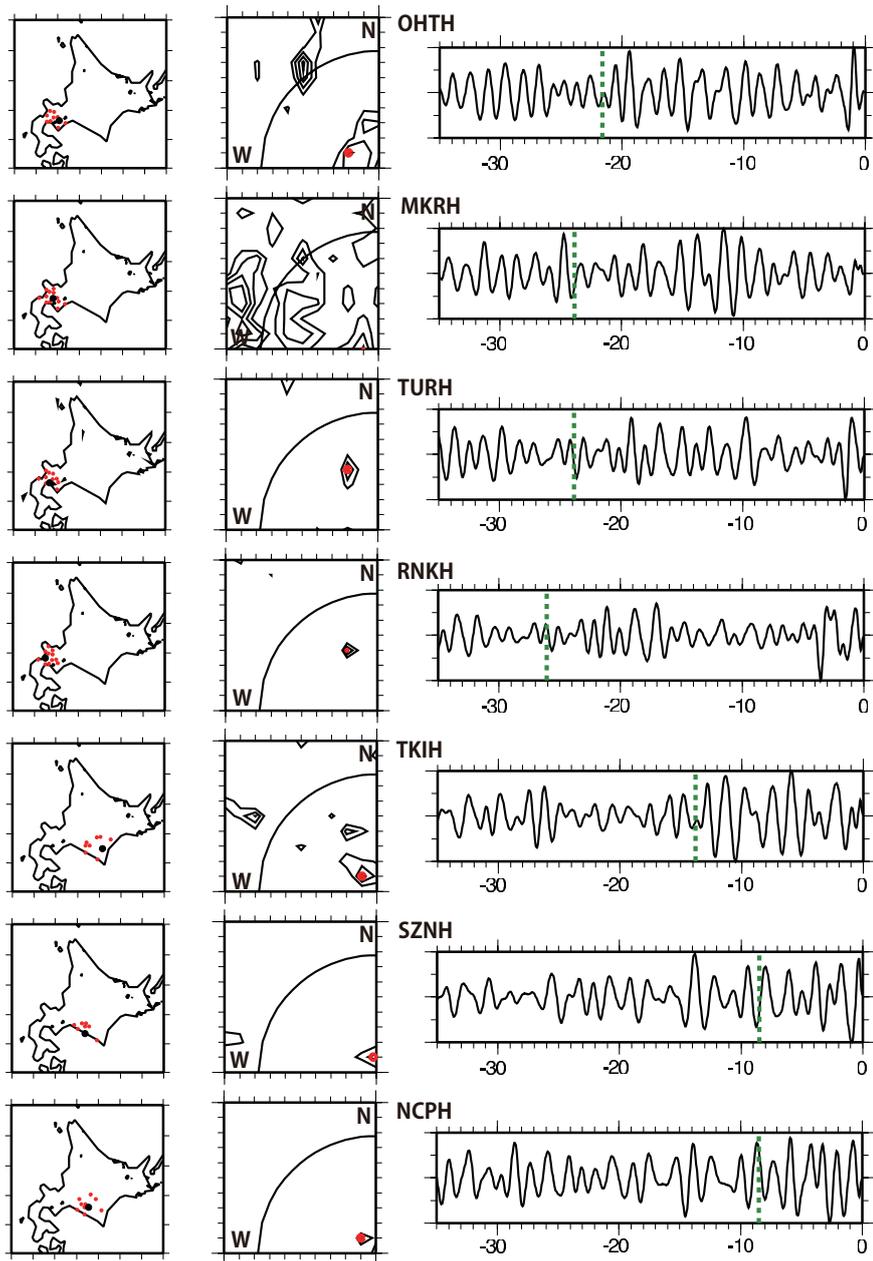


Figure 9: Examples of  $f$ - $k$  spectral analysis. The reference and adjacent stations in the left, contours of power spectra in the wavenumber domain in the center, and corresponding beam outputs in the right with the dotted lines as the estimated  $ScSp$  arrivals.

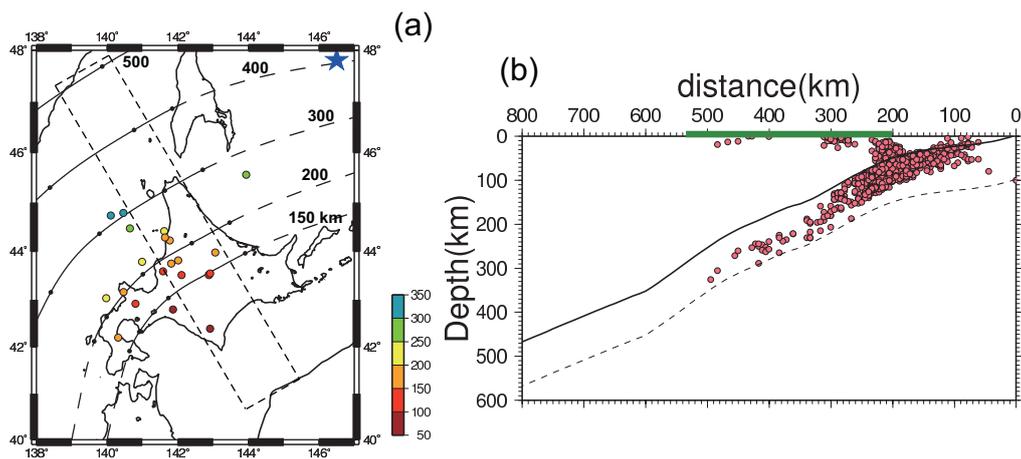


Figure 10: (a) Comparison of the contours for depths of the upper plate boundary derived from the NA algorithm with the conversion depths of  $ScSp$  phase estimated by the  $f-k$  spectral analysis, and (b) plate geometry in the region represented by the block of (a) with revision of the conversion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