

1 **Fine structure of tremor migrations beneath the Kii Peninsula, Southwest Japan,**
2 **extracted with a space-time Hough transform**
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16 **Key Points:**

- 17
- 18 • We developed a new method using a space-time Hough transform to objectively extract
19 tremor migrations.
 - 20 • Tremor migrations show fine structures in which multiple short-duration tremor
21 migrations occur during long-duration tremor migration.
 - 22 • The relation between migration speed (V_{mi}) and duration (T) follows $V_{mi} \propto T^{-0.5}$.

23 Abstract

24 Tectonic tremors occurring on subducting plate boundaries are known to migrate at
25 various timescales and migration speeds. Spatiotemporal patterns of tremor migration are key to
26 investigating the rupture growth of slow earthquakes. However, spatiotemporal patterns are not
27 sufficiently simple to visually define tremor migrations. This study developed a space-time
28 Hough transform to objectively extract tremor migrations. The space-time Hough transform
29 enables the extraction of multiple tremor migrations with various durations, migration directions,
30 and migration speeds. We applied this method to a catalog of tremors for the period from 2012 to
31 2014, which was determined from the data analysis of a dense seismic array deployed in the Kii
32 Peninsula, Southwest Japan. We successfully extracted 1,010 tremor migrations with durations
33 ranging from 10 min to 24 h. Along-strike migrations propagating southwestward were
34 predominant in the northeastern part of the Kii Peninsula, whereas those propagating
35 northeastward were principal in the southwestern part. Regarding the along-dip direction, tremor
36 migrations propagating in the up-dip directions were predominant in the deep part, and those
37 propagating in the down-dip directions were principal in the shallow part. The patterns of along-
38 strike migrations were related to the distribution of tremor energies, suggesting that tremor
39 migrations may be controlled by heterogeneous structures of frictional properties on the plate
40 interface. We further found that the migration speed is proportional to the inverse of the square
41 root of the duration. This relation implies that a diffusion process controls the growth of fault
42 ruptures behind tremor migrations.

43

44 Plain Language Summary

45 Tectonic tremors, which are continuous seismic signals with a predominant frequency of
46 2–8 Hz, have been discovered in subduction zones worldwide. The tremor activity continues for
47 several hours to days, and source locations migrate at speeds ranging from 10 km/day to 1,000
48 km/day. Tremor migrations provide us with key to understanding the associated fault ruptures.
49 However, their durations, migration directions, and migration speeds have variations that are too
50 large to be characterized visually. Therefore, it is necessary to objectively extract the
51 characteristics of tremor migrations. We developed a space-time Hough transform to extract
52 tremor migrations and applied it to data from a tremor catalog in the Kii Peninsula, Southwest

53 Japan. We extracted 1,010 tremor migrations with durations ranging from 10 min to 24 h. The
54 tremor migrations consist of long-duration migrations at slow speeds and short-duration
55 migrations at high speeds. The migration speeds decreased as the durations increased, suggesting
56 that there was a diffusive process behind tremor migrations. We identified four areas where
57 tremor migration was active. Migration patterns are different in each area and are related to the
58 distribution of tremor energies. The results suggest that the migration patterns may reflect the
59 frictional properties of the plate interface.

60 **Keywords:** Tectonic tremor, Tremor migration, space-time Hough transform, Kii Peninsula,
61 Rapid tremor reversal (RTR), slow earthquakes

62

63 1 Introduction

64 Slow earthquakes are phenomena in which fault ruptures grow more slowly than regular
65 earthquakes and have been observed in subduction zones worldwide (e.g., Obara & Kato, 2016;
66 Schwarz & Rokosky, 2007). Events with various durations detected using geodetic and seismic
67 data are categorized as slow earthquakes: low-frequency earthquake (LFE), tectonic tremor, very
68 low-frequency earthquake (VLFE), and slow slip event (SSE) (Obara & Kato, 2016). These
69 events occur in the deep or shallow extensions of megathrust-locked zones. Some previous
70 studies have detected slow earthquakes in advance of megathrust earthquakes (e.g., Ito et al.,
71 2013; Kato et al., 2012; Radiguet et al., 2016; Socquet et al., 2017). Therefore, it is important to
72 understand the physical processes of slow earthquakes and their connection to megathrust
73 earthquakes.

74 Slow earthquakes have a significant characteristic that the source locations migrate (e.g.,
75 Hirose & Obara, 2010; Shelly et al., 2007; Takemura et al., 2019). Tremor migrations are known
76 to exhibit the following characteristics depending on the timescale. Tremor migration with a
77 duration ranging from several hours to days is one of the major characteristics, and this tremor
78 migration is referred to as the main front in the present study. The main front propagates along
79 the strike of the subducting plate at a speed of approximately 10 km/day (e.g., Houston et al.,
80 2011; Obara, 2010). On a timescale of several hours, tremor migration at a speed of
81 approximately 100 km/day propagates in the reverse direction of the main front, which is called

82 rapid tremor reversal (RTR) (Houston et al., 2011). A tremor streak is a tremor migration that
83 propagates parallel to the subducting direction at a speed of approximately 1,000 km/day on a
84 timescale of several hours (e.g., Ghosh et al., 2010; Shelly et al., 2007). Fault ruptures of SSEs
85 are suggested to occur behind these tremor migrations because slow earthquakes occur
86 simultaneously (e.g., Hirose & Obara, 2010). Spatiotemporally coupled slow earthquakes are
87 referred to as episodic tremor and slip (ETS) (Rogers & Dragert, 2003). Therefore, by assuming
88 an ETS, it may be possible to investigate SSEs from tremor migrations (Bletery et al., 2017).
89 Tremor migration is key to understanding the growth of fault ruptures of slow earthquakes.

90 Tremor migrations have been discussed as the spatiotemporal evolutions of source
91 locations projected on the axis along the strike of a subducting plate (e.g., Houston et al., 2011;
92 Obara, 2010). However, when we discuss the patterns of tremor migrations in detail, it is not
93 sufficient to investigate the spatiotemporal evolutions of tremor migrations only along the strike
94 axis. We must consider the spatiotemporal changes on an axis perpendicular to the along-strike
95 axis as well. Moreover, because tremor migrations show complex spatiotemporal structures (e.g.,
96 Houston et al., 2011; Sagae et al., 2021), we need to develop a method to objectively extract
97 tremor migrations and investigate their fine structures. Previous studies have developed methods
98 for automatically extracting tremor migrations. Obara et al. (2012) extracted tremor migrations
99 beneath the Kii Peninsula in Southwest Japan by using a two-step process. First, a linear trend
100 was extracted from a spatiotemporal plot of tremor locations projected on the along-strike axis.
101 Second, a tremor migration was extracted by applying the principal component analysis to the
102 data for tremor locations and occurrence times. Bletery et al. (2017) extracted tremor migrations
103 in Cascadia by using a different two-step process from Obara et al. (2012). In the first step, a
104 clustering process was performed to identify clusters of tremor events and their durations. In the
105 next step, they extracted a tremor migration in the cluster by applying linear regression to
106 spatiotemporal plots of tremor locations projected on multiple axes.

107 These previous studies commonly estimated tremor migrations using linear regression on
108 the projected axis. Thus, their methods are constrained in that there is only one migration in one
109 time window or one cluster. To investigate the fine structures of tremor migrations, a method to
110 extract multiple tremor migrations, regardless of the lengths of the time windows and projected
111 axes, is necessary. Therefore, in the present study, we developed a space-time Hough transform
112 to objectively extract tremor migrations and applied the method to data of tectonic tremors

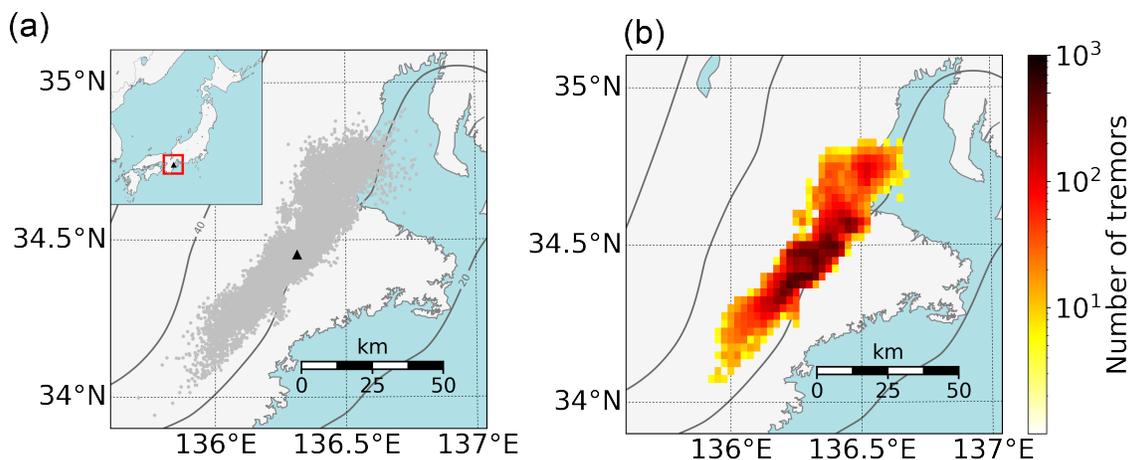
113 beneath the Kii Peninsula, Southwest Japan. We investigated the spatial characteristics of tremor
 114 migrations and discussed the factors controlling the growth of tremor migrations.

115 2 Data and Method

116 2.1 Data of tremor catalog

117 We used a catalog of tremors determined using a dense seismic array on the Kii
 118 Peninsula, Southwest Japan (Sagae et al., 2021). The catalog contained 25,155 tremor events that
 119 occurred between July 2012 and July 2014 (Figure 1). Tremor locations were determined by
 120 backprojection onto the interface of the Philippine Sea Plate (Hirose et al., 2008), and the
 121 number of detections was 2.2 times more than that obtained by the envelope correlation method
 122 (Obara, 2002) using network stations (Imanishi et al., 2011). The temporal resolution of the
 123 catalog was 1 min, and the uncertainty of the horizontal location was approximately 2.0 km on
 124 average. The tremor locations showed a belt-like distribution along the strike at depths of 30–35
 125 km (Figure 1a). The present study defined the region where the tremor events occur as the tremor
 126 zone. We clearly observed the locations where the number of tremor events was high or low
 127 (Figure 1b). During the two years, 12 tremor episodes with durations longer than 12 h were
 128 detected, in which various tremor migrations (e.g., RTR, tremor streak) were observed.

129



130 **Figure 1.** (a) Distribution of tremor locations beneath the Kii Peninsula, Southwest Japan from
 131 July 2012 to July 2014. The gray dots show tremor locations, and the black triangle shows the
 132 location of the seismic array. The solid curves show depth contours of the Philippine Sea Plate

133 (Hirose et al., 2008). **(b)** The number of tremor events. Colors show the cumulative number of
134 tremor events inside cells separated by intervals of 0.025° along longitude and latitude.

135

136 2.2 Space-time Hough transform

137 We focused on the Hough transform (Hough, 1962) for extracting multiple tremor
138 migrations in one time window. The Hough transform is an image-processing technique that can
139 extract straight lines from a 2-D image. In the 2-D Hough transform, any straight line is
140 represented by $\rho = x \cos \theta + y \sin \theta$, where x and y are the locations of an event point, ρ is the
141 distance from the origin to the straight line, and θ is the direction of perpendicular to the straight
142 line. Some combinations of (ρ, θ) express straight lines with different slopes that pass through an
143 event point (x, y) . These combinations of (ρ, θ) constitute a sine curve in the space of (ρ, θ) . The
144 best straight line is extracted by searching for the combination of (ρ, θ) where the sine curve
145 calculated for each event point intersects the most. A technique of counting the number of
146 intersections is called “vote”. Even if there are multiple straight lines in a 2-D image, the method
147 can distinguish these lines as different combinations of (ρ, θ) . Therefore, the 2-D Hough
148 transform enables us to extract multiple straight lines from the image by the technique of “vote”.
149 The Hough transform in 3-D space can be used to extract planes. In seismology, the 3-D Hough
150 transform has the potential to extract a fault plane by applying the method to the data of seismic
151 source locations (longitude, latitude, and depth). However, a previous study has established some
152 limitations of the Hough transform (Ouillon et al., 2008). First, the method cannot determine the
153 spatial extent of the straight line or plane because those represented by the combination of
154 parameters have an infinite length or size. Second, the Hough transform cannot deal with the
155 spatial spread of a straight line or plane (e.g., fault thickness) because the equations that express
156 them do not consider the uncertainty of the source location. Given our situation, we consider the
157 plate boundary as the fault plane by assuming that tremors occur on the plate interface because
158 previous studies have reported that LFEs and tremors occur near the plate boundary (e.g., Ghosh
159 et al., 2012; Shelly et al., 2006). Tremor migration (temporal evolution of tremor locations on the
160 plane) is represented by a straight line in a (2+1)-D space-time (2-D in the plane and 1-D in time)
161 by assuming a constant migration speed in a duration. However, the conventional Hough
162 transform cannot extract a straight line because additional information on the direction vector

163 within the plane is necessary. Therefore, we must introduce a new Hough transform to extract a
 164 straight line in the (2+1)-D space-time, considering the uncertainties of the tremor locations.

165 A previous study in astronomy extracted a straight line in the (2+1)-D space-time using
 166 the Hough transform to investigate the movements of celestial bodies in observed images (Morii,
 167 2019). Motivated by a previous study, we newly developed a space-time Hough transform to
 168 extract tremor migrations as straight lines in the (2+1)-D space-time. A new point of our method
 169 is that we can consider the uncertainties of tremor locations in the extraction of tremor migration
 170 by giving spatial spread to the straight line (by considering a cylinder). We consider (x, y, t) as a
 171 coordinate of a tremor event, where x is the longitude (the east is positive), y is the latitude (the
 172 north is positive), and t is the detection time. An arbitrary position of the straight line in the
 173 (2+1)-D space-time is represented using tyt -Euler angle (Figure 2). The tyt -Euler angle shows
 174 rotations of the coordinate system by θ , ϕ , and ψ , where θ is the zenith angle, ϕ is the azimuth,
 175 and ψ is the rotation angle. The details of the Euler angle are provided in the Supporting
 176 Information (Text S1). The equation of the straight line in (2+1)-D space-time is represented as
 177 follows:

178

$$179 \quad \begin{pmatrix} x \\ y \\ t \end{pmatrix} = (\rho + r \cos \lambda) \vec{\alpha} + (r \sin \lambda) \vec{\beta} + m \vec{\gamma}, \quad (1)$$

180

181 where

$$182 \quad \vec{\alpha} = \begin{pmatrix} -\sin \phi \sin \psi + \cos \theta \cos \phi \cos \psi \\ \cos \phi \sin \psi + \cos \theta \sin \phi \cos \psi \\ -\sin \theta \cos \psi \end{pmatrix}$$

$$183 \quad \vec{\beta} = \begin{pmatrix} -\sin \phi \cos \psi - \cos \theta \cos \phi \sin \psi \\ \cos \phi \cos \psi - \cos \theta \sin \phi \sin \psi \\ \sin \theta \sin \psi \end{pmatrix} \quad (2)$$

$$184 \quad \vec{\gamma} = \begin{pmatrix} \sin \theta \cos \phi \\ \sin \theta \sin \phi \\ \cos \theta \end{pmatrix},$$

185

186 ρ is the distance from the origin to the straight line (cylindrical axis), λ is the parameter that
 187 expresses the angle around the cylindrical axis measured counterclockwise from the vector $\vec{\alpha}$,
 188 and m is the parameter that determines the position on the straight line. r is the radius of the
 189 cylinder, with values ranging from zero to r_{max} , where r_{max} corresponds to the location
 190 uncertainty. $\vec{\gamma}$ is the unit direction vector of the straight line, $\vec{\alpha}$ is the unit vector in the same
 191 direction as the foot of the perpendicular line ($\rho\vec{\alpha}$), and $\vec{\beta}$ is the unit vector perpendicular to both
 192 $\vec{\alpha}$ and $\vec{\gamma}$. The vectors of $\vec{\alpha}$ and $\vec{\beta}$ are within the plane shown by the large blue circle in Figure 2a.
 193 Thus, any position of the cylinder in (2+1)-D space-time can be represented by four parameters
 194 (ρ, θ, ϕ, ψ). In particular, we can represent the migration speed as $\tan \theta$ and the migration
 195 direction as ϕ . When a tremor event is included inside the cylinder, the parameter m is
 196 eliminated from Equation 1:

197

$$198 \quad \begin{cases} X = \rho \sin \psi + r \sin(\lambda + \psi) = -x \sin \phi + y \cos \phi \\ Y = \rho \cos \psi + r \cos(\lambda + \psi) = x \cos \theta \cos \phi + y \cos \theta \sin \phi - t \sin \theta \end{cases} \quad (3)$$

199

200 The parameter λ is eliminated using Equation 3:

201

$$202 \quad (X - \rho \sin \psi)^2 + (Y - \rho \cos \psi)^2 \leq r_{max}^2. \quad (4)$$

203

204 In the space-time Hough transform, we prepare bins of parameters (ρ, θ, ϕ, ψ) that correspond
 205 to straight lines. We perform a “vote” to the corresponding “bin” when a tremor event satisfies
 206 Equation 4. The bin with the maximum number of votes represents the straight line that best
 207 explains the event data. When there are multiple straight lines that show large number of votes in
 208 the same time window, these lines can be extracted separately by the Hough transform because
 209 votes for different lines are cast on different “bins”. This advantage enables us to relax the
 210 constraint of one migration in one time window imposed in previous studies. The square root of
 211 the left-hand side of Equation 4 expresses the space-time distance (D_{st}) between the tremor event
 212 and the cylindrical axis:

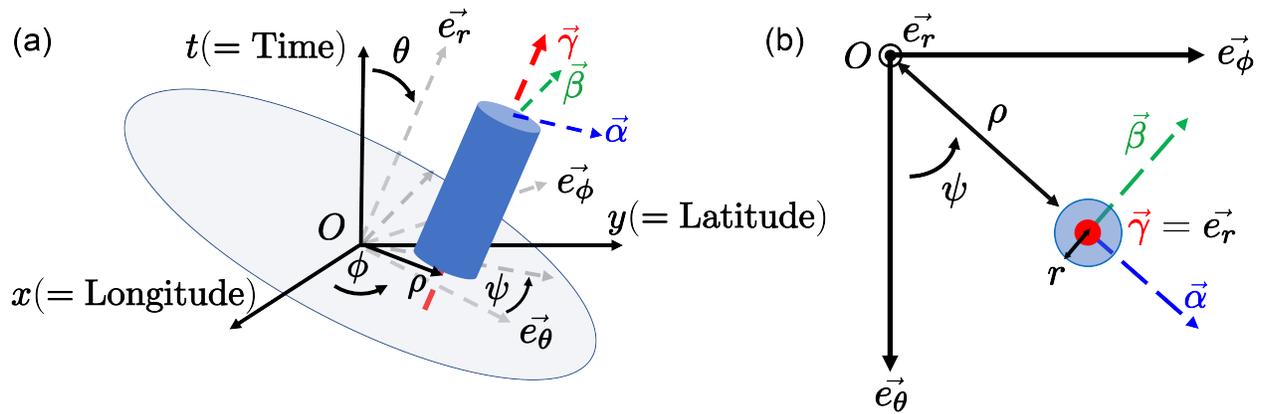
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$$D_{st} = \sqrt{\delta x^2 + \delta y^2 + C^2 \delta t^2}, \quad (5)$$

215

216 where δx and δy are spatial errors with respect to the cylindrical axis, δt is the temporal error,
 217 and C is the parameter that connects space and time with a unit of speed. When we set the radius
 218 of the cylinder (r_{max}) based on the uncertainty of the tremor location, the space-time Hough
 219 transform can extract tremor migrations by considering the tremor uncertainties. In this case,
 220 parameter C should be set such that r_{max}/C is equal to the temporal resolution of the tremor
 221 catalog. If C is set smaller than the above value, the time series of tremor events projected onto
 222 the straight line may change from the original values because the temporal error is allowed up to
 223 r_{max}/C (the temporal error may exceed the temporal resolution of the catalog).

224



225 **Figure 2.** (a) Schematic diagram of the space-time Hough transform. x is the longitude (the east
 226 is positive), y is the latitude (the north is positive), and t is the detection time. ρ is the distance
 227 from the origin to the straight line (cylindrical axis), θ is the zenith angle, ϕ is the azimuth, and
 228 ψ is the rotation angle. The large blue circle shows a plane perpendicular to the unit direction
 229 vector of the straight line ($\vec{\gamma}$). (b) Schematic diagram of the coordinate around the vector $\vec{\gamma}$. The
 230 vectors of \vec{e}_θ , \vec{e}_ϕ , and \vec{e}_r are standard unit vectors, which are consistent with those in the polar
 231 coordinate system. r is the radius of the cylinder.

232

233 2.3 Data processing

234 Before applying the space-time Hough transform to the tremor catalog data, we set the
 235 values of parameters r_{max} and C . In the present study, r_{max} was set to 2.5 km based on the mean
 236 uncertainty of the horizontal location in the tremor catalog (Sagae et al., 2021). C was set to 150
 237 km/hr (= 2.5 km/min) because the temporal resolution of the catalog was 1 min. The tremor
 238 locations (longitude, latitude) were converted to a plane rectangular coordinate system (x, y) in
 239 kilometers, with the origin set at the center of the seismic array (136.31°E, 34.45°N) by using the
 240 code of EPSG:6674. We prepared bins of parameters (ρ, θ, ϕ, ψ) to extract tremor migrations
 241 using the space-time Hough transform. ρ was set in a range of 0–120 km with an interval of 0.25
 242 km, ϕ and ψ were set in a range of 0–350° with an interval of 10°, and θ ($\tan \theta$) was set in a
 243 range of 2–60 km/hr with an interval of 1 km/hr in addition to (0.125, 0.25, 0.5, 0.75, 1.0, 1.25,
 244 and 1.5) km/hr.

245 We prepared time windows with lengths (T_w) of 1, 2, 3, 4, 6, 8, 12, and 24 h to extract
 246 tremor migrations for various durations. In each time window, we applied a clustering process to
 247 a time series to determine the temporal extent of tremor migrations. Our clustering process for
 248 time series is different from that of Bletery et al. (2017), who identified a cluster of tremor events
 249 with a length of time window by clustering. Firstly, we define a first tremor event in the time
 250 window and make a “cluster”. The detection time for the first tremor event is t_1 . Secondly, we
 251 define the i -th tremor event that occurred after the first tremor event as the i -th target event with
 252 a detection time of t_i . We calculate the time interval $t_i - t_{i-1}$ between the target event and the
 253 previous event that occurred immediately before. Finally, if the time interval is shorter than
 254 $5 \times T_w$ minutes, the target event is classified into a “cluster” to which the previous event belongs.
 255 For example, when $t_2 - t_1$ is shorter than $5 \times T_w$, the second target event is classified into the
 256 cluster to which the first tremor event belongs. If the time interval is longer than $5 \times T_w$ minutes,
 257 the target event is classified into a new “cluster”. We determined the time interval ($5 \times T_w$) for
 258 the clustering by trial and error, while visually checking tremor migrations extracted in the time
 259 window of $T_w = 1$ h. The time interval is considered to be related to the detection capability of
 260 the tremor catalog. As the tremor distribution becomes spatiotemporally sparse in the low-quality
 261 catalog, tremor migrations are not visible on a short timescale. In this case, the time interval
 262 should be increased.

263 After clustering, we applied the space-time Hough transform to the clusters of tremor
 264 events in the time window of each length (T_w) as follows:

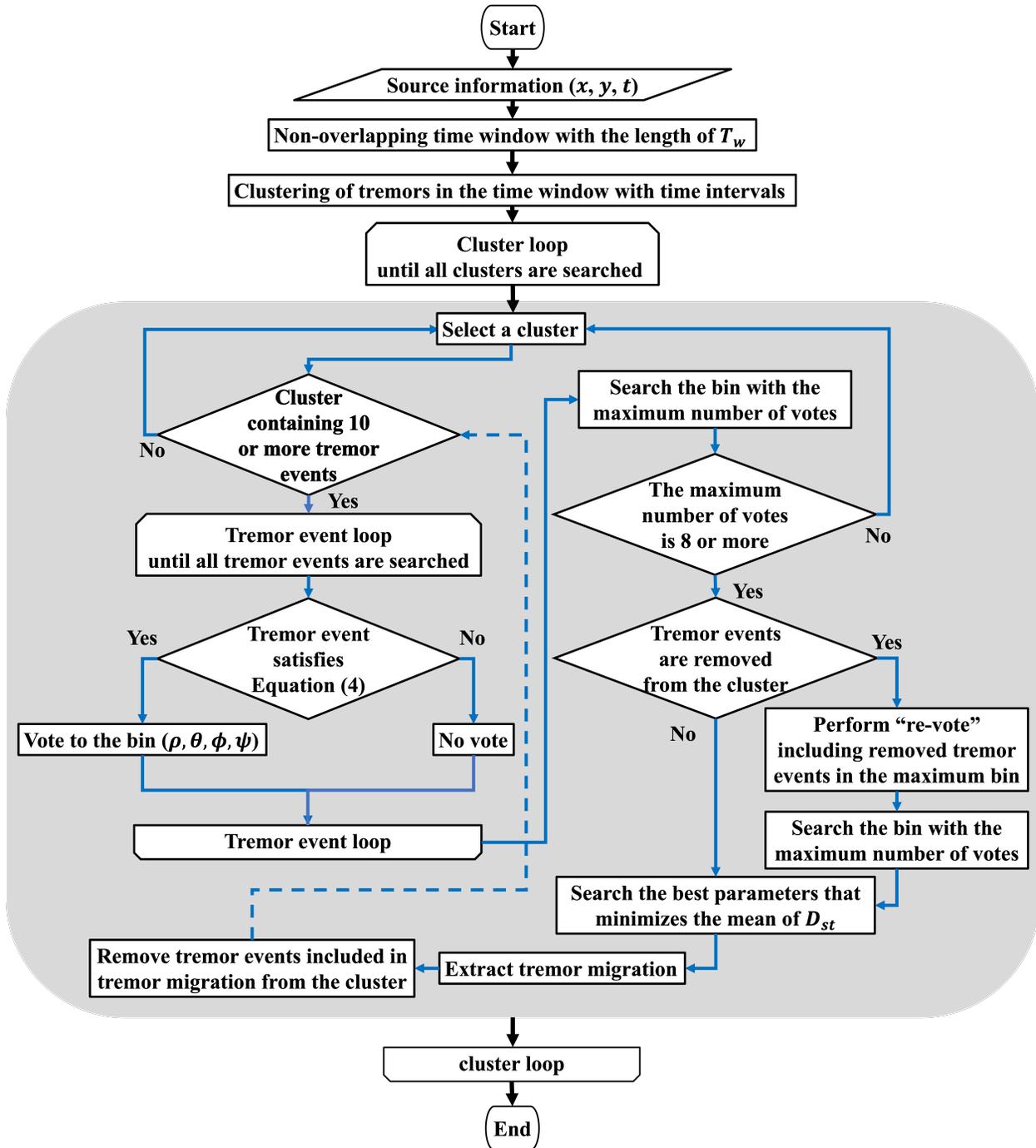
265 (A) We select a time window that contains ten or more tremor events while moving the
 266 window from the beginning of the catalog without overlapping.

267 (B) We perform a “vote” to a corresponding “bin” when a tremor event within a cluster
 268 estimated by clustering satisfies Equation 4. We extract a tremor migration whose “bin”
 269 (ρ, θ, ϕ, ψ) shows the maximum number of votes. In the present study, the number of
 270 votes must be eight or more. When multiple “bins” show the same maximum number of
 271 votes, we extract the tremor migration that minimizes the mean values of space-time
 272 distances (D_{st} , Equation 5) averaged over voted tremor events.

273 (C) Tremor events belonging to the tremor migration are removed from the cluster. If the
 274 cluster still contains ten or more tremor events, we return to (B) and further extract
 275 tremor migrations in the cluster. When the maximum “bin” contains eight or more
 276 votes, we perform a “re-vote”, which is a “vote” including the removed tremor events.
 277 This is because there may be tremor events belonging to multiple tremor migrations
 278 among the removed ones. If there are less than ten tremor events in the cluster or the
 279 maximum number of votes is less than eight, we deal with other clusters in the time
 280 window. When the searches of all clusters in the time window are completed, we return
 281 to (A) and select the other time windows that satisfy the condition of (A).

282 A detailed flowchart of the above process is shown in Figure 3. We define the duration of
 283 the tremor migration as $t_{max} - t_{min}$, where t_{min} is the detection time of the first tremor event
 284 included in the tremor migration and t_{max} is the detection time of the last tremor event. After
 285 tremor migrations are extracted in all time windows, overlapping ones with the same parameters
 286 (e.g., date and time, duration, ρ , and ϕ) extracted in multiple time windows are removed.

287



288 **Figure 3.** Flowchart of the space-time Hough transform.

289

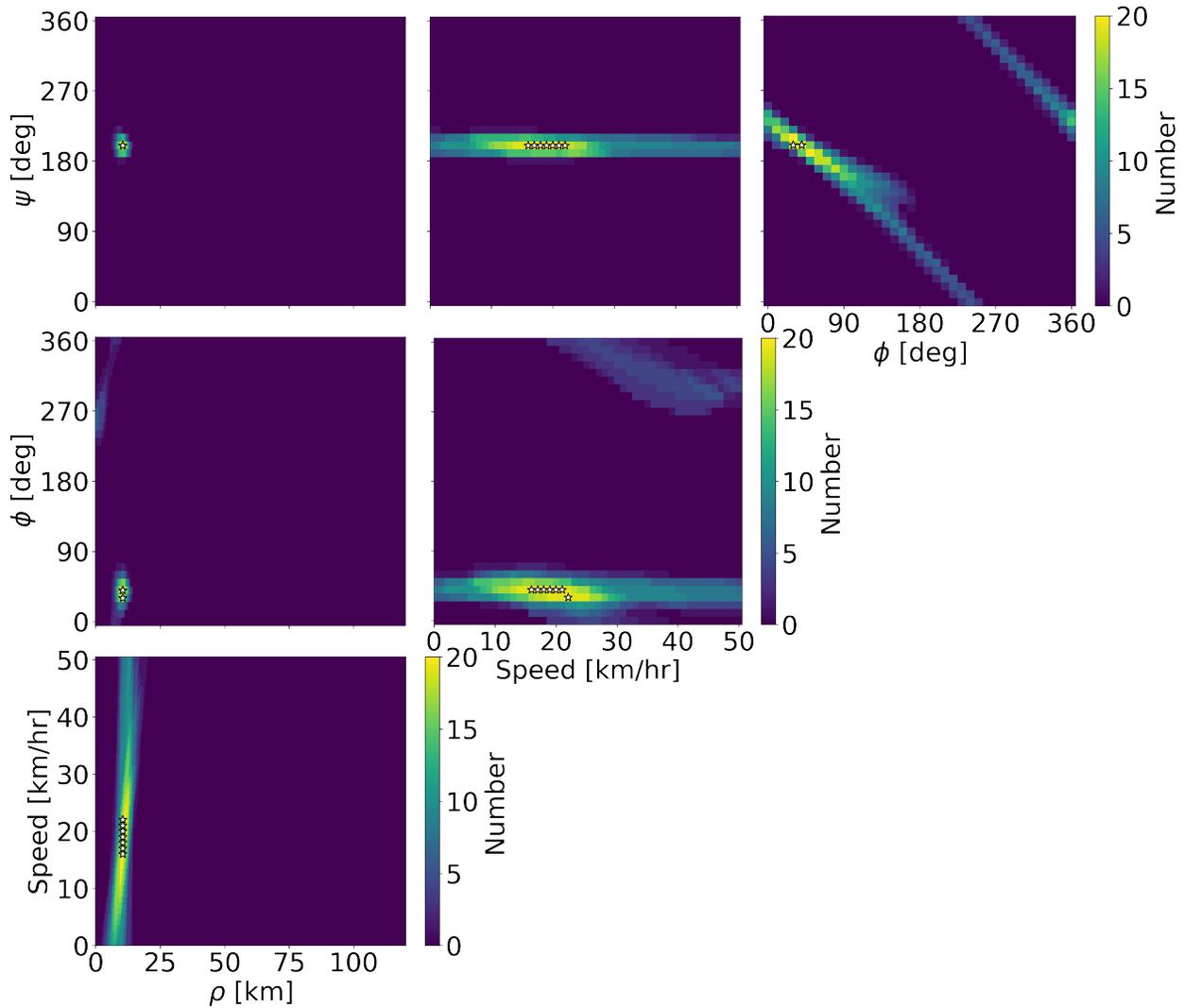
290 Figure 4 shows an example of votes for a tremor migration with a duration of 22 min.

291 Each panel shows the number of votes for the two parameters by fixing the remaining two

292 parameters to the best values. In this tremor migration, the maximum number of votes is 20, as

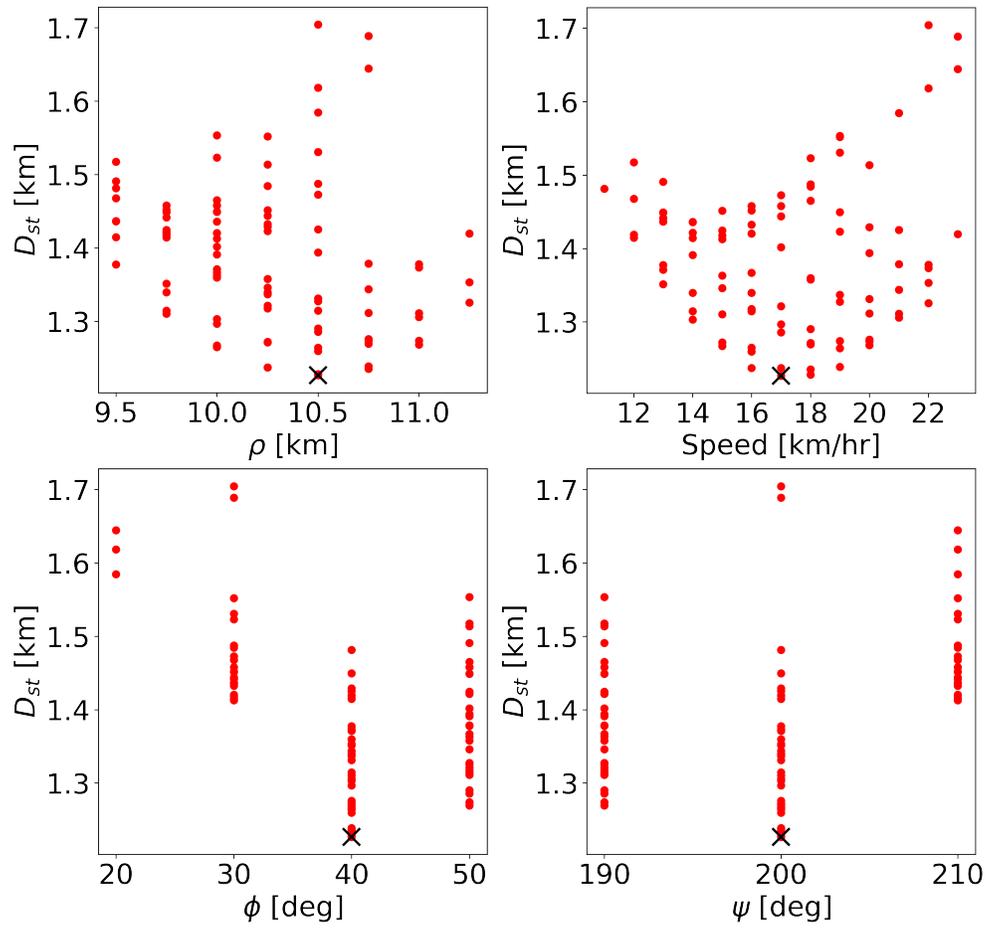
293 shown by the white stars in Figure 4. From the maximum values, the space-time Hough
294 transform objectively determines candidates of the best parameters for tremor migrations by the
295 technique of “vote”. When there are multiple candidates with the same maximum number of
296 votes, we use the space-time distance (D_{st} , Equation 5) to identify the best parameters. Figure 5
297 shows the distribution of the space-time distance (D_{st}) for the candidate parameters in Figure 4.
298 The red dots are the mean values of D_{st} for the candidates, and the black cross is the minimum
299 value. The minimum value of the mean D_{st} enables determination of the best parameters among
300 the candidates (ρ, θ, ϕ, ψ) with the maximum number of votes. Figure 6 shows an example of
301 tremor migrations extracted in a time window with a length of 2 h. We succeeded in extracting
302 three different tremor migrations with the durations of 22 min, 36 min, and 53 min during the 2
303 h. The tremor migration with the duration of 22 min (red line) is the example shown in Figures 4
304 and 5. Our method can objectively extract the complex patterns of tremor migrations in a zigzag
305 style. This result means that the space-time Hough transform newly developed in the present
306 study enables us to extract multiple tremor migrations with various durations regardless of the
307 length of the time window.

308



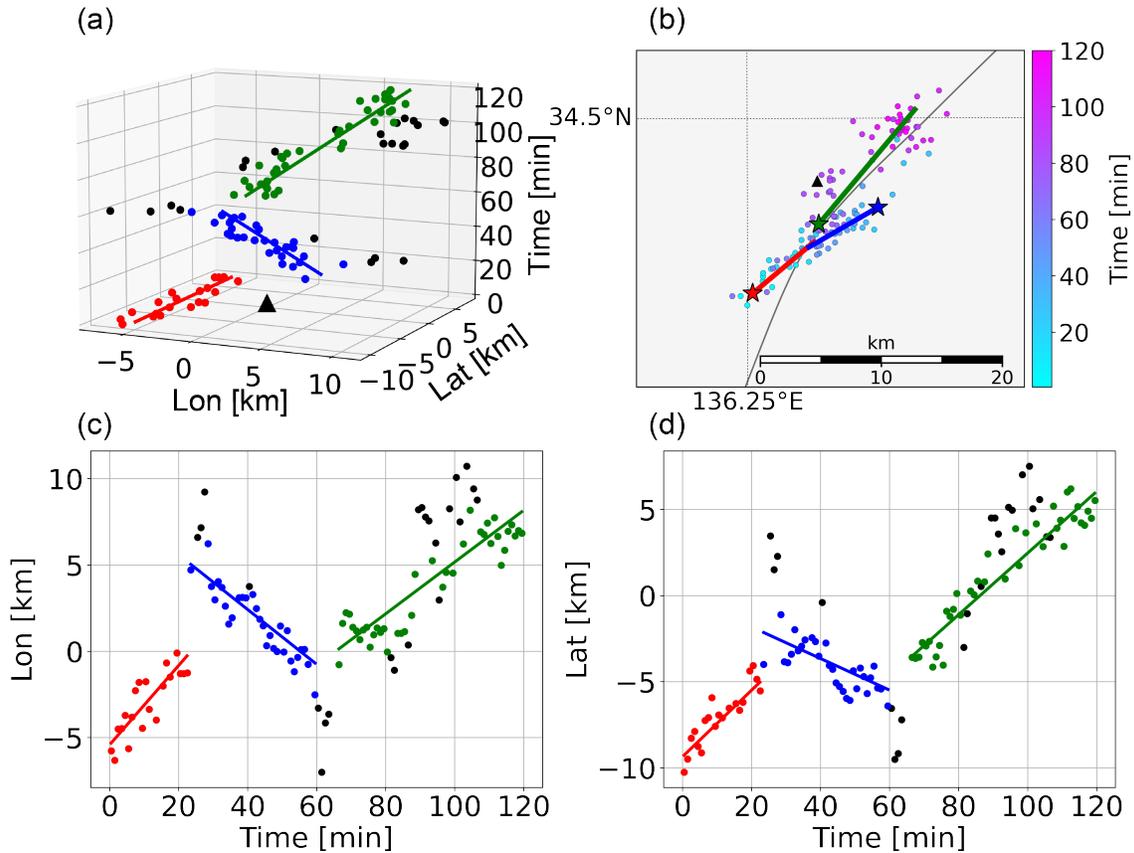
309 **Figure 4.** The number of votes for tremor migration with the duration of 22 min. Color bar
 310 shows the number of votes. Each panel shows the number of votes for two parameters by fixing
 311 the remaining two parameters to the best ones. The maximum number of votes is 20. The white
 312 stars show candidates of the best parameters with the same maximum votes. The best parameters
 313 of the tremor migration are $\rho = 10.5$ km, migration speed ($= \tan \theta$) = 17 km/hr, $\phi = 40^\circ$, and
 314 $\psi = 200^\circ$ as shown in Figure 5.

315



316 **Figure 5.** Distribution of space-time distance (D_{st}) for candidates of parameters with the same
 317 maximum number of votes. The candidates are combinations of parameters with the maximum
 318 votes in Figure 4. The red dots show mean D_{st} values whose maximum number of votes is 20.
 319 The black cross shows the minimum value of the mean D_{st} .

320



321 **Figure 6.** An example of tremor migrations extracted in one time window with the length of 2 h.
 322 (a) Tremor migrations in the (2+1)-D space-time. The red, blue, and green lines show tremor
 323 migrations with durations of 22 min, 36 min, and 53 min, respectively. The red, blue, and green
 324 dots show tremor events composing each tremor migration. The black dots are tremor events that
 325 do not belong to tremor migrations. The black triangle shows the origin set at the location of the
 326 array (136.31°E, 34.45°N). (b) Map view of tremor migrations. Each line shows tremor
 327 migrations and the colored stars are starting points of the three tremor migrations. The dots and
 328 their colors represent tremor locations and their timings. (c) Space-time plot of tremors between
 329 the longitude and the time. (d) Space-time plot of tremors between the latitude and the time.

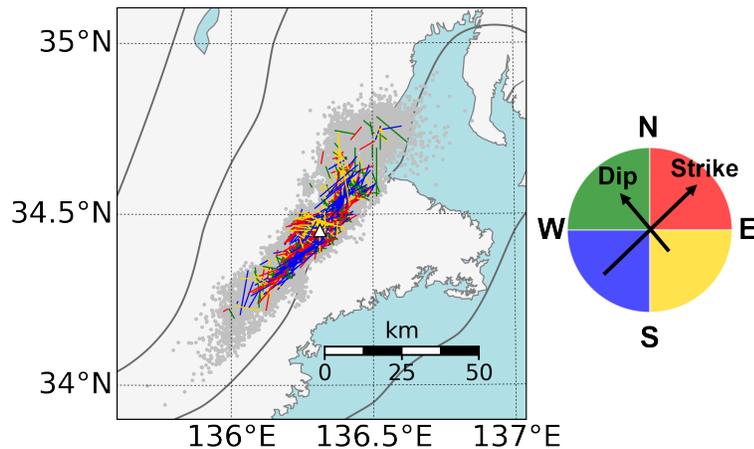
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331 3 Results

332 3.1 Tremor migrations extracted during a tremor episode

333 During the two years from July 2012 to July 2014, we succeeded in extracting 1,010
 334 tremor migrations with durations ranging from 10 min to 24 h (Figure 7). Tremor migrations
 335 were categorized into four patterns based on their migration directions. We defined the along-
 336 strike direction as 45° clockwise from the north and the along-dip direction as perpendicular to
 337 the strike. The tremor migrations are represented by the lines with different colors: the red lines
 338 express tremor migrations with directions of $0\text{--}90^\circ$ clockwise from the north (northeast
 339 direction); the blue lines represent those with directions of $180\text{--}270^\circ$ (southwest direction); the
 340 yellow lines represent those with directions of $90\text{--}180^\circ$ (up-dip direction), and the green lines
 341 represent those with directions of $270\text{--}360^\circ$ (down-dip direction). Tremor migrations appear to
 342 behave differently depending on area. The details are presented in Section 3.2.

343



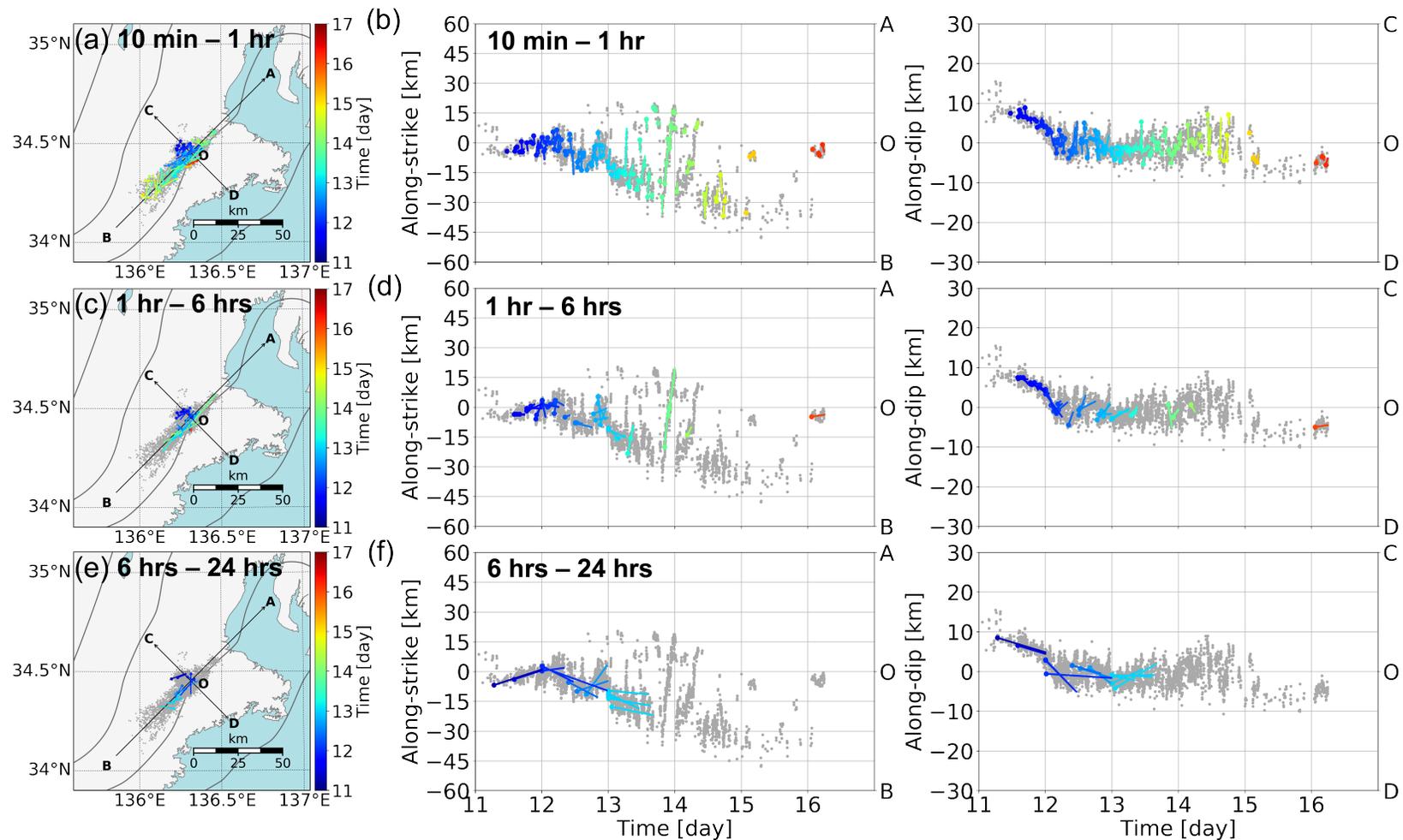
344 **Figure 7.** Distribution of tremor migrations from July 2012 to July 2014. The gray dots show
 345 tremor locations, and the white triangle shows the location of the seismic array. The lines show
 346 directions of tremor migrations, where red lines are directions of $0\text{--}90^\circ$ clockwise from the north
 347 (northeast direction), blue lines are directions of $180\text{--}270^\circ$ (southwest direction), yellow lines are
 348 directions of $90\text{--}180^\circ$ (up-dip direction), and green lines are directions of $270\text{--}360^\circ$ (down-dip
 349 direction), respectively. The color diagram is shown on the right.

350

351 Figure 8 shows examples of tremor migrations that are extracted during a tremor episode
352 from August 11th to 16th, 2012. In this tremor episode, Sagae et al. (2021) found a pattern of the
353 main front by visual inspection: tremors started from the down-dip side of the tremor zone, first
354 propagated in the up-dip direction, and then migrated northeastward and southwestward. The
355 present study extracted 171 tremor migrations during the same tremor episode. Figures 8a and 8b
356 show 120 tremor migrations with durations ranging from 10 min to 1 h. We detected not only
357 RTRs and tremor streaks reported in Sagae et al. (2021) but also many complex tremor
358 migrations that were not easily identified by visual inspection. Figures 8c and 8d show 38 tremor
359 migrations with durations ranging from 1 h to 6 h, and Figures 8e and 8f represent 13 tremor
360 migrations with durations ranging from 6 h to 24 h. These 51 tremor migrations show up-dip
361 migrations and bilateral migrations along the strike. In particular, up-dip migrations in the initial
362 stage of the tremor episode (August 11th in Figure 8) show not only the along-dip component but
363 also the along-strike component (northeast direction). Tremor migrations in the other episodes
364 propagate in the similar path (Figure S8). Figure 9 zooms up the tremor episode occurring on
365 August 13th, 2012 to see fine structures of spatiotemporal distribution of tremor migrations. By
366 comparing tremor migrations with different durations (00:00–14:00 in Figures 9b, 9d, and 9f),
367 we recognized multiple tremor migrations with short durations within those with long durations.
368 We further noticed that migration speeds slowed down as durations increased. The relationship
369 between migration speed and duration is discussed in Section 4.3. Focusing on tremor migrations
370 with durations ranging from 6 h and 24 h, we found that multiple straight lines appear to be
371 parallel (Figure 9f). This result shows that the tremor migrations have spatial spread beyond the
372 uncertainties of the tremor locations. In the present study, we can judge whether or not tremor
373 migrations spread two-dimensionally because the space-time Hough transform can extract tremor
374 migrations considering the uncertainties of tremor locations. This is an advantage of the space-
375 time Hough transform. Results of other tremor episodes are shown in the Supporting Information
376 (Figures S2–S12).

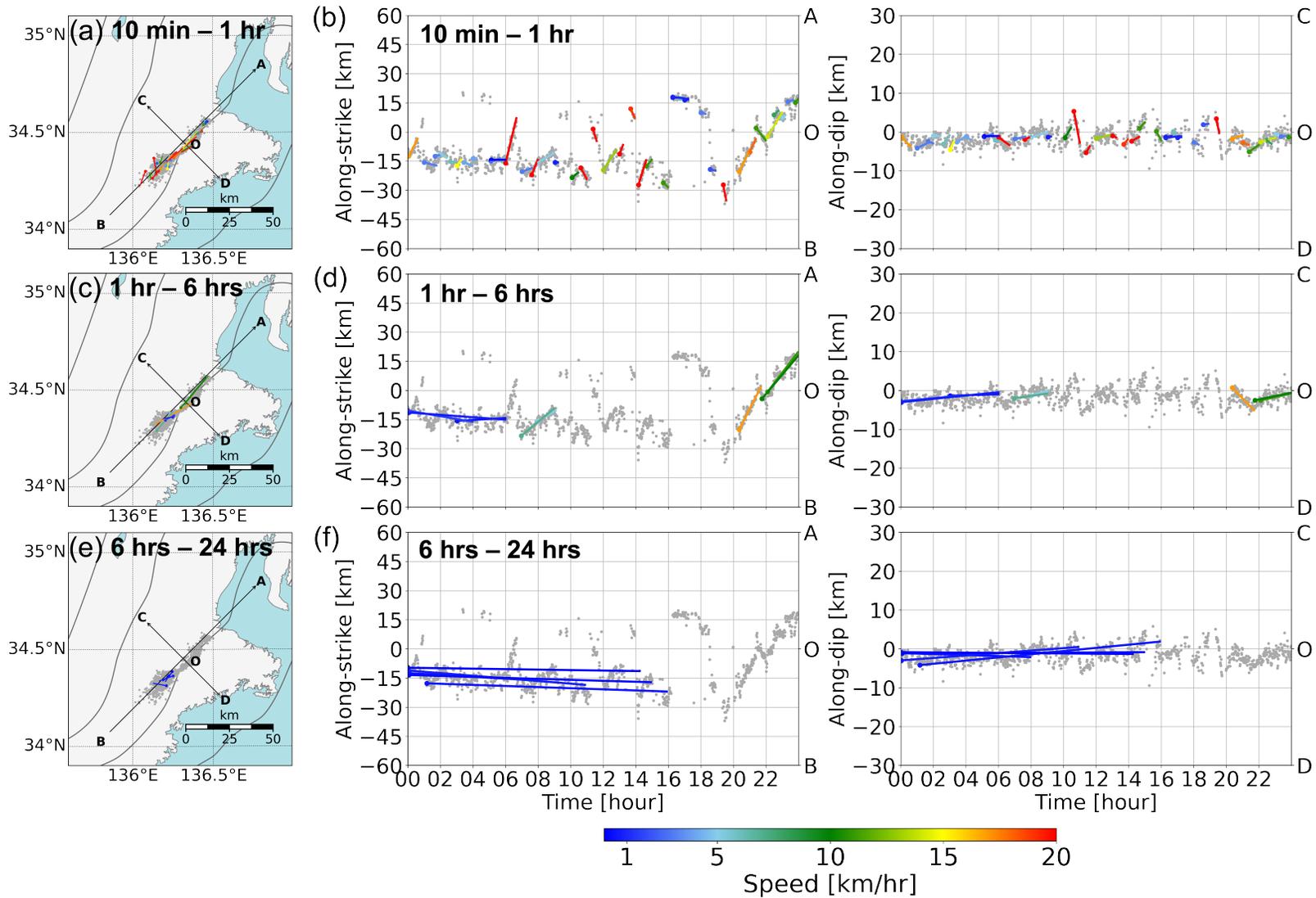
377

378



379 **Figure 8.** Tremor migrations during a tremor episode from August 11th to 16th, 2012. (a) Map view of the tremor migrations with
 380 durations ranging from 10 min to 1 h. The gray dots show tremor locations. Colored lines and dots show tremor migrations and their
 381 starting points, and the colors show the starting time of tremor migrations. (b) Spatiotemporal plots of the tremor migrations with the
 382 same durations as that of (a). The left panel shows spatiotemporal evolutions of tremor migrations along the strike (A–B) and the right

383 panel shows spatiotemporal evolutions of those along the dip (C–D). (c), (d) Same as (a) and (b), but for tremor migrations with
384 durations ranging from 1 h to 6 h. (e), (f) Same as (a) and (b), but for tremor migrations with durations ranging from 6 h to 24 h.
385



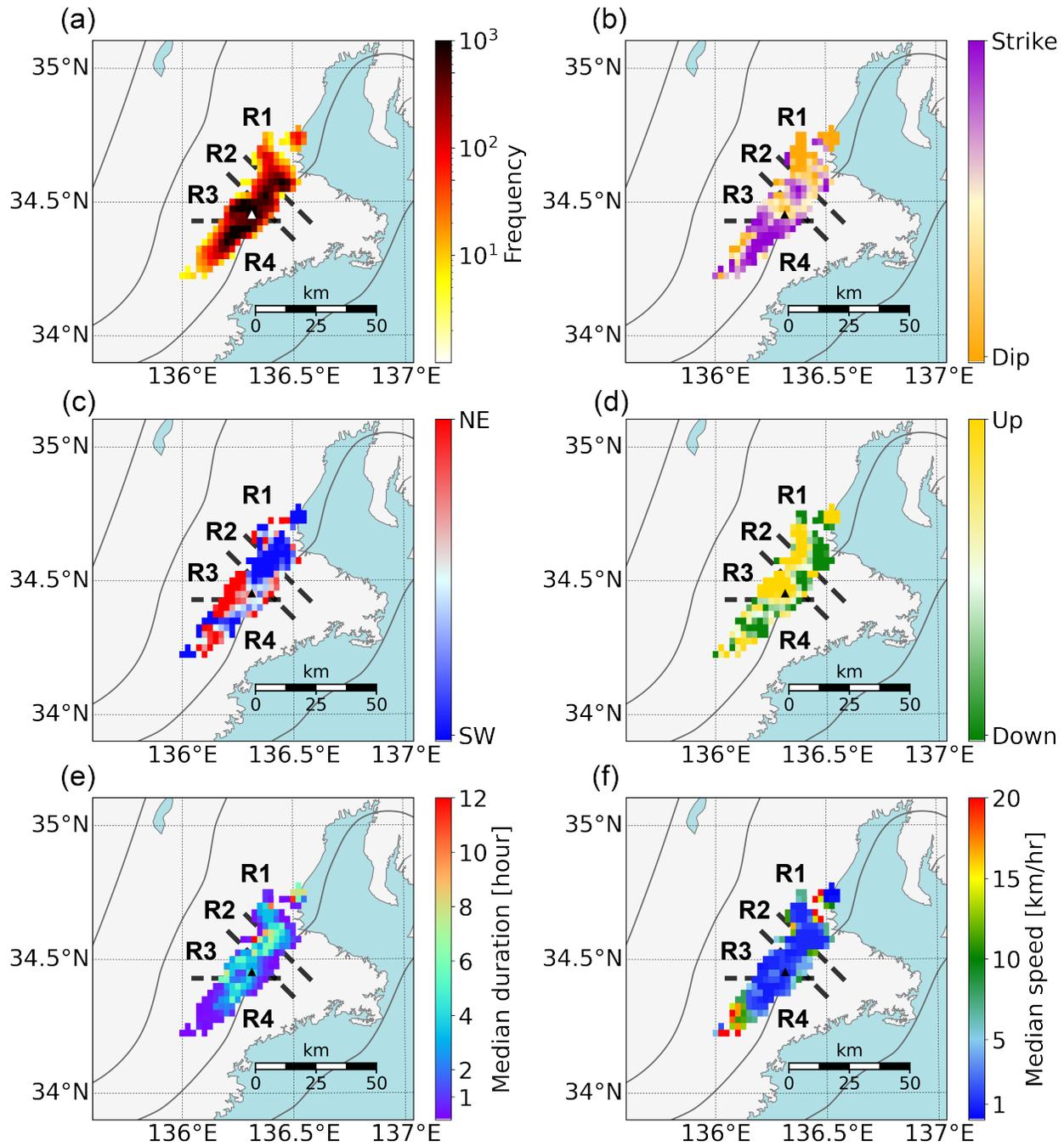
386 **Figure 9.** Same as Figure 8, but for tremor migrations zooming on August 13th, 2012. The colors show migration speeds.

387

388 3.2 Spatial distribution of tremor migrations

389 Figure 10a shows the frequency distribution of tremor events included in the tremor
390 migrations. The number of tremor events was counted inside cells that are arranged at intervals
391 of 0.025° along longitude and latitude. Comparing the spatial distribution of all tremor events
392 (Figure 1b) and the frequency in Figure 10a, we found four areas (R1–R4) where the frequency
393 of tremor events was relatively high beneath the Kii Peninsula. Figure 10b shows the spatial
394 distribution of the predominant directions of tremor migrations. For each cell, we calculated
395 predominant directions of tremor migrations as a ratio of the number of tremor migrations with
396 directions of $0\text{--}90^\circ$ and $180\text{--}270^\circ$ over the total number of tremor migrations with directions of
397 $0\text{--}360^\circ$. Our result shows that along-strike migrations (violet) are more predominant on the up-
398 dip side of the tremor zone. This characteristic is similar to that reported by Obara et al. (2012).
399 Moreover, we found that along-dip migrations (orange) were predominant in R1 and R3, and
400 along-strike migrations were principal in R2 and R4 (Figure 10b). The areas R2 and R4
401 correspond to the areas where RTRs were reported by visual checking in Sagae et al. (2021). The
402 characteristics of R1–R4 are discussed in more detail in Section 4.1.

403



404 **Figure 10.** (a) Frequency distribution of tremor events included in tremor migrations. The white
 405 triangle shows the location of the array. The color bar shows the frequency of tremor events. The
 406 dashed lines are additional lines to distinguish the areas R1–R4, where the frequency of tremor
 407 events is high. (b) Spatial distribution of predominant directions of tremor migrations. The black
 408 triangle shows the location of the array. The violet color shows that tremor migrations along the
 409 strike are predominant (0–90° and 180–270° clockwise from the north), and the orange color

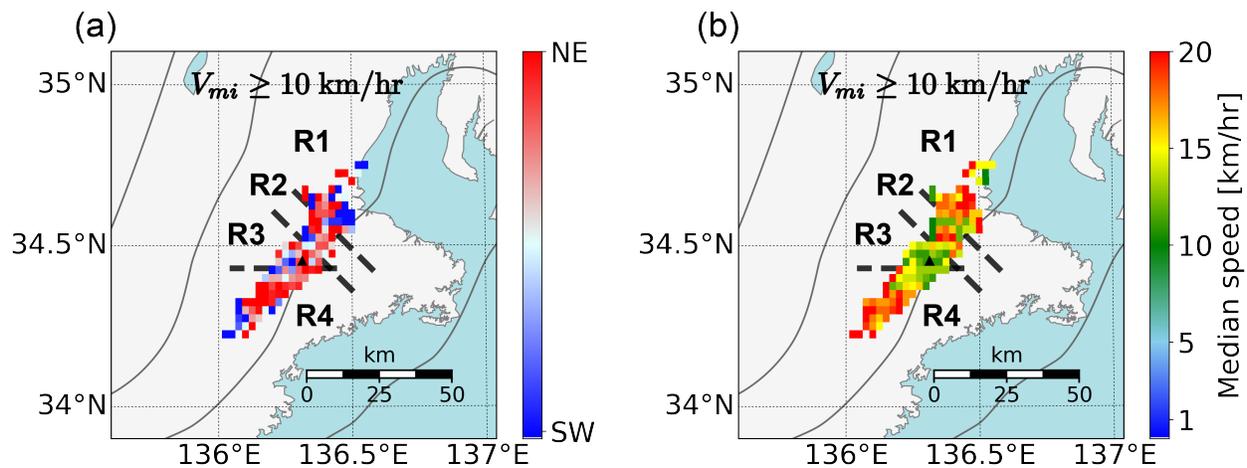
410 shows that tremor migrations along the dip are predominant ($90\text{--}180^\circ$ and $270\text{--}360^\circ$). (c) Spatial
411 distribution of predominant directions of tremor migrations along the strike. The red and blue
412 colors show the predominant directions of the northeast ($0\text{--}90^\circ$) and southwest ($180\text{--}270^\circ$),
413 respectively. (d) Spatial distribution of predominant directions of tremor migrations along the
414 dip. The yellow and green colors show predominant directions of the up-dip ($90\text{--}180^\circ$) and
415 down-dip ($270\text{--}360^\circ$), respectively. (e) Spatial distribution of median duration of tremor
416 migrations. (f) Spatial distribution of median speed of tremor migrations.

417

418 Figures 10c and 10d show the predominant directions of tremor migrations along the
419 strike and dip, respectively. The predominant direction along the strike was defined as the ratio
420 of the number of tremor migrations with directions of $0\text{--}90^\circ$ over the total number of along-
421 strike migrations with directions of $0\text{--}90^\circ$ and $180\text{--}270^\circ$. The predominant direction along the
422 dip was the ratio of the number of tremor migrations with directions of $90\text{--}180^\circ$ over the total
423 number of along-dip migrations with directions of $90\text{--}180^\circ$ and $270\text{--}360^\circ$. Regarding the along-
424 strike direction (Figure 10c), we observed significant changes in the predominant directions at
425 the boundary between R2 and R3. Northeastward tremor migrations (red) were predominant in
426 the southwest area, while southwestward tremor migrations (blue) were principal in the northeast
427 area. For the along-dip direction (Figure 10d), up-dip migrations (yellow) were predominant on
428 the down-dip side of the tremor zone and down-dip migrations (green) were principal on the up-
429 dip side. This characteristic of along-dip migrations is a new finding of the present study.

430 To characterize the spatial distribution of the duration and speed of tremor migrations, we
431 calculated the median values for each cell. The results are presented in Figures 10e and 10f.
432 Areas where the median duration is relatively long (6 h or more) correspond well to those where
433 the median speed is relatively slow (1 km/hr or less). The main front is characterized by a
434 duration ranging from several hours to days and a speed of approximately 10 km/day. The values
435 of the long median duration and slow median speed were consistent with the characteristics of
436 the main front. Our results show the locations where the main front with long durations often
437 occurs. When we investigated tremor migrations with high speeds (10 km/hr or more), their
438 spatial characteristics were different from the patterns of the main front shown in Figure 10.
439 Figure 11a shows the predominant directions of along-strike tremor migrations with speeds of 10

440 km/hr or more. Areas where southwestward tremor migrations are predominant in Figure 10c
 441 (blue) change their patterns to those where northeastward tremor migrations are principal (red in
 442 Figure 11a). Figure 11b shows spatial distribution of the median speed for tremor migrations
 443 with speeds of 10 km/hr or more. Tremor migrations with high speeds were found even in areas
 444 where the median duration was relatively long and the median speed was slow. These results
 445 show that high-speed tremor migrations occur inside the main front and that the inside of the
 446 main front is rich in spatiotemporal variations in tremor migrations. Thus, our results reveal fine
 447 structures of tremor migrations not only in time (Figures 8 and 9) but also in space (Figures 10
 448 and 11).
 449



450 **Figure 11.** (a) Spatial distribution of predominant directions of tremor migrations with high
 451 speeds along the strike. The dashed lines and the black triangle are the same as those in Figure
 452 10. Tremor migrations with speeds of 10 km/hr or more are used to estimate the migration
 453 patterns. Colors are the same as those in Figure 10c. (b) Spatial distribution of median speed of
 454 tremor migrations with speeds of 10 km/hr or more. Colors are the same as those in Figure 10f.
 455

456 4 Discussions

457 4.1 Comparison of the spatial distribution of tremor migrations with previous studies

458 We describe the characteristics of the four areas (R1–R4) in further detail. In area R1,
 459 tremor migrations had a component propagating southwestward (Figure 10c), although along-dip

460 migrations were predominant (Figure 10b). Up-dip migrations were predominant on the down-
461 dip side of the tremor zone (Figure 10d). This result corresponds to the observations that tremors
462 start from the down-dip side of the tremor zone and propagate in the up-dip direction (Sagae et
463 al., 2021).

464 For area R2, previous studies established that tremor episodes tended to stop in R2 (e.g.,
465 Nakamoto et al., 2021; Sagae et al., 2021), and that there were tremor patches with high radiated
466 energies in R2 (Nakamoto et al., 2021; Yabe & Ide, 2014). The present study shows that along-
467 strike migrations are predominant (Figure 10b) and tremor migrations tend to propagate
468 southwestward (Figure 10c). Although tremor migrations with high speeds of 10 km/hr or more
469 were predominant in along-strike directions beneath most of the Kii Peninsula, along-dip
470 migrations were principal in R2 (Figure S13). This result suggests that area R2 is a characteristic
471 field (e.g., tremor patches arranged subparallel to the dip; fluid conduits along the dip) to
472 generate tremor streaks along the dip, as observed in a previous study (Figure S14 in Sagae et al.,
473 2021). The implications of tremor streaks are outside the scope of the present study.

474 In area R3, along-dip migrations were predominant (Figure 10b) and tremor migrations
475 propagated not only in the up-dip direction but also northeastward (Figures 10c and 10d). When
476 tremor migrations reach the upper limit of the tremor zone, they are less likely to propagate from
477 R3 to R1 beyond R2. This characteristic is observed as changes in the predominant direction of
478 the along-strike migration around the boundary between R2 and R3 (Figure 10c). Previous
479 studies have also observed these characteristics (e.g., Ando et al., 2012; Sagae et al., 2021).

480 In area R4, tremor migrations were predominant in the along-strike direction (Figure
481 10b). In addition, tremor migrations on the up-dip side of the tremor zone propagated in both the
482 northeast and the southwest directions (white color in Figure 10c). These results reflect the
483 observations that RTRs repeatedly occur in R4 (Sagae et al., 2021). Interestingly, most of the
484 tremor migrations propagated in the down-dip direction (Figure 10d), and up-dip migrations
485 propagating directly from R3 to R4 rarely occurred. This characteristic is obtained from the
486 results that the down-dip migration and the along-strike migration propagating northeastward are
487 principal around the boundary between R3 and R4 (Figures 10c and 10d).

488 Previous studies have investigated the characteristics of tremor migrations beneath the
489 Kii Peninsula (Obara et al., 2012; Wang et al., 2018). Wang et al. (2018) classified tremor

490 locations beneath the Kii Peninsula into 17 segments using a 2-D Hidden Markov model and
491 examined tremor activities among the segments. They calculated transition probabilities which
492 explained the migration patterns among the segments. Furthermore, areas with high transition
493 probabilities of tremor activities among the segments were classified into four subsystems along
494 the strike (K1–K4, Figure 6 in Wang et al., 2018). Subsystems K3 and K4 in their results
495 included the four areas with the high frequency of tremor events (R1–R4) in our results. Some
496 characteristics of tremor migrations in R1–R4 are recognized in tremor activities among the
497 segments reported by Wang et al. (2018). For example, up-dip migrations propagating
498 northeastward were found in R3 (propagation from segment 10 to 11, Figure 6 in Wang et al.,
499 2018). There were almost no up-dip migrations propagating directly from R3 to R4 (propagation
500 from segment 10 to 9, Figure 6 in Wang et al., 2018). Our results provide new insights. For
501 example, up-dip migrations were predominant on the deep part of the tremor zone and down-dip
502 migrations were principal on the shallow part (Figure 10d). In R1, up-dip migrations were
503 predominant on the deep part of the tremor zone and tremor migrations tended to propagate
504 southwestward (to R2). These differences in the characteristics of tremor migrations were
505 attributed to the fact that Wang et al. (2018) could not investigate tremor migrations inside each
506 segment.

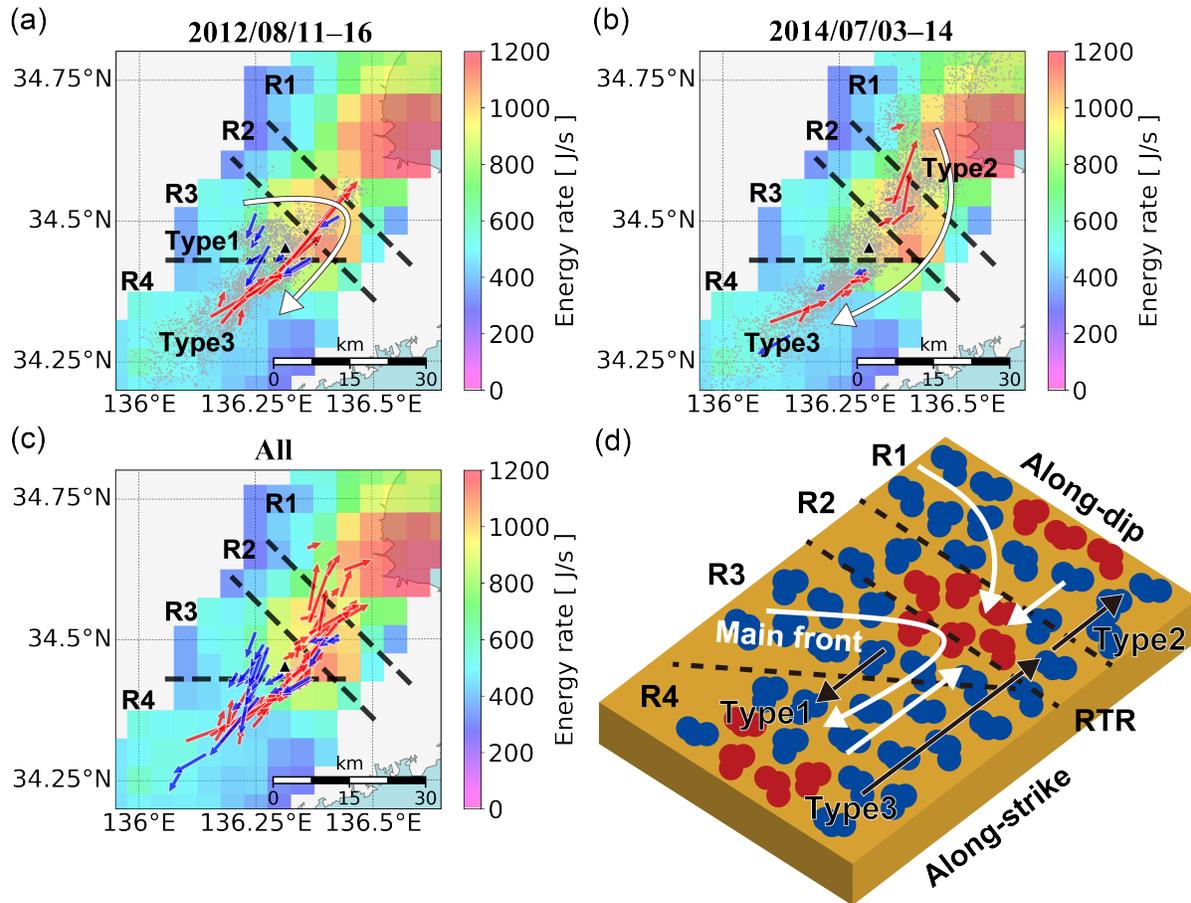
507 4.2 Relationship between tremor migrations and heterogeneous distribution of fault 508 strength on the plate interface

509 Previous studies have suggested that the spatial distribution of tremor energies reflects
510 the heterogeneity in fault strength on the plate boundary (e.g., Kano et al., 2018a; Yabe & Ide,
511 2014). They also suggested that tremor patches with high radiated energies are related to the
512 growth of along-strike migrations (Nakamoto et al., 2021; Yabe & Ide, 2014). Before the tremor
513 patch with high energy was ruptured, tremors migrated from the tremor patch with low energy on
514 the deep part of the tremor zone to that with high energy on the shallow part. When the tremor
515 patch with high energy was broken, tremors migrated along the strike after the occurrence of
516 burst activity (e.g., Shelly, 2010). The behavior of the tremor migrations was influenced by
517 whether or not the tremor patch with high energy was broken. In the Kii Peninsula, the location
518 of the high-energy tremor patch (Nakamoto et al., 2021; Yabe & Ide, 2014) corresponds to R2 in
519 the present study. Up-dip migrations propagating into R2 were observed in R1 and R3 (Figures

520 10c and 10d). Moreover, in R2, along-strike migrations were predominant (Figure 10b) and
521 tremor episodes tended to stop (Sagae et al., 2021). Our results suggest that the existence of a
522 tremor patch with high energy controls the pattern of tremor migration before and after the
523 tremor patch is broken.

524 RTRs have been observed to occur repeatedly in the same areas beneath the Kii Peninsula
525 (Sagae et al., 2021). To discuss the relationship between the spatial distribution of RTRs and that
526 of tremor patches, we systematically detected RTRs as follows: First, we searched for cells that
527 contained starting points of tremor migrations with speeds of 10 km/hr or more. We then
528 detected RTRs when the migration directions were opposite to the predominant direction inside
529 the cells obtained in Figure 10c (the predominant direction of along-strike migration). Figures
530 12a and 12b show the spatial distribution of the RTRs during a tremor episode from August 11th
531 to 16th, 2012, and a tremor episode from July 3rd to 14th, 2014, respectively. The white arrow
532 shows the pattern of the main front, and the spatiotemporal evolutions of tremor migrations
533 during those tremor episodes are shown in Figure 8 and Figure S12. The background colors show
534 the median energy rates of the tremors (Yabe & Ide, 2014). The median energy rates were
535 calculated in cells arranged at an interval of 0.05° along longitude and latitude, when the cells
536 contained 100 or more tremor events that were located within 10 km.

537



538 **Figure 12.** (a) Spatial distribution of RTRs during a tremor episode from August 11th to 16th,
 539 2012. The red arrows show RTRs propagating northeastward, and the blue arrows show those
 540 propagating southwestward. The white arrow shows the pattern of the main front and the gray
 541 dots show tremor locations. The dashed lines and the black triangle are the same as those in
 542 Figure 10. The background colors show median energy rates (Yabe & Ide, 2014). (b) Same as
 543 (a), but for RTRs during a tremor episode from July 3rd to 14th, 2014. (c) Same as (a), but for all
 544 RTRs detected in the present study. (d) Schematic diagram of the distribution of tremor patches
 545 and tremor migrations beneath the Kii Peninsula. The red and blue dots show strong tremor
 546 patches with high energies and weak ones with low energies, respectively. The white arrows
 547 show the patterns of the main front. The black arrows (Type1–Type3) show the patterns of
 548 RTRs.

549

550 In Figures 12a and 12b, the three types of RTRs are presented. The first is the
 551 southwestward RTR that occurs near the southwest side of R2 (blue arrows shown by Type1 in

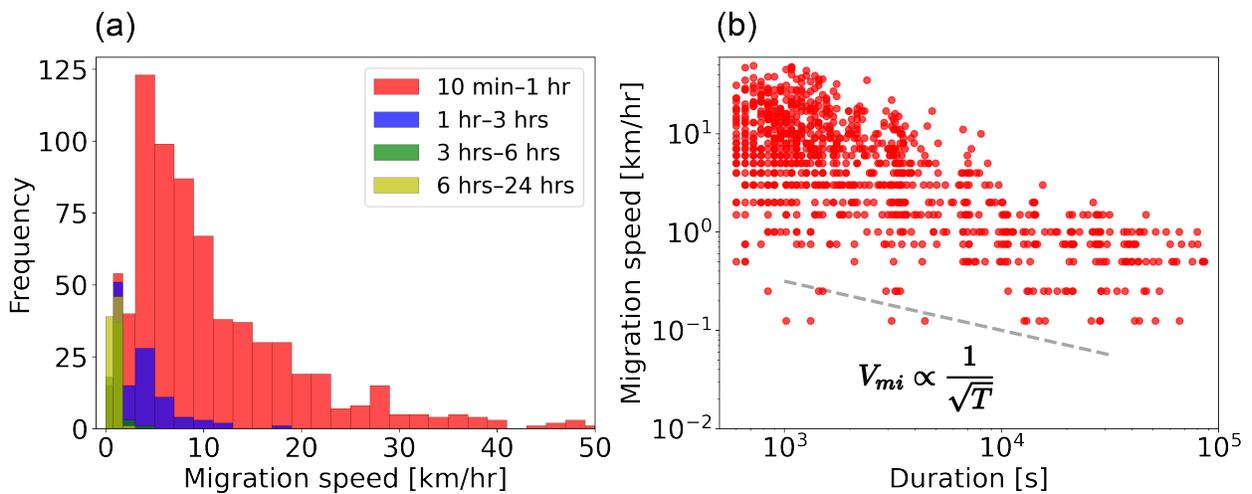
552 Figure 12a) when the main front propagates from the southwest side of R2 to the northeast. The
553 second is the northeastward RTR that occurs near the northeast side of R2 (red arrows shown by
554 Type2 in Figure 12b) when the main front propagates from the northeast side of R2 to the
555 southwest. The third is the northeastward RTR that occurs near the southwest side of R4 (red
556 arrows shown by Type3 in Figures 12a and 12b) when the main front propagates southwestward
557 in R4. The third sometimes propagated from R4 to R2 (red arrows in Figure 12a). The three
558 types of RTRs were found during other tremor episodes (Figure S14). Figure 12c shows all the
559 RTRs detected in the present study. The spatial distribution of the RTRs appears to be a
560 superposition of the three types of RTRs for the most part. Thus, our results suggest the existence
561 of areas in which RTRs occur repeatedly. In addition, the median energy rates appear to be
562 relatively high near areas where the three types of RTRs are found (R2 and the southwest side of
563 R4). The occurrence of the three types of RTRs seems to depend on the directions from which
564 the main front reaches the tremor patches. We show a schematic diagram of the spatial
565 distribution of tremor migrations (Figure 12d) by summarizing the characteristics of areas R1–
566 R4 discussed in Section 4.1 and those of RTRs in this section. Ando et al. (2012) explained the
567 pattern of RTR based on a stress diffusion model. They interpreted RTR as a phenomenon in
568 which weak patches with low energies that were reloaded or healed behind a front of stress
569 diffusion were broken again when the front reached strong patches with high energies and the
570 strong patches were ruptured. This interpretation of the RTR explains the distribution of tremor
571 patches and the patterns of the RTRs in the present study (Figure 12). Thus, we consider that the
572 patterns of the RTRs are controlled by the distribution of tremor patches with various frictional
573 properties. Our results imply that the fine structures of tremor migrations and the distribution of
574 tremor energies are key to investigating the frictional properties of the plate interface.

575 4.3 Relation between migration speed and duration

576 Diffusive tremor migrations, which are tremor migrations with their speeds decreasing
577 with increasing durations (Obara et al. 2012), were often observed in the front of tremor
578 activities during tremor episodes (e.g., Ando et al., 2012; Ide, 2010). We examined the
579 relationship between migration speeds and durations based on our data set. Figure 13a shows
580 histograms of the migration speeds versus duration. For the durations ranging from 10 min to 1 h
581 (red), 1 h to 3 h (blue), 3 h to 6 h (green), and 6 h to 24 h (yellow), the most frequent values of

582 migration speeds are 3 km/hr, 1.5 km/hr, 0.75 km/hr, and 0.5 km/hr, respectively. As Obara et al.
 583 (2012) reported, we also found that tremor migrations slowed down as the durations increased.
 584 We quantitatively investigated the relationship between migration speed and duration. Figure
 585 13b shows the relationship between the migration speed (V_{mi}) and the duration (T). We found
 586 that the relation $V_{mi} \propto T^{-0.5}$ holds for tremor migrations. When we consider a diffusion process,
 587 the relation $V_{mi} = \frac{L}{T} = \sqrt{\frac{D}{T}}$ is derived based on the relation $L^2 = DT$, where L is the propagation
 588 distance, and D is the diffusion coefficient. Thus, our results quantitatively suggest that the
 589 growth of the tremor migrations is controlled by the diffusion process. Stress diffusion and pore-
 590 pressure diffusion are candidates for explaining the diffusion process (e.g., Ando et al., 2012;
 591 Cruz-Atienza et al., 2018; Farge et al., 2021). Understanding the physical mechanisms behind
 592 slow earthquakes will be the focus of our future work.

593



594 **Figure 13.** (a) The histograms of migration speeds in their respective durations. Red, blue,
 595 green, and yellow are the histogram of migration speeds for tremor migrations with durations
 596 ranging from 10 min to 1 h, 1 h to 3 h, 3 h to 6 h, and 6 h to 24 h, respectively. (b) The
 597 relationship between migration speed (V_{mi}) and duration (T). The gray dashed line shows the
 598 relation $V_{mi} \propto T^{-0.5}$.

599

600 5 Conclusions

601 The present study newly developed the space-time Hough transform to objectively
602 extract tremor migrations. The advantage of this method is that multiple tremor migrations can
603 be extracted regardless of the lengths of time windows and projected axes because a technique of
604 “vote” enables us to distinguish the four parameters representing the tremor migration. The
605 space-time Hough transform was applied to the data of tectonic tremors beneath the Kii
606 Peninsula, Southwest Japan. Consequently, we succeeded in extracting 1,010 tremor migrations
607 with durations ranging from 10 min to 24 h between July 2012 and July 2014.

608 Investigating the spatial distribution of tremor migrations, we found four areas (R1–R4)
609 with the large number of tremor events composing tremor migrations. The followings are the
610 characteristics of the tremor migrations in these areas: In areas R1 and R3, tremor migrations
611 were predominant in the along-dip direction. In areas R2 and R4, tremor migrations were
612 predominant in the along-strike direction. These patterns of tremor migrations represent the
613 behavior of the main front because their spatial distribution of the median duration (6 h) and the
614 median speed (1 km/hr) are consistent with the main front characteristics. We systematically
615 detected RTRs based on the spatial characteristics of the main front, and the three types of RTRs
616 with different patterns were found near R2 and R4. The patterns of tremor migrations (main front
617 and RTR) are related to the distribution of tremor energies, suggesting that the distribution of
618 tremor migrations reflects the fault strength on the plate interface. In addition, we investigated
619 the relationship between migration speed and duration. Tremor migrations slowed down as the
620 durations increased, and the relation $V_{mi} \propto T^{-0.5}$ held. This relationship suggests that a diffusion
621 process controls the growth of tremor migrations.

622 The space-time Hough transform can objectively extract tremor migrations from any data
623 in the tremor catalog worldwide if we set the parameters based on their tremor uncertainties and
624 temporal resolution. The tremor migrations extracted using our method include information on
625 their locations, timing, durations, migration directions, and migration speeds. Therefore, if we
626 comprehensively extract tremor migrations by using the space-time Hough transform, their
627 spatiotemporal characteristics will help understand the rupture process of slow earthquakes
628 worldwide.

629

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632 information on their energy rates (Yabe & Ide, 2014). We would like to thank Editage
633 (www.editage.com) for English language editing.

634 **Conflict of Interest**

635 The authors declare that they have no known financial or non-financial competing
636 interests.

637 **Data Availability Statement**

638 The catalog of tremor migrations in the present study is available from Data Set S1 in the
639 Supporting Information. The tremor catalog of Yabe & Ide (2014) can be downloaded from
640 ‘Slow Earthquake Database’ (Kano et al. 2018b; <http://www-solid.eps.s.u-tokyo.ac.jp/~sloweq/>),
641 which is supported by the Japan Society for the Promotion of Science (JSPS) KAKENHI Grant
642 Number JP16H06472 and JP21H05200.

643

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