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Detailed fault structure of the Tarutung Pull-Apart Basin in Sumatra, Indonesia, derived from local earthquake data

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Abstract

The Tarutung Basin is located at a right step-over in the northern central segment of the dextral strike-slip Sumatran Fault System (SFS). Details of the fault structure along the Tarutung Basin are derived from the relocations of seismicity as well as from focal mechanism and structural geology. The seismicity distribution derived by a 3D inversion for hypocenter relocation is clustered according to a fault-like seismicity distribution. The seismicity is relocated with a double-difference technique (HYPODD) involving the waveform cross-correlations. We used 46,904 and 3,191 arrival differences obtained from catalogue data and cross-correlation analysis, respectively. Focal mechanisms of events were analyzed by applying a grid search method (HASH code). Although there is no significant shift of the hypocenters (10.8 m in average) and centroids (167 m in average), the application of the double difference relocation sharpens the earthquake distribution. The earthquake lineation reflects the fault system, the extensional duplex fault system, and the negative flower structure within the Tarutung Basin. The focal mechanisms of events at the edge of the basin are dominantly of strike-slip type representing the dextral strike-slip Sumatran Fault

System. The almost north-south striking normal fault events along extensional zones beneath the basin correlate with the maximum principal stress direction which is the direction of the Indo-Australian plate motion. The extensional zones form an en-echelon pattern indicated by the presence of strike-slip faults striking NE-SW to NW-SW events. The detailed characteristics of the fault system derived from the seismological study are also corroborated by structural geology at the surface.

Keywords: focal mechanism, seismicity, structural geology, extensional duplex, flower structure, Sumatran Fault, pull-apart basin.

1. Introduction

The convergence between the Indo-Australian and Eurasian plates has produced the subduction zone beneath Indonesia. The shape of the subduction zone beneath Sumatra collocates with the volcanic arc (Fig. 1) as also often found in other areas (e.g. Tatsumi, 1989). In case of oblique subduction, a trench-parallel strike-slip fault system can occur along the volcanic arc. The Liquiñe-Ofqui Fault Zone accommodating the northward motion of a continental forearc sliver relative to the South-American continent (Cembrano et al., 1996; Lange et al., 2008) and the San Andreas Fault System taking up most of the shear component (Teyssier et al., 1995) are among the examples of this case. The 1650 km long strike-slip Sumatran Fault accommodates the trench-parallel shear component of this convergence along the magmatic arc (Bellier and Sébrier, 1994; McCaffrey, 2009; Sieh and Natawidjaja, 2000). Therefore, the shape of the SFS corresponds to that of the Sumatran subduction zone and the Sumatran volcanic arc (Sieh and Natawidjaja, 2000).

A geomorphological study of Sieh and Natawidjaja (2000) revealed that the SFS is partitioned into 19 major sections, mostly caused by the changes in the rate and direction of

55 the Indo-Australian plate motion along Sumatra. This segmentation is characterized by
56 several pull-apart basins caused by dilatational step-overs (Muraoka et al., 2010; Sieh and
57 Natawidjaja, 2000). Though the SFS is segmented, the magnitudes of earthquakes were large
58 enough to devastate the region, such as the 1994 Mw 6.8 Liwa and the 2013 Mw 6.2 Aceh
59 earthquakes.

60 The segments of the SFS show different characteristics (Sieh and Natawidjaja, 2000). In the
61 southern part of the Sumatra island, the Sunda segment (6.75S to 5.9S) is characterized by
62 normal and dextral faulting on the surface, as also indicated by normal fault earthquakes on
63 the western side of the graben, while reverse slip was found along the Kemuring segment
64 (5.3-4.35 S). In central Sumatra, the SFS is characterized by the presence of a bifurcation
65 around 0 - 1.7 N composed of segments (Sieh and Natawidjaja, 2000). Weller et al. (2012)
66 observed a dextral strike-slip duplex system of the bifurcation linked by smaller sinistral
67 strike-slip faults. The mechanism of the extensional duplex system along a bent strike-slip
68 fault is responsible for the presence of a flower structure as described in detail by Woodcock
69 and Fischer (1986).

70 More to the north of the bifurcation, the SFS is characterized by the Renun segment which is
71 the longest segment and one of the largest graben along the SFS traversing the western flank
72 of the Toba caldera (Sieh and Natawidjaja, 2000). The Tarutung district, characterized by the
73 Tarutung Pull-Apart Basin in the north and the Sarulla graben in the south, is located between
74 these two major features, the Toba caldera and the bifurcation segments (Fig. 1). Bellier and
75 Sébrier (1994) suggested that the Tarutung Pull-Apart Basin was developed due to a larger
76 step-over of the previous fault system and as the latest evolution of the great Toba caldera
77 within the older step-over region.

The Tarutung Basin hosts several geothermal manifestations (Fig. 2). At least 18 springs (i.e. cold and warm) discharge along the Tarutung Basin margins (Nukman & Moeck, 2013) and about 13 hot springs discharging in the Sarulla area (Gunderson et al., 1995). It has been suggested that the geothermal system in the Tarutung region is controlled by the fault system (Muksin et al., 2013a). Along the SFS, normal faults along pull-apart basins play an important role as major discharge zones for geothermal fluids (Muraoka et al., 2010). Therefore, it is important to study the fault system in the Tarutung region to understand the structural controls on the geothermal system in the region. This paper presents the fault structure along the Tarutung Basin derived from local earthquake seismicity, as well as the focal mechanism analysis enriched by geological field investigation.

2. Data and Methods

2.1. Previous work

The research started with the deployment of 42 short period seismic instruments for 10 months starting in May 2011, in the district of North Tapanuli Sumatra, Indonesia (Fig. 2). The network covered the area of the Tarutung Basin in the north and the Sarulla graben in the south. The details of the seismic experiment and the data preprocessing are explained in Muksin et al. (2013a) and Muksin et al. (2013b). An automatic picking algorithm (Nippres et al., 2010) was used to detect the arrivals of P and S waves of earthquakes and then the arrivals were revised manually.

For simplification, the earth structure initially was assumed to consist of layers forming a 1D velocity model. We applied HYPO71 (Lee and Valdes, 1985) based on the global 1D velocity model of IASP91 (Kennett and Engdahl, 1991) to produce the first estimate location of 2,586 earthquakes. The earthquake localization was further improved by using the simultaneous inversion for hypocenter relocation and 1D velocity structure (VELEST

software, Kissling et al., 1994). In extension to the previous step (application of HYPO71 based on a fixed velocity-depth function), the 1D velocity model was now modified during the inversion together with the hypocenter locations to better explain the travel time data. Only events with a minimum of 10 station recordings were used in this inversion and subsequent steps. More details of the inversion using VELEST can be found in Muksin et al. (2013a).

The final 1D layered velocity model obtained by VELEST was used to construct an initial 3D velocity structure. The 3D model consists of regularly spaced grid nodes with individual velocity values. A tomographic inversion was then carried out to determine the optimum velocity structure and seismicity distribution within this 3D model using the SIMUL2000 software (Eberhart-Phillips and Michael, 1998; Evans et al., 1994; Thurber, 1983).

The iterative inversion procedure includes Approximate Ray Tracing (Thurber, 1983) to predict travel times, comparison with observed travel time data, and updates of velocity values and hypocenter locations using a damped least-squares algorithm. The iteration process is repeated until the RMS misfit between observed and predicted travel times is minimized. The details of the 3D tomographic inversion are presented in Muksin et al. (2013a).

2.2. New relocation and focal mechanism

The seismicity resulting from the 3D tomographic inversion was then relocated using a double difference relocation scheme (hypoDD) (Waldhauser and Ellsworth, 2000). In general, earthquakes which occur along the same fault segment can be assumed to show similar source mechanisms, and, hence, produce similar waveforms at a receiver. The main idea of this technique is to minimize the residuals between the observed and the calculated travel times of neighboring events observed at one particular station. Two closely located

127 events are considered to be neighboring, if the distance between the events is much smaller
128 than the event-station distance and the size of the velocity heterogeneity (Waldhauser and
129 Ellsworth, 2000). High-resolution relative hypocenters will be obtained when the residuals
130 are minimized. The conjugate least squares inversion method is used in this technique.

131 We used the cross-correlation of waveforms in the relocation procedure. The delineation of
132 the resulting earthquake distribution seems to form a micro-fault system around the basin. We
133 then clustered the earthquakes into 10 groups based on this lineation (Fig. 3) indicated by
134 different colors. The clustering was carried out in space.

135 The maximum distance between an earthquake pair in each cluster was set 1 km. This
136 configuration is plausible since input for the HYPODD was from the result of a 3 x 3 km grid
137 size SIMUL2000 routine.

138 Using the double difference relocation, the residual between the observed and the predicted
139 arrival times for pairs of earthquakes recorded by a similar receiver is evaluated. The velocity
140 model used in HYPODD relocation is the one obtained from VELEST which was also used
141 for the initial model for the 3D tomographic inversion (Muksin et al., 2013a). We used
142 46,904 and 3,191 arrival differences obtained from catalogue data and cross-correlation
143 analysis, respectively. The neighbor threshold used was 10 links, with stations no more than
144 80 km from the event pairs. We constrained the arrival time differences obtained from cross-
145 correlation less than 0.05 s and a correlation factor greater than 70%.

146 We calculated the focal mechanism of the events based on the visually inspected and
147 manually picked first polarity of the P waves using the HASH software (Hardebeck and
148 Shearer, 2002). In the analysis of the focal mechanism, we only include seismic events
149 having more than 8 polarity records. The take-off angles for each observation are calculated
150 based on the ray tracing in the 3D velocity model obtained from SIMUL2000. The seismicity

distribution and the focal mechanisms are then compared with the surface geological field survey to better analyze the fault structure of the region.

2.3. Structural geology observation

Fault kinematic results from Tarutung rock outcrops by Nukman & Moeck (2013) are used to constrain the interpretation of the fault system in the area. The fault kinematics are derived from a striations and subsidiary fractures analysis (Nukman & Moeck, 2013). The measured trend of fractures, veins, and lineaments of thermal manifestations are also used in the fracture analysis by comparing their fracture attitude to the main fault orientation (Nukman and Moeck, 2013). Most of the structural measurements are taken from rock unit of Miocene to Recent age.

3. Results

From the HYPODD relocation we found, that after 16 iterations the average RMS of waveform cross-correlation and earthquake catalogue are 0.33 ms and 0.47 ms, respectively. The average change in the hypocenter is 10.8 m and the average shift of centroids is 167 m. The largest change is contributed to the relocation of the first cluster which contains the largest number of earthquakes. The use of the double difference relocation reduced the number of events from 809 to 735 because the outlier events were excluded. The summary of the relative relocation statistics is provided in Table 1.

Fig. 4 shows the hypocenter location resulting from the 3-D inversion (SIMUL2000) and the relative relocation (HYPODD). In general, the use of the relative relocation does not significantly change the hypocenter location. However, it significantly sharpens the lineation

of the earthquakes along the main SFS and along the secondary fault system around the Tarutung Basin.

Given the ray azimuth and takeoff angles derived from a 3D inversion, each focal mechanism is calculated for different trials indicated by black thin lines on each fault plane solution in Fig. 5a. A grid search procedure is performed to find fault plane solutions which explain the data. Following Hardebeck and Shearer (2002) we perform 50 trials with a 5^0 interval. The preferred solution represents the most probable mechanism of all acceptable mechanisms. Fig. 5a shows some examples of the focal mechanisms with different quality defined in Table 2. After removing outliers indicated by black dots on the white areas and white dots on the black areas in Fig. 5a the average of acceptable solutions is chosen as the preferred mechanism. In the procedure of the focal mechanism calculation, the solution with the largest difference from the average is excluded and the new average is calculated until all remaining mechanisms are within 30^0 of the average.

The mechanism quality criteria shown in Table 2 are similar to the criteria used by Hardebeck and Shearer (2002). We assume that the focal mechanisms with quality B (31 events), C (23 events) and D (376 events) are acceptable. From 725 events, only 430 events have acceptable focal mechanisms which are located at latitude larger than 1.85^0 . Because of poor station coverage, earthquakes located in Sarulla (southern part of Tarutung) have low quality focal mechanisms (E and F criteria). The majority of the earthquakes along the main fault is right lateral strike-slip associated with the NW-SE striking main fault (Fig. 4 and Fig. 5b). Along the secondary fault system within the Tarutung Basin the earthquakes are more complex containing NW-SE strike-slip, NS strike-slip and (oblique) normal mechanisms (Fig. 6).

4. Discussion

4.1 Fault system

4.1.1 The Seismicity along Sumatran Fault and the basin margin

We focus the analysis of the fault structure on the area surrounding the Tarutung Basin. Since the stations along the Sarulla Basin (the southern part of the network) were only located along the fault, we could not derive good quality focal mechanisms for the events in the south. As shown in Fig. 6, in the south of Tarutung (outside of the basin), the earthquakes are distributed along the main SFS. This earthquake cluster is mostly strike-slip associated with the strike-slip fault of the main SFS. The seismicity distribution also confirms that the Tarutung Basin is a pull-apart basin. The two active flanks (the eastern and the western) of the SFS are delineated by the seismicity. The events along these two flanks are mostly strike-slip similar to the SFS. The western flank of the fault seems to be more active than the eastern flank.

The earthquake distribution in and around the Tarutung Basin reflects the geometry of the basin. The boundary line of the basin in Fig. 6 is obtained from Nukman and Moeck (2013). A large number of earthquakes occurred at the northwestern and southeastern corners of the basin. The normal fault system at the southeastern corner of the basin (Fig. 6 in Nukman and Moeck (2013)) is also reflected by the seismicity pattern. The high seismicity in the corner of the basin is associated with the fault bend. A pull-apart basin along a strike-slip fault normally starts to develop at the fault bend (e.g. Woodcock and Fisher, 1986). The large number of the earthquakes at the fault bends (at both corners) indicates that the basin is very active and the basin is still developing.

220 **4.1.2 Extensional zones**

221 In addition to the boundary faults, we notice large number of earthquakes related to a set of
222 secondary faults. The secondary fault system associated with the extensional zones from
223 Nukman and Moeck (2013) is also indicated by the almost north-south direction strike-slip
224 and (oblique) normal fault earthquakes (Fig. 6). Some extensional zones within the basin can
225 be observed in the topography. The extensional zones derived from the lineation of seismicity
226 are consistent with those obtained from the geological observation. The black and blue nearly
227 N-S striking extensional zones (Fig. 6) represent the fault zones derived from geological
228 observation and seismicity lineation, respectively. The N-S and NNE-SSW strike of fault
229 plane solutions along the extensional faults correlates with the maximum principal stress
230 direction. The almost N-S compressional stress would be induced by the nearly N-S Indo-
231 Australian plate motion. The extensional faults form an en-echelon pattern indicated by the
232 NW-SE dextral strike-slip earthquake along the northern extensional zones.

233 **4.1.3 The conceptual model**

234 In order to study the fault system at depth we rotate the seismicity, the faults, and the basin
235 geometry so that the secondary fault system (the extensional zones) is perpendicular to the X-
236 axis as shown in Fig. 7a. All earthquakes are then projected onto the Y axis showing the
237 distribution of the earthquakes at depth (Fig. 7b). We deduce the vertical fault system from
238 the depth to the surface based on the seismicity pattern. The derived fault system is indicated
239 by the thick transparent light blue lines overlaying the seismicity. In Fig. 7b we exclude the
240 seismicity along the main SFS and along the basin margins in order to analyze the vertical
241 pattern of the seismicity within the Tarutung Basin. The earthquakes did not occur at shallow
242 depth, most likely because the basin is filled with unconsolidated material until a depth of 2.5
243 km, as indicated in the Vp images (Muksin et al., 2013a).

244 The secondary fault system appears to be very steep as also found by the geological studies
245 (Nukman and Moeck, 2013). The vertical seismicity pattern also correlates with the location
246 of the extensional zones at the surface as observed by the geological mapping.

247 From the seismicity pattern and the focal mechanisms we propose a simplified conceptual
248 model of the fault system in the Tarutung Basin as shown in Fig 8. The layers in Fig. 8 are
249 taken from from seismic velocity derived from the Vp and Vp/Vs tomography study (Muksin
250 et al., 2013a – Fig. 15). Different layers represented by the variation of seismic velocities are
251 caused mostly by the changes in rock types. The map view of the seismicity shows imbricate
252 fault arrays in strike-slip systems splaying on the Tarutung Pull-Apart Basin. This indicates
253 the presence of almost symmetrically extensional duplexes occurring at a releasing bend
254 between 1.96° and 2.07° N (Fig. 6). Normal or oblique normal faults should accompany the
255 extensional duplexes to accommodate the extension caused by the NW-SE dextral strike-slip
256 main SFS. The conceptual model (Fig. 8) shows dip-slip faults resulting in the extensional
257 duplexes in the cross-section view. In a fault-perpendicular cross-section, this structure would
258 be recognized as a negative flower structure. Nukman and Moeck (2013) suggested that
259 several parallel WNW–ESE striking normal faults in the east of the Tarutung Basin indicate
260 the presence of negative flower structure (see Fig. 3 in Nukman and Moeck, 2013).
261 Following Nukman and Moeck (2013), the strike direction of these parallel normal faults has
262 rotated clockwise to WNW-ESE.

263 Although the extensional duplex system is not observed clearly on the surface it is revealed
264 by the accurate hypocenter locations in the small Tarutung Basin. Extensional duplex faults
265 are often observed at a bend or a step-over offset of a strike-slip fault (Woodcock and
266 Fischer, 1986). A slightly different type of an extensional duplex system is observed in the
267 vicinity of the bifurcation just south of the Tarutung district (Weller et al., 2012). Other
268 duplex systems might also be found along the SFS since several fault bends and step-over

offsets are visually observed (e.g. Singkarak and Suoh pull-apart basins). Similar extensional duplex systems are found in other areas for example along the *Liquiñe-Ofqui Fault Zone*, southern Chile (Cembrano et al., 1996) and York Cliffs strike-slip fault system, southern coastal Maine, USA (Swanson, 1990).

4.2 Fault controlled geothermal system

It has been proposed that the geothermal resource in the Tarutung area is controlled by the fault system (Muksin, et al., 2013a, 2013b; Nukman & Moeck 2013). This interpretation is based on the high V_p/V_s structure and the high seismic attenuation anomalies (Muksin, et al., 2013a, 2013b). The ratio of helium isotope as measured by Halldórsson et al. (2013) shows a low value (i.e R/R_a 1.6-1.7). This low R/R_a indicates that a heat source in the crust is more dominant than one from the mantle. Niasari et al. (2012) suggested that the geothermal resource in Tarutung is a result of deep fluid circulation according to the interpretation of the magnetotelluric data.

At the eastern junctions of the extensional zones and the eastern margin of the basin we found travertine (indicated by blue ellipses in Fig. 6). Nukman and Moeck (2013) and Hochstein and Sudarman (1993) suggested that these travertine dykes explain the characteristics of the geothermal reservoir. The presence of the travertine dykes in the eastern margin indicates that high hydrogen-carbonate rich hot fluid is fed from depth (6-10 km) to the east (Nukman and Moeck, 2013). At depth, the fluid uses the faults as pathways while at shallow depth the fluid is transported along a more permeable zone in the east (Hochstein and Sundarman, 1993). At the surface, Nukman and Moeck (2013) observed large number of west-dipping normal faults (e.g. around Panabungan) and fractures in the east that ease the fluid transport.

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292

5. Conclusion

We derived the fault structure at depth from the seismicity relocation and focal mechanism analysis and supported by geological evidence. The application of the relative relocation scheme sharpens the seismicity distribution reflecting the fault lineation more clearly, although the cluster centroids do not change significantly. The seismicity distribution images well the geometry of the Tarutung Pull-Apart Basin at depth. Along the western and eastern margin as well as along the fault south of the Tarutung Basin the earthquakes are mostly strike-slip associated with the dextral strike-slip SFS.

The delineation of the events shows the presence of the strike-slip extensional duplex at the releasing bend within the Tarutung Pull-Apart Basin which is not clearly observed at the surface. The extensional duplex system forms a negative flower structure of the Tarutung Basin. Two duplex faults derived from the seismicity distribution coincide with extensional zones found by geological observation. The array of parallel extensional zones accommodates the almost N-S maximum stress associated with the direction of the Indo-Australian and Sunda plates convergence. The geothermal system in the Tarutung area seems to be a fault-controlled system which uses the fault zones (at depth) as the fluid pathways. We suggest that the hot fluid is transported to the more dilatational, more fractured and more permeable region in the east.

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395

396 **FIGURE CAPTION**

397 Fig. 1: Regional tectonic setting of Sumatra and Tarutung district (box) is located between
398 the Toba caldera and the bifurcation. The location of the Singkarak and the Suoh Basins are
399 represented by the white circles.

400

401 Fig. 2: Station distribution covering the Tarutung and the Sarulla Basin deployed for 10
402 months starting May 2011.

403

404 Fig. 3: The earthquakes were clustered based on a fault-like seismicity distribution obtained
405 from the 3D inversion. The earthquakes are then relocated by using double difference
406 technique. Different colors represent different group of events.

407

408 Fig. 4: The comparison between the hypocenters obtained from SIMUL2000 (LEFT) and
409 HYPODD relocation (RIGHT). Color indicates earthquake depths.

410

411 Fig. 5: The results of focal mechanism analysis. (a) Examples of preferred solutions of focal
412 mechanisms characterized as B, C, and D defined in Table 2. White and black dots represent
413 down and up polarities, respectively. The thin lines show 10 different possible solutions with
414 higher RMS values. (b) The total strike direction of all focal mechanisms.

415

416 Fig. 6: The seismicity pattern and selected focal mechanisms plotted onto the topographic
417 map. Topography is ASTER G-DEM (30 m resolution). The basin geometry and the
418 extensional zones are represented by the black solid lines (after Nukman & Moeck, 2013).
419 The blue lines indicate the extensional zones derived from the seismicity. The red stars, the
420 white circles, and the blue ellipses respectively represent the hot springs, the seismicity, and
421 the travertines.

422

423 Fig. 7: (a) The rotated map view of the seismicity. (b) The seismicity at all depth projected to
424 X coordinate. The seismicity along the main fault is excluded in Fig. b. The thick transparent
425 light-blue lines indicate the vertical fault system deduced from the seismicity pattern.

426

427 Fig. 8: Simplified conceptual model of the fault system in the Tarutung Basin. The layers are
428 derived from seismic velocity layers indicating different rock types (Muksin et al., 2013a).

429

430 **TABLES**

431 Table 1. Statistics of hypoDD relocation of 10 main clusters after 16 iterations. CC refers to
 432 cross-correlation and CT means catalogue.

433

Cluster	Number of events	Events mean shift				CC-RMS (ms)	CT-RMS (ms)
		x (m)	y (m)	z (m)	t (ms)		
1	188	33.5	25.5	9.9	0.1	0.596	0.486
2	151	2.5	3.2	16.7	0.6	0.201	0.471
3	76	7.7	7.2	7.9	0.1	0.455	0.533
4	58	1.8	0.9	14.7	0.4	0.347	0.440
5	58	4.6	5.7	1.3	0.0	0.239	0.472
6	52	4.3	3.6	1.2	0.1	0.405	0.498
7	39	1.1	1.5	11.5	0.3	0.310	0.432
8	39	0.2	1.8	4.1	0.1	0.315	0.470
9	34	1.9	1.6	4.7	0.4	0.322	0.550
10	21	0.9	1.0	1.8	0.2	0.152	0.424

434

435 Table 2. The mechanism quality criteria used in the focal mechanism calculation.

Quality	Average misfit	RMS fault plane uncertainty	Station distribution ratio	Mechanism probability	Number of events
A	≤ 0.15	$\leq 25^0$	≥ 0.5	≥ 0.8	0
B	≤ 0.20	$\leq 35^0$	≥ 0.4	≥ 0.7	31
C	≤ 0.30	$\leq 45^0$	≥ 0.3	≥ 0.6	23
D	Maximum azimuthal gap $\leq 90^0$, maximum takeoff angle gap $\leq 60^0$				376
E	Maximum azimuthal gap $> 90^0$, maximum takeoff angle $> 60^0$				26
F	Fewer than 8 polarities				269

436

Figures

Figure 1: Regional tectonic setting of Northern Sumatra and Tarutung district (box) is located between the Toba caldera and the bifurcation.

Figure 2: Station distribution covering the Tarutung and the Sarulla basin deployed for 10 month starting May 2011.

Figure 3: The clusters of the seismicity distribution obtained from the 3D inversion based on the delineation. The earthquakes are then relocated by using double difference technique. Different colors represent different group of events.

Figure 4: The comparison between the hypocenters obtained from SIMUL2000 (LEFT) and HYPODD relocation (RIGHT). Color indicates earthquake depths.

Figure 5: The results of focal mechanism analysis. (a) Examples of preferred solutions of focal mechanisms characterized as B, C, and D defined in Table 2. White and black dots represent down and up polarities, respectively. The thin lines show 10 different possible solutions with higher RMS values. (b) The total strike direction of all focal mechanisms.

Figure 6: The seismicity pattern and selected focal mechanisms plotted onto the topographic map. Topography is ASTER G-DEM (30 m resolution). The basin geometry and the extensional zones are represented by the black solid lines (after Nukman & Moeck, 2013). The blue lines indicate the extensional zones derived from the seismicity. The red stars, the white circles, and the blue ellipses respectively represent the hot springs, the seismicity, and the travertines.

Figure 7: (a) The rotated map view of the seismicity. (b) The seismicity at all depth projected to X coordinate. The black and blue marks on the surface in Fig. b represent the locations of extensional zone derived from the geological observation and the seismicity, respectively. The seismicity along the main fault is excluded in Fig. b. The thick transparent light-blue lines indicate the vertical fault system deduced from the seismicity pattern.

Figure 8: Simplified conceptual model of the fault system in the Tarutung Basin. The layers are adopted from Muksin et al. (2013a).