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**The 2016 Mw 6.5 Pidie Jaya, Aceh, North Sumatra Earthquake: Reactivation
of an Unidentified Sinistral Fault in a Region of Distributed Deformation**

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Abstract

On December 6, 2016, an Mw 6.5 earthquake occurred in Pidie Jaya, Aceh,
about 30 km to the north of Sumatran Fault (SF) that killed more than 100 people

24 and destroyed approximately 3,000 buildings. Mainshock focal mechanism
25 inversions using regional BMKG broadband data and teleseismic waveform data
26 all indicate a strike-slip event with a centroid depth of 11-15 km. The observed
27 macro intensity data show that most of the damaged buildings are distributed
28 along the coast, approximately perpendicular to the ruptured fault strike instead
29 of parallel with it. The strong shaking/damage sites are primarily located on the
30 coastal sedimentary soils, highlighting the importance of site conditions in
31 determining risk. We used one-month data recorded by nine temporal broadband
32 stations to locate aftershocks with grid search and double-difference algorithms,
33 thereby resolving a linear trend of seismicity aligned in NE-SW direction. The
34 refined aftershock locations indicate a left-lateral rupture that is in agreement with
35 the preliminary finite fault slip inversion as well as geomorphic signatures of local
36 geological structure. Using a well-located M_L 4.2 aftershock for path calibration,
37 we relocated the mainshock epicenter with regional P-wave arrivals. The refined
38 epicenter falls within the cloud of the well-located aftershocks while locations
39 from the global and regional catalogs are located 10–20 km away. Aftershock
40 focal mechanisms determined by the first motion reveal similar solutions as the
41 mainshock. This earthquake sequence ruptured a previously unidentified fault
42 that either located at the west of the fault that produced the 1967 M_w 6.1
43 earthquake sequence, or is actually at the same fault. The Pidie Jaya earthquake
44 and other off Sumatran Fault events suggest strong distributed crustal
45 deformation in Aceh, highlighting the need for better understanding of active
46 faulting and seismic hazard in this region.

47

48 **1. Introduction**

49 On the early morning of Wednesday, December 07, 2016, 05:03:33 local time
50 (Dec 06, 22:03:33 UTC), an Mw 6.5 earthquake rocked the northern coastal area
51 of north Aceh in the Pidie Jaya region (here after named as Pidie Jaya
52 Earthquake). The BMKG (Agency for Meteorology, Climatology, and Geophysics
53 of Indonesia) reported an epicenter location of 5.29°S and 96.22°E, with a
54 shallow depth of 15 km. The Pidie Jaya Earthquake occurred at the moment
55 before dawn when many people were still asleep and many others were in the
56 mosques for Morning Prayer. The earthquake caused heavy damage within a
57 radius of approximately 35 km of the epicenter. In total, 101 people were killed
58 (mainly caused by building collapsing), over 800 people were injured, thousands
59 were displaced and thousands of buildings collapsed or were severely damaged.
60 The estimated economic loss was about 139 Million USD according to the
61 National Disaster Management Authority of Indonesia (BNPB). This earthquake
62 was well recorded by the national strong motion and broadband networks with
63 closest station being ~80 km away (Figure 1). Within five minutes of the origin
64 time, BMKG reported the hypocenter location and magnitude of the earthquake.
65 A few minutes later, GFZ-Potsdam and USGS at international level also issued
66 similar information (Table 1). All three institutions inferred a similar location and
67 magnitude of the earthquake, with difference in location up to ~20 km (Figure 1).
68 After the earthquake, both BMKG and USGS released estimated ground shaking
69 intensity maps and its potential impacts (*Shakemap*, Wald et al., 2005). However,

these preliminary intensity maps are based on simplified models and sparse datasets, and cannot account for more localized shaking effects.

Local people's understanding of earthquakes in Aceh has improved since the shaking and tsunami experience from the Mw 9.3 earthquake in 2004 (e.g. Lay et al., 2005). Nevertheless, post-earthquake interviews of people on site indicate that the Pidie Jaya earthquake was very surprising to them because the shaking was quite different in nature from their experience of the 2004 earthquake. The 2016 event produced very sharp shaking and jerked vertically, in contrast with the shocks in 2004 that were relatively slow and moved horizontally. This is possibly because the 2016 earthquake occurred much closer to them and the ground shaking was dominated by high-frequency body waves, while more remote 2004 event produced stronger long period surface-waves. In this paper, we combine interviews and site investigations to produce an updated intensity map for the Pidie Jaya earthquake, shown in Section 2.

As shown in Figure 1, Pidie Jaya is located at the northern coast of Aceh, part of northern Sumatra, where the Indian Ocean Plate subducts beneath the Sunda Plate at about 5.2-6.0 cm/year (McCaffrey, 1992; Sieh and Natawidjaja, 2000). While the subduction process has generated significant uplift all along Sumatra, the mountainous ridge that traverses the island is widest and highest in Aceh, where elevations reach ~3381 meters above sea level (Barber et al., 2005). Oblique subduction has produced the right-lateral Sumatran Fault (SF) system

93 through a slip partitioning process (McCaffrey, 1992, 2009). Fast slip rates of
94 ~2.7-3.8 cm/year have previously been proposed for the SF in the Aceh region
95 (Bennett, 1980; Sieh et al., 1994; Genrich et al., 2000). However, a more
96 accurate study suggests that the average slip rate along most of the SF,
97 including in Aceh, is between ~1.5 to ~1.6 cm/year (Bradley et al., 2017). A
98 portion of the total strain produced along this complex convergent margin has
99 been distributed within the Sumatran crust, and is responsible for the complex
100 modern topographic pattern, with many active faults occurring away from the
101 main strand of the SF. This is particularly true for the region of the 2016 Pidie
102 Jaya earthquake, where two main SF strands (~5.5°N) appeared to be nearly
103 free of horizontal geodetic strain (Genrich et al., 2000). It was proposed that the
104 strain in this region was likely taking place further to the east on the
105 Lhokseumawe (LHOK) and Samalanga-Sipopok (SAM-SIP) faults (Genrich et al.,
106 2000). The 2016 Mw 6.5 Pidie Jaya earthquake was located in the place very
107 close to the northwestern tip of the SAM-SIP Fault. While initial reports (e.g.
108 USGS, BMKG, GCMT) of the earthquake indicated a strike-slip focal mechanism,
109 the preferred strikes (149°/55°) of those fault plane solutions differed from that of
110 the SAM-SIP Fault (~180°), suggesting rupture of a previously unidentified fault.
111

112 The national permanent seismic network was installed gradually by BMKG after
113 the Mw 9.3, 2004 earthquake. It has now reached a station spacing of ~100 km
114 in Sumatra, which is still insufficient to detect and relocate relatively small
115 earthquakes and aftershock swarms with enough precision to resolve fault

geometries. Previous temporary networks installed in northern Sumatra have proved to be highly valuable for seismic velocity structure inversions and detection of active faults (Muksin et al., 2014; 2018, submitted). Therefore, to better locate aftershocks and understand fault structure, one week after the Pidie Jaya Earthquake, BMKG, GFZ-Potsdam (German Research Center for Geosciences), ITB (Bandung Institute of Technology) and UNSYIAH (Syiah Kuala University) installed a temporary seismic network composed of nine broadband stations in the ruptured area. The network was distributed along the coast with an average station spacing of ~15 km (Figure 1). The network was named as Pijay-Net and operated for about one month (14/12/2016-15/01/2017), providing valuable waveform dataset for aftershock relocation and focal mechanism studies.

In this study, we first summarize the macro intensity distribution, damage extension, and ground motion characteristics of the mainshock along with site response analyses. We then relocate the mainshock, relocate the aftershocks that were recorded by the Pijay-Net, and determine the focal mechanisms of relatively large aftershocks using P-wave first motion. Finally, we present a finite fault inversion that uses the fault geometry constrained by the relocated seismicity.

2. Intensity and ground motion

138 Three days after the earthquake, a team from BMKG arrived in Pidie Jaya to
139 collect mainshock intensity data. We investigated building damage at 49 sites in
140 the vicinity of the epicenter region, and documented the damage with
141 photographs and interviews. Here, we use the intensity scale defined by BMKG.
142 This new intensity scale, SIG-BMKG (*Skala Intensitas Gempabumi*-BMKG)
143 (Muzli et al., 2016), is a simplified version of MMI (Modified Mercalli Intensity). It
144 was designed to facilitate local understanding of earthquake impacts and
145 implementation of hazard preparation and mitigation throughout Indonesia. SIG-
146 BMKG has been used in routine dissemination of significant earthquake
147 information in Indonesia since 2016 (see Data and Resources). The SIG-BMKG
148 recognizes only five levels, as shown in Table 2 along with the corresponding
149 MMI classification.

150

151 We used interview reports and inspections of building and infrastructure damage
152 to determine the SIG-BMKG intensity at the 49 sites, shown as circles in Figure
153 2. In general, the intensities derived from interviews have larger uncertainties, as
154 they are subjective; on the other hand, inspections of buildings resulted in more
155 accurate intensity estimations. Photographs of damage at these sites (numbered
156 in Figure 2) can be found in the supplementary materials (Figure S1), with
157 representative damage shown in Figure 3. The number of fatalities and damaged
158 buildings are shown in Table 3. The maximum inferred intensity is V in SIG-
159 BMKG or IX in MMI (Modified Mercalli Intensity), corresponding with total building
160 collapse (e.g., Figure 3). It is likely that the complete building collapse was

caused by a combination of poor structure design, strong shaking and site effect. At several sites, collapsed buildings neighbored structures exhibiting only light damage, indicating very different building design and quality. For instance, site #31 (Figure 3a) and #32 (Figure 3b) are directly adjacent but the degrees of damage are substantially different. The most severe building damage was found near the relocated mainshock epicenter (see details of relocation in next Section). The damage zone spreads in a nearly east-west direction, parallel to the coastline, with only a few damage reports from inland areas to the south of the mainshock epicenter. The direction of the building collapse or movement agreed well with a left lateral strike-slip focal mechanism (e.g. sites #10, #11, #27 and #40 in Figure S1), consistent with the fault geometry defined by the relocated aftershocks. These photos provide independent evidence for the ruptured fault plane, preferring the one with a strike of 055° . The aftershock distribution also implicates the fault plane with strike of 055° , rather than the orthogonal plane with strike of $\sim 149^{\circ}$, which is more parallel to the coast and to the Sumatran Fault.

We therefore assume a relocated hypocenter of $96.225^{\circ}\text{E} / 5.235^{\circ}\text{N} / 15\text{km}$, M_w of 6.5, and a strike-slip focal mechanism of the mainshock and predict the distribution of Peak Ground Velocity (PGV) and Peak Ground Acceleration based on the GMPE in Zhao et al. (2006) and Newmark and Hall (1982). We then convert the PGV into intensity, with V_{s30} (the average shear wave velocity down to 30 meters) taken into account (Figure 2) (Wald et al., 2005). The conversion of

184 ground motion to intensity is based on the empirical formula of GMICE (Ground
185 Motion to Intensity Conversion Equation) as described by Worden et al. (2012). It
186 shows that the maximum predicted intensity is VIII in MMI at the relocated
187 epicenter location. This predicted intensity is slightly smaller than that implied by
188 the observed damage (see Figures 2 and S1, e.g. index #18, #38 and #40),
189 probably due to poor building quality. The predicted intensity map also shows an
190 elongated distribution of high intensity along the coast. The east-west oriented
191 damage zone in the residential area was likely strongly related to site effects
192 rather than the finite rupture process, as the soft soil (very low Vs30) zone is
193 distributed along the coast instead of along the strike of the fault (Figure 4).
194 Further inland to the south, the population is relatively low and is a hilly area,
195 where the soil is harder and thinner than the coastal area. Thus, the damage
196 reported in this area is much less.

197

198 The thickness of sediment in the coastal region is approximately 4.0 km
199 according to Crust1.0 (Laske et al., 2013). However, Crust1.0 is a low-resolution
200 model, and a more accurate sedimentary structure in this region awaits further
201 investigation. Other data that can indicate the thickness of the soil layer and
202 amplification effect are the HVSR (Horizontal to Vertical Spectral Ratios) from
203 ambient seismic noise data (Nakamura, 1989, 2008). Many studies (e.g. Parolai
204 et al., 2002; Gosar and Lenart, 2010) have shown that there is a strong
205 correlation between the resonance frequency from HVSR and soil thickness. The
206 results of HVSR from ambient noise data at Pijay-Net stations are shown in

207 Figure 5, where peak resonance frequency ranges from 0.7 to 8.0 Hz, indicating
208 variable of soil thickness beneath the stations. The lowest resonance frequency
209 is observed at the A22 station (0.7 Hz) corresponding with a 188 m soil thickness
210 based on an empirical formula in Parolai et al. (2002). This soil layer has a
211 significant effect on the local amplification of ground motion and resonance.
212 Based on HVSR (Table 2 in Zhao et al., 2006), we also estimated the site
213 classification at the 8 Pijay-Net stations. We found that in general the HVSR
214 derived site classifications agree well with that derived from Vs30 (Figure 4),
215 however, there are some discrepancies, for instance, the site classification of
216 A21 is A+B and D from HVSR and Vs30, respectively. This difference is not
217 unexpected, as Vs30 is derived from topography and has large uncertainties
218 (e.g. Lemoine et al., 2012).

219

220 As part of the Pijay-Net, we also deployed one strong motion station (JAKO) at
221 5.2393°N and 96.2499°E near the major event epicenter, two days after the
222 earthquake (see the station location in Figure 1), which has recorded the
223 aftershocks between 09/12/2016 and 11/12/2016. An aftershock with m_b of 4.9
224 was recorded by this station; the three component waveform of the earthquake
225 recorded is shown in Figure 6. Because the epicenter was located only 19 km
226 away, the recorded PGA was ~67 gals. Using data from national strong motion
227 network (BMKG), we assembled all strong motion records for the earthquake
228 sequence. We plotted all the Peak Ground Acceleration (PGA) against the
229 hypocenter distance in Figure 7, along with the PGA predictions from GMPE

(Ground Motion Prediction Equation) described in Zhao et al. (2006). We used GMPE from Zhao et al. (2006) because there is still no GMPE available in Sumatra, and the region of Japan, which was studied in Zhao et al. (2006), is probably one of the most similar places to Sumatra in terms of tectonics. Both Sumatra and Japan are located on the overriding plates in the subduction zone systems, where the significant ground motion comes from the megathrust on the plate interface and earthquakes on the inland faults. The predicted PGA and PGV of the mainshock at the epicenter location (5.235N; 96.225E) are 284 gals and 23.8 cm/s, respectively. Overall, the ground motions predicted by GMPE are comparable with our observations for the mainshock (see Figure 7), although the prediction underestimates the PGA at the closest sites and overestimates it in the far field for the M4.9 and M4.2.

During the post-earthquake survey, we did not locate clear evidence of surface rupture along the strike of the fault. However, the earthquake did produce some localized surface deformations along the coastal area (Figure S1, e.g. index #22 and #28). As shown in the following Section, the strike of the fault defined by the aftershocks and focal mechanisms does not align with the strike of these surface deformations. As the largest asperity in the preliminary finite rupture model (see Section 4) and the majority of aftershocks (see Section 3) were also located at the depth range of 8-20 km, the observed surface cracks were likely caused by secondary ruptures, post seismic deformation, or near-surface effects.

3. Seismicity relocation and aftershock focal mechanism inversion

To better understand the fault geometry and associated tectonics, we used the arrival time picks on the waveform data recorded by Pijay-Net to locate the aftershocks that occurred between 14/12/2016 and 15/01/2017. The regional broadband data, which is the closest at 80 km away from the aftershocks, were not included for the small events relocation. During this period, Pijay-Net has recorded more than 300 events with the magnitudes larger than 0.50. Among these events, we have 260 quakes with $M_L > 1.0$, for which we can pick P-wave arrivals with high accuracy. Since the stations are very close to the event locations, the averaged accuracy of arrival picks is as high as ~ 0.1 s. These picks were then used to locate the earthquakes through a grid search manner (e.g. Wei et al., 2015). To calculate the theoretical arrival time, we use the Crust1.0 model (Laske et al., 2013) and a grid spacing of 0.5 km. After the initial grid search, we further relocate the events with a double difference algorithm implemented in hypoDD (Waldhauser and Ellsworth, 2000; Waldhauser, 2001). The relocation results in map view and vertical profiles are shown in Figure 8. We also plotted USGS locations for the historical 1967 M6.1 earthquake sequence on the same figure (shown as blue circles). The surface projection of the relocated seismicity shows a clear lineation that has a fault length dimension of ~ 20 km and strikes towards an azimuth of $\sim N042^\circ$, agreeing well with the strike of one of the fault plane solutions of the mainshock. Interestingly, a vertical cross section along the direction perpendicular to this strike reveals more complexity in the aftershock distribution. The majority of the seismicity defines a fault plane

276 that dips $\sim 63^\circ$ towards southeast, again consistent with one of the mainshock
277 fault plane solutions. However, there are at least two vertical branches at depths
278 of 12 and 18 km (Figure 8), indicating possible vertical segmentation of the fault.
279 The lineup of the seismicity at one of the branches dips $\sim 25^\circ$ to the northwest.
280 This part of the seismicity is very localized as indicated in the map view, and
281 could represent a small fault that either ruptured during or was subsequently
282 activated by the mainshock. A planar extrapolation of the main seismicity along a
283 dip angle of 63° intersects the surface about 5 km to the west of the seismicity
284 cloud. This surface projection coincides with linear topographic ridges that align
285 with the strike of the fault, which mark anticlines and synclines deforming Late
286 Miocene and Pliocene sediments and overlying Pleistocene arc volcanics
287 (Bennett et al., 1980; Figure 8). We name this structure the Panteraja Fault. The
288 depth of aftershocks are primarily distributed between 8 to 23 km, with the
289 deepest event located at a depth of 28 km (Figure 8), indicating that the lower
290 crust is seismogenic as the crustal thickness in this region is only 30 km
291 according to Crust1.0 model. The depth of the seismicity is further verified by
292 inspecting the relative arrival time between P and S waves at the closest station
293 A22 (Figure 9). It is clear that, the deepest event has the largest S to P
294 differential arrival time. A deep potential seismogenic depth should therefore be
295 considered in the future seismic hazard estimation in this region. Deeper
296 seismogenic zone can physically facilitate longer rupture dimension along strike
297 and therefore generate larger earthquakes (Weng and Yang, 2017). This factor
298 should be taken into consideration in the future seismic hazard estimation in this

region. Notably, the preferred strike of $\sim 055^\circ$ is inconsistent with the orientation of north-south strike-slip faults that appear on maps but have no clear topographic expression (such as the Samalanga-Sipopok Fault), as well as with the north-south strikes of inverted basin-bounding normal faults of the well-known North Aceh basin just to the east of the study area (Barber et al., 2005).

Among the 260 aftershocks there are 23 events having the magnitudes larger than 3.0. The largest magnitude (M_L 4.2) recorded by Pijay-Net occurred on 17/12/2016 was also well recorded by the regional network. However, the location of this earthquake from USGS epicenter report is 15.5 km away from our relocated epicenter. As our location is much more accurate than the global and regional catalogs due to our proximal and dense network, we can calibrate the paths to the BMKG and GFZ or IRIS broadband stations and refine the epicenter of the mainshock. To do that, we calculate the theoretical arrival times using Crust1.0 velocity model at regional broadband stations (Figure 1) for the M_L 4.2 aftershock and compare them with high-quality handpicked arrivals. The residuals are then used to correct the theoretical arrival time for the mainshock. With this correction, we refine the mainshock epicenter in a grid search manner. Our relocation of the mainshock epicenter (5.235N; 96.225E) is consistent with our relocated aftershocks (Figures 8 and S2). The path calibration for these regional stations can be used to refine the location of future earthquakes in northern Sumatra.

322 We then estimate focal mechanisms of the large aftershocks ($M_L > 3.0$) using
323 inversion of the P-wave first motion data from the Pijay-Net, with an approach
324 proposed by Suetsugu (1997). Waveform records of $M_L > 3.0$ events show clear
325 P-wave first motion polarities due to their relatively large magnitude. All together,
326 we have obtained focal mechanisms of 17 events, which are shown in Figure 8
327 both in map view and depth profiles. The majority of these events have a
328 mechanism similar to that of the mainshock; such consistency further verifies the
329 fault geometry determined by our refined seismicity. We also invert the double-
330 couple solution of the mainshock by using broadband waveforms recorded by the
331 regional BMKG stations that have a good azimuthal coverage for the earthquake.
332 After removing the instrument response from the raw data, we applied the Cut-
333 and-Paste (CAP) method (Zhu and Helmberger, 1996) to invert for
334 strike/dip/rake/ M_w /depth of the earthquake in a grid search manner. A 1D
335 velocity model extracted from Collings et al. (2012) was used to calculate the
336 Green's function library for the inversion. The depth resolution and best
337 waveform fits are shown in Figures S3 and S4, respectively. Both data and
338 synthetics show the largest amplitude on the tangential components, which is
339 typical for a strike-slip focal mechanism. As shown, the centroid depth of the
340 earthquake is ~ 11 km, which is in agreement with the finite slip distribution
341 derived from teleseismic inversion as shown in the following section. (The
342 relocated aftershocks and focal mechanism can be found in the supplement
343 material)
344

4. Finite fault slip model

Although the magnitude of the Pidie Jaya Earthquake is relatively small ($M_w 6.5$) compared with other damaging events, we attempted a teleseismic finite fault inversion in order to resolve the fault plane of the earthquake. We downloaded broadband teleseismic P-waves recorded by the Global Seismic Network (GSN) from IRIS (see Data and Resources). We removed the instrument response and converted the waveform data into displacement at 2.0 Hz and lower frequency. We used a hypocenter of 15 km, as determined by BMKG, and a 1D velocity model extracted from Crust1.0 in the inversion. Adopting an inversion scheme proposed by Ji et al. (2001), we performed finite fault inversions using the two fault planes in the GCMT solution, allowing the slip to vary from 0 to 3 m and the rupture speed to change from 2.0 to 3.0 km/s. Interestingly, as shown in Figures 10 and S5, it is clear that the inversion on a fault plane with a strike of 057° and dip of 63° fits the data much better than the auxiliary fault plane, which is again consistent with the relocated seismicity and surface geology. The slip distribution the finite fault inversion (~ 12 km) also agrees well with the centroid depth in the moment tensor solution obtained by regional waveform inversions (Figures S3 and S4).

5. Discussion

Despite the rapidly increasing population of Aceh, the location, geometry and slip rates of many secondary but still hazardous faults remain uncertain. These faults

are more active in Aceh than other secondary faults in Sumatra, as shown by background seismicity (Figure 1 inset). Over the last 100 years, off-SF faults in Aceh have produced 17 $M > 5.5$ shallow events, compared with only three such events in the rest of Sumatra. These earthquakes include a $M_w 6.1$ earthquake took place near the SAM-SIP Fault in 1967 about 12 km away from the recent Pidie Jaya earthquake (USGS, Pesicek et al., 2010a, 2010b) and the $M_w 6.1$ Bener Meriah Earthquake in 2013 that occurred about 50km away (BMKG). A GPS velocity profile across the SF near the 2016 Pidie Jaya earthquake shows a smooth transition in fault-parallel velocity across the Sumatran Fault trace, indicating that the surrounding crust is stressed by fault locking (Ito et al., 2012). Transmission of stress from the subduction interface and across the Sumatran Fault is presumably responsible for earthquakes such as the Pidie Jaya event. However, because the slip rates of secondary faults are presumably very low, it is challenging to identify them even with decadal GPS data. Although the national broadband network in Sumatra region is coarse (~100 km station spacing), temporary seismic networks can be installed to densify the station coverage and provide near field data to precisely locate micro seismicity or aftershocks (e.g. Muksin et al., 2018, submitted). We therefore suggest installing more temporary short period seismic network in the region to complement the national broadband network, particularly after significant earthquakes.

The geological context of the moderate magnitude ($M 6+$) earthquakes in Aceh remains unclear and could be improved through more detailed field and

391 geophysical observations of active faulting. Certainly, the Pidie Jaya Earthquake
392 highlights the hazard posed by auxiliary faults oriented at high angle to the
393 Sumatran Fault. Thus far, earthquakes on off-Sumatran Fault structures in Aceh
394 have been strike-slip events, but comparison with other strike-slip margins and
395 the occurrence of very high topographic relief in the region suggests that thrust or
396 normal mechanism events could also occur. Assessment of earthquake hazard
397 and risk typically relies on geological mapping of active faults; however, the 2016
398 Pidie Jaya and 2013 Bener Meriah earthquakes clearly show that unmapped
399 structures of unexpected orientation may rupture even in areas where basement
400 fault systems have already been mapped. Geophysical monitoring may therefore
401 prove to be a more reliable method for discovering active faults in this region
402 prior to damaging ruptures.

403

404 To better prepare for future damaging earthquakes in Sumatra, it is also critical to
405 collect the seismic ground shaking data from local to regional scale, which can
406 be used for a series of studies that include site effects and attenuations, as partly
407 covered in this study. Temporary network and national strong motion and
408 broadband networks provide the fundamental dataset for such analyses. With
409 more data collected and analyzed, much better GMPEs in Sumatra or Aceh can
410 be derived. In addition to off-Sumatran Fault earthquakes, such as Pidie Jaya
411 Earthquake in this study, the Sumatran region experiences gigantic megathrust
412 earthquakes that can generate strong ground shaking at both long period and
413 high frequencies (e.g., Jousset & Douglas, 2007). The civil engineering

community usually ignores long period ground shaking; however, the long period shaking produced by the 2011 Tohoku-Oki earthquake swayed the top of a 52-floor building in Osaka bay more than 1.3 m horizontally, despite the building being located more than 800km away from the epicenter (Kanamori, 2014). Such 3D structural complexity as well as building responses should also be taken into consideration for future seismic hazard preparation, in particular for Jakarta, capital city of Indonesia.

6. Conclusions

The results of aftershock analysis from Pijay-Net and mainshock relocation shows that the ruptured fault plane has a strike of 42° , dip of 63° and fault dimension of ~20 km along strike and as deep as 25 km. The depth of the aftershocks are primarily distributed between 8 to 23 km with maximum depth of 28 km. We name this structure the Panteraja Fault and tentatively correlate it with near-surface deformational features that parallel its strike. Focal mechanisms of aftershocks with magnitude greater than 3 also indicate a fault geometry consistent with relocated seismicity and the focal mechanism of the mainshock. Damage caused by the earthquake was distributed primarily in the east-west direction, instead of along the strike of the rupture fault plane, due to the effect of ground motion amplification caused by greater sediment thickness along the coastline. To better understand the neo-tectonics and prepare for the future seismic hazard, we suggest improving the seismic monitoring of the entire Aceh region.

437

438 **7. Data and Resources**

439 Seismograms of the aftershocks used in this study were collected by the
440 temporary network of Pijay-Net. These data will be released to public after five
441 years through the data center of webdc.eu or IRIS or a data center at Earth
442 Observatory of Singapore. Some aftershock and mainshock seismograms were
443 collected from Agency for Meteorology, Climatology, and Geophysics (BMKG),
444 GEOFON Global Seismic Network (GFZ-Potsdam) and Global Seismic Network
445 (GSN) from IRIS (iris.edu). Part of historical catalog data were obtained from
446 USGS website and ISC (1900-1959). Damage photos were collected during the
447 field survey. An example of earthquake information based on intensity scale of
448 SIG-BMKG on BMKG website: www.bmkg.go.id/berita/?p=english-magnitude-6-5-earthquake-hits-aceh&lang=EN
449 (last accessed on May 3, 2018). Some plots
450 were made using the Generic Mapping Tools version 4.5.6
451 (www.soest.hawaii.edu/gmt; Wessel and Smith, 1998, Wessel et al., 2013). All
452 other data and resources used in this paper came from published sources listed
453 in the references.

454

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Figures:

Figure 1 Shallow seismicity (depth <50km) and seismic networks in northern Sumatra, Indonesia. Green, yellow, black and blue triangles showing broadband, strong motion, temporary networks and temporary strong motion stations, respectively. The transparent, grey, white and red stars indicate the hypocenter location of the major event from the GEOFON Global Seismic Network (GFZ-Potsdam), USGS, BMKG and this study, respectively. White circles indicate the historical inland earthquakes with magnitudes larger than 5.5 since 1907 (Nugraha et al., 2018, Pesicek et al., 2010a, 2010b, USGS, BMKG and ISC). Red, yellow and white circles in inset figure showing the historical events on the Sumatran Fault, off-Sumatran Fault and subducting slab, respectively.

Figure 2 The updated intensity map of the Pidie Jaya earthquake. Circles indicate the locations of damage observations, colored by the intensity. Note that we use Earthquake Intensity Scale of BMKG (SIG-BMKG). Numbers connected to the circles are the indexes of photos in Figure S1. The red star shows the relocated mainshock epicenter. Transparent triangles indicate the locations of temporary Pijay-Net stations.

485

486 **Figure 3** Post-event survey photographs of closely adjacent sites showing drastically
487 different responses of buildings to similar ground shaking intensity. **a)** Site #31 (left):
488 complete collapse of a building, Kec. Meurah Dua at 5.233°N; 96.268°E and **b)** Site #32
489 (right): minimal damage of an office at the same subdistrict at 5.235°N 96.274°E.

490

491 **Figure 4** Intensity data collected during the post-event survey (colored circles) overlaid
492 on empirical Vs30 map (Wald and Allen, 2007; Allen and Wald, 2009). See Figure 2 for
493 the intensity definition of the circles. The NEHRP (The National Earthquake Hazards
494 Reduction Program) site classification (A, B, C, D and E, representing the hard rock,
495 rock, soft rock, stiff soil and soft soil, respectively) is based on Vs30. The red star shows
496 the relocated mainshock epicenter. Colored triangles indicate the locations of temporary
497 Pijay-Net stations, the colors represent site classification based on HVSr (see Figure 5).

498

499 **Figure 5** HVSr at Pijay-Net stations, solid and dashed lines showing the average HVSr
500 and its 95% confidence level, respectively. The variable frequency response patterns
501 and different peak magnitudes of HVSr illustrate the importance of local site conditions
502 for shallow amplification of seismic waves. Site classifications based on HVSr (see
503 Table 2 in Zhao et al., 2006) are shown on each subfigure below the station names.

504

505 **Figure 6** The strong motion record at station JAKO of the m_b 4.9 aftershock
506 event on December 11th with the PGA ~67 gals. The hypocentral distance to the
507 station is ~19 km.

508

Figure 7 PGA as a function of source distance for the major event and aftershocks with different magnitudes and source distances up to 600 km. The solid lines show predicted PGA based on GMPE from Zhao et al. (2006) for crustal events with the magnitudes 2, 3, 4, 5, 6, 6.5 and 7, from lower to higher, respectively. The labels on green circles indicate the station names of temporary network.

Figure 8 Aftershock distribution and focal mechanism solution of the 2016 Pidie Jaya earthquake after relocation using grid search and hypoDD methods. Numbers on the focal mechanism solution are the event ID in supplementary file. Green squares indicate the three events with their waveforms recorded at station A22 (grey triangle) as shown in Figure 9. Blue circles indicate the sequence of historical significant earthquake in 1967 with the magnitude of mainshock is 6.1.

Figure 9 Waveforms of the deepest event (28 km) and other two events (21 km and 11 km) at station A22 (see the event locations in Figure 8). The S (T2) to P (T1) differential arrival times increase with event depth (h).

Figure 10 Teleseismic finite fault inversion result of the mainshock. The top panel shows the teleseismic displacement waveform fits where the data is shown in black and the synthetic in red. The station names are indicated at the beginning of each waveform pair along with the azimuth (upper) and epicenter distance (lower) in degree. The peak amplitude in the data in micrometers is displayed at the end of each waveform. The lower left panel shows the depth profile of the finite fault slip model in which the contours indicate the rupture time and the arrows indicate the slip direction. The lower right panel is the moment rate function of the finite fault model.

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(a) Site - 31

(b) Site - 32

Figure

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Table 1 Hypocenter locations of mainshock from three institutions

No	Origin Time (UTC)	Latitude	Longitude	Mag. (Mw)	Depth (Km)	Source
1	2016/12/06 22:03:35	5.290	96.220	6.5	15	BMKG
2	2016/12/06 22:03:32	5.281	96.108	6.5	8.2	USGS
3	2016/12/06 22:03:33	5.320	96.070	6.5	10	GFZ

Table 2 Earthquake Intensity Scale of BMKG (SIG-BMKG)

SIG-BMKG	Description	MMI
I	Not felt except by a very few under especially conditions	I - II
II	Felt	III - V
III	Light Damage	VI
IV	Moderate Damage	VII - VIII
V	Heavy Damage	IX - XII

Table 3 Casualties and building damages produced by the earthquake (BNPB).

No	Description	Total
1	Deaths	101
2	Injured	857
3	House Damaged	
	- Heavy	2,992
	- Moderate	94
	- Light	8,582

Electronic Supplement to

The 2016 Mw 6.5 Pidie Jaya, Aceh, North Sumatra Earthquake: Reactivation of an Unidentified Sinistral Fault in a Distributed Deforming Region

by Muzli MUZLI, Muksin UMAR, Andri Dian NUGRAHA, Kyle Edward BRADLEY, Sri WIDIYANTORO, Kemal ERBAS, Philippe JOUSSET, Supriyanto ROHADI, Irwandi NURDIN, and Shengji WEI

This electronic supplement contains damage photos and their locations, figures of relative mainshock relocation, depth resolution and focal mechanism solution of the mainshock using Cut and Paste (CAP) method (Zhu and Helmberger, 1996), focal mechanism solutions using first motion polarity, teleseismic finite fault inversion of the mainshock for the fault plane with strike of 148° , and the double-difference hypocenter relocation of the aftershocks using hypoDD (Waldhauser and Ellsworth, 2000; Waldhauser, 2001; Paige and Saunders, 1982).

Figures

Figure S1 (a-g) Damage photos caused by the 2016 Mw 6.5 Pidie Jaya Earthquake.

Figure S2 Relative mainshock relocation by using the path calibration from the ML 4.2 aftershock which was recorded by the temporary array. The stations are represented by the triangles and the contours indicate the grid search research results. The regional stations used in relative relocation of the mainshock are shown in the upper right inset.

Figure S3 Depth resolution of the mainshock using Cut-and-Paste (CAP) method.

Figure S4 (a-b) Focal mechanism solution of the mainshock using Cut-And-Paste method; the red lines are synthetics and the data is in black, green lines are not used in the inversion. The first number beneath each waveform pair is time shift (TS, positive means 1D model is faster) and the second number is cross-correlation (CC) coefficient in percentage. The station names (Sta) are indicated at the beginning of the waveform traces along with the epicenter distance (D, upper in km) and azimuth (Az, lower in degree), frequency ranges for Pnl waves and surface waves are shown at the top of each page along with focal mechanism information.

Figure S5 Teleseismic finite fault inversion result of the mainshock for the fault plane with strike of 148° and dip of 83° . The top panel shows the teleseismic displacement waveform fits where the data is shown in black and the synthetic in red. The station names are indicated at the beginning of each waveform pair along with the azimuth (upper) and epicenter distance (lower) in degree. The peak amplitude in the data in micrometers is displayed at the end of each waveform. The lower left panel shows the depth profile of the finite fault slip model in which the contours indicate the rupture time and the arrows indicate the slip direction. The lower right panel is the moment rate function of the finite fault model.

Data

Download:

SRL_Muzli_etal_esupp_hypocenter_relocation.csv [Size: ~24 KB]. Relocated hypocenter of the aftershocks using double-difference algorithm (hypoDD).

SRL_Muzli_etal_esupp_focal_mechanism_solutions.csv [Size: ~2 KB]. Focal mechanism solutions of the aftershocks with the magnitude (MI) larger than 3.0.

SRL_Muzli_et al_esupp_intensity_observations.csv [Size: ~2 KB]. Locations and level of intensity observations based on SIG-BMKG intensity scale (Muzli et al., 2016).

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**Supplemental Material (All Other Files, i.e. Movie, Zip,
csv)**

SRL_Muzli_etal_esupp_hypocenter_relocation.csv

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**Supplemental Material (All Other Files, i.e. Movie, Zip,
csv)**

SRL_Muzli_etal_esupp_focal_mechanism_solution.csv

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**Supplemental Material (All Other Files, i.e. Movie, Zip,
csv)**

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