Field Survey of the 2018 Sulawesi Tsunami: Inundation and Run-up Heights and Damage to Coastal Communities

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Abstract—On September 28, 2018, a large earthquake and its accompanying tsunami waves caused severe damage to the coastal area of Palu Bay, in the central western part of Sulawesi Island, Indonesia. To clarify the distribution of tsunami inundation and run-up heights, and damage to coastal communities due to the tsunami, the authors conducted a field survey 1 month after the event. In the inner part of Palu Bay tsunami inundation and run-up heights of more than 4 m were measured at many locations, and severe damage by the tsunami to coastal low-lying settlements was observed. In the areas to the north of the bay and around its entrance the tsunami inundation and run-up heights were lower than in the inner part of the bay. The tsunami inundation distance depended on the topographical features of coastal areas. The southern shore of the bay experienced a longer inundation distance than other shores, though generally severe damage to houses was limited to within around 200 m from the shoreline. The main lessons that can be learnt from the present event are also discussed.

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1. Introduction

At 18:02 local time (Indonesia Central Standard Time, UTC + 8) on September 28, 2018, a large earthquake of Mw 7.5 took place on Sulawesi Island, Indonesia. This earthquake and its accompanying hazards, including a tsunami, landslides, and liquefaction, caused severe damage to the central western part of Sulawesi Island, including two coastal municipalities facing Palu Bay: Palu City, the capital of Central Sulawesi Province, and Donggala Regency, located north of Palu. According to the Indonesian National Disaster Management Agency (2018), this event caused 2101 fatalities (1727 in Palu, 171 in Donggala, and 203 in other municipalities) and 1373 were missing/buried, as of November 20, 2018.

The United States Geological Survey (USGS) estimated that the origin of the earthquake was located at 0.255°S and 119.840°E, 20.0 km deep and that it was caused by a strike-slip fault (USGS 2018). Since seismic events caused by a strike-slip fault typically do not result in any significant vertical displacement of the ground, they are usually considered unlikely to generate large tsunamis. However, video images posted online show that destructive tsunami waves inundated the Palu Bay coastline soon after the earthquake, which indicates that something had actually generated a significant tsunami. An aerial video taken by a pilot, who took off from the

airport in Palu City just before the earthquake occurred, captured circular waves that were generated along the west side of Palu Bay, which implies that tsunamis were generated by submarine landslides triggered by the earthquake.

Although Prasetya et al. (2001) suggested that submarine slumping triggered by an earthquake in the Makassar Strait (outside of Palu Bay) could be a secondary mechanism of tsunami generation, to the authors' knowledge there has been no discussion of the risk of landslide-generated tsunami inside Palu Bay before the 2018 event. However, the results of field observation and numerical simulations of the 2018 event show that the combination of co-seismic deformation at the bottom of the sea [including both the vertical displacement and the effect of the horizontal displacement on a steep ocean bottom slope (Tanioka and Satake 1996)] and local mass movements (landslides, land subsidence, and liquefied gravity flow) along the Palu Bay coastline generated a series of tsunami waves that hit locations throughout the bay (Muhari et al. 2018; Arikawa et al. 2018; Sassa and Takagawa 2019; Heidarzadeh et al. 2019; Takagi et al. 2019; Omira et al. 2019). The evidence so far appears to point to landslides in coastal areas as the trigger for the different tsunami waveforms witnessed.

The authors conducted a field survey 1 month after the event to obtain some basic information about it, such as the tsunami inundation and run-up heights,

and damage to buildings and coastal infrastructure (especially focusing on how far from the shoreline did severe damage to houses take place) at each coastal community. Several other international teams also conducted field surveys in the coastal area affected by the tsunami, with a summary of such surveys being reported elsewhere (Arikawa et al. 2018; Muhari et al. 2018; Robertson 2019; Omira et al. 2019). In the present paper the authors detail the results of their own survey, which covers both the circumference of Palu Bay and the area to the north of it, aiming to summarize lessons learnt from the event for developing better disaster risk reduction strategies, in addition to complementing the surveys that were conducted by the other teams.

The present paper will first summarize past tsunami events recorded in Sulawesi Island, based on existing tsunami catalogues. Then the results of the authors' field survey will be presented. Finally, the characteristics of the distribution of tsunami inundation and run-up heights, damage patterns, and lessons that can be derived to improve disaster risk management will be discussed.

2. Past Tsunami Events on Sulawesi Island

Table 1 shows major tsunami events caused by earthquakes on Sulawesi Island based on the existing records of global tsunami catalogues (Soloviev and

Table 1

Major tsunami events caused by earthquakes on Sulawesi Island, based on the records of global tsunami catalogues [magnitudes are from the tsunami database of NGDC/WDS (2018)]

| Date	Source location	Magnitude	Damaged areas	Tsunami catalogue
December 29, 1820	7°S/119°E	7.5	Coast from Bonthain to Bulukumba	Soloviev and Go (1984)
November 17, 1857	1.35°N/125.2°E	–	Kema	Soloviev and Go (1984)
December 13, 1858	1°N/126°E	7.3	Entire eastern coast of Sulawesi Island	Soloviev and Go (1984)
June 28, 1859	1°N/126.5°E	7.0	Kema	Soloviev and Go (1984)
July 29, 1859	0°N/125.5°E	7.3	Kema	Soloviev and Go (1984)
September 6, 1889	1°N/126.25°E	8.0	Kema	Soloviev and Go (1984)
December 1, 1927	0.5°S/119.5°E	6.3	Palu Bay, Talise	Soloviev and Go (1984)
May 20, 1938	0.7°S/120.3°E	7.6	Ampibabo, Parigi	Soloviev and Go (1984)
April 11, 1967	3.3°S/119.4°E	5.5	Tinambung	Soloviev and Go (1984)
August 15, 1968	0.2°N/119.8°E	7.4	Donggala, Tambu, Mapaga	Soloviev and Go (1984)
February 23, 1969	3.1°S/118.9°E	7.4	North of Madjene	Soloviev et al. (1992)
January 1, 1996	0.724°N/119.981°E	7.9	Tonggolobibi	Lander et al. (2003)
May 4, 2000	1.105°S/123.573°E	7.6	Luwuk, Peleng	Lander et al. (2003)
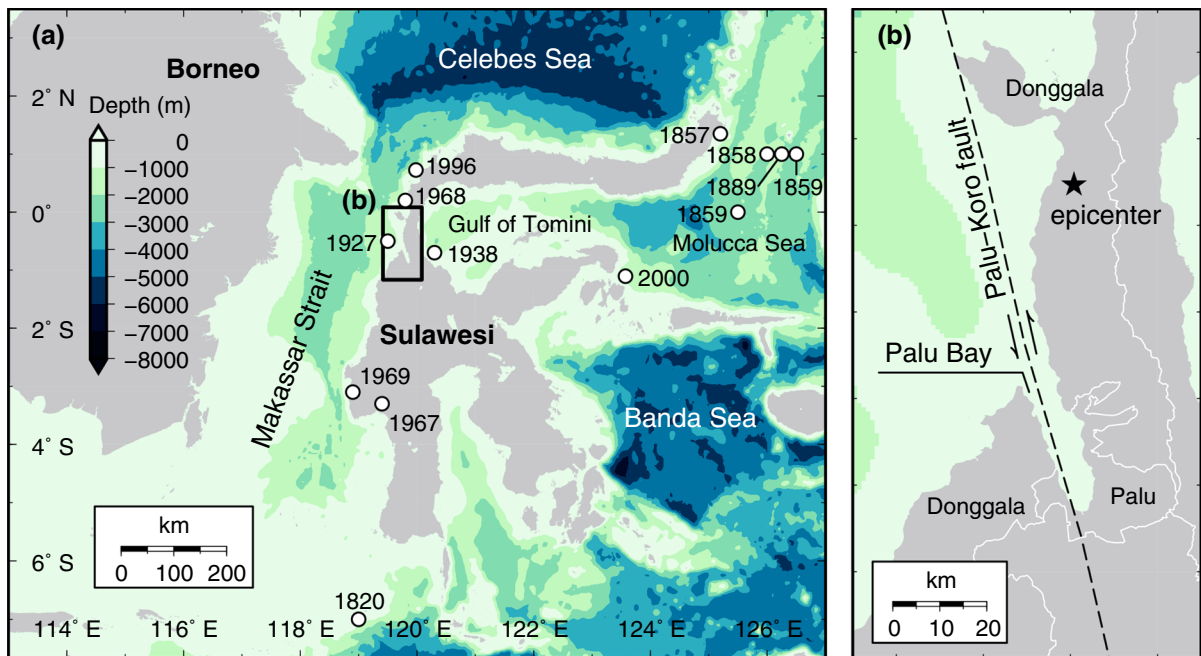
Figure 1
Maps of Sulawesi Island: **a** source locations of past tsunami events on Sulawesi Island, **b** location of the Palu-Koro transform fault line, which traverses Palu Bay (using the plate boundary data of Coffin et al. (1998)) and the epicenter of the 2018 earthquake (USGS 2018)

Go 1984; Soloviev et al. 1992; Lander et al. 2003). This table only contains events with a clear description of tsunami damage in the coastal area of Sulawesi Island (for example, loss of lives, building damage, or ships being stranded onshore). There is a limited amount of information available for events between 1820 and 1969, whereas two recent tsunamis (in 1996 and 2000) were detailed in field surveys conducted by other researchers (Pelinovsky et al. 1997a, b; Koike et al. 2001).

In total there are 13 major tsunami events recorded, with their locations shown in Fig. 1a. Three of these events (in 1927, 1968, and 1996) took place on the northwestern coast of Sulawesi Island, which faces the northern Makassar Strait. Three others (in 1820, 1967, and 1969) occurred on the southwestern coast of the island, which faces the southern Makassar Strait. Six events (in 1857, 1858, June 1859, July 1859, 1889, and 2000) took place around the Molucca Sea, and one (in 1938) occurred in the Gulf of Tomini. Even though previous work (Hamzah et al. 2000; Horspool et al. 2014) mentioned that seismic activity around Sulawesi Island is lower than

that in other regions in Indonesia, such as the southern coast of Sumatra and Java Islands, it can be said that most areas of Sulawesi (except the southeastern part of the island) have the potential of experiencing a nearshore event, and thus should have disaster risk reduction strategies in place. Based on these records of past tsunami events, the northern part of the island has been more frequently inundated by tsunamis than other parts of the island. The tsunami hazard assessment made by Baeda (2011) and the eastern Indonesia tsunami hazard map proposed by Løvholt et al. (2012) also show that the northern part of the island is the area that has the highest risk.

Palu Bay is a long narrow bay that runs in a north–south direction (approximately 30 km long and 6–7 km wide), and is connected to the Makassar Strait to the north, as shown in Fig. 1b. The bay bathymetry is characterized as being very steep, with depths of over 500 m at its deepest section (Indonesian Geospatial Information Agency 2018). The central western coast of Sulawesi Island, where Palu Bay is located, is one of the most active seismic areas on the island, since there is a left-lateral strike-slip

fault line (Palu-Koro fault) lying right under the bay. Prasetya et al. (2001) mentioned that the 1927, 1968, and 1996 earthquakes all occurred along this fault zone. The results of an analysis using radar data (Geospatial Information Authority of Japan 2018) clearly show that during the 2018 earthquake the east side of Palu Bay moved northwards and the west side southwards, indicating that the earthquake took place along this fault zone.

Among the three past tsunami events that have occurred due to earthquakes on the Palu-Koro fault zone (in 1927, 1968, and 1996), records of tsunami damage in Palu Bay can only be found for the 1927 event. According to the description of the 1927 event from the catalogue of Soloviev and Go (1984), a tsunami wave of 15 m inundated the coastal area of Palu Bay, causing 14 deaths and 50 injuries. It is interesting to note that the description mentions "the sea became 12 m deeper", which implies that land subsidence or a submarine landslide might have taken place during the event (as will be mentioned later, a similar type of phenomenon took place during the 2018 event).

3. Field Survey

The authors conducted a field survey of the coastal communities affected by the tsunami throughout Palu and Donggala from the 27th to 31st of October 2018, around 1 month after the event. At each coastal community the authors measured tsunami inundation and run-up heights, observed damage to buildings and coastal infrastructure, and interviewed local residents. During each measurement the coordinates of the position were recorded by a handheld GPS instrument (Montana 650, Garmin) and its elevation was measured by using a laser ranging instrument (Impulse 200LR, Laser Technology Inc.), target prism, and staffs (Esteban et al. 2017b). The interviews with local residents were conducted by authors who were native speakers of Bahasa Indonesia, and translated into English for the benefit of the other authors.

Table 2 shows the results of the survey of tsunami inundation and run-up heights. It was difficult to obtain information on the tsunami arrival time at some of the locations surveyed, as many local residents relocated or evacuated immediately after the

Table 2

Tsunami inundation and run-up heights (either inundation height (I) or run-up height (R))

No.	Place	Latitude (S)	Longitude (E)	Type	Height (m)	Flow depth (m)	Target
1	Silae, Palu	0°52′18.6″	119°49′59.8″	I	4.40	1.55	Mudline on a wall (outside a building)
2	Silae, Palu	0°52′31.9″	119°50′08.2″	I	4.56	3.57	Broken branches
3	Taman Ria, Palu	0°52′51.0″	119°50′18.7″	I	5.17	4.82	Broken branches
4	IAIN Palu campus, Palu	0°53′06.0″	119°50′42.9″	I	2.99	1.61	Mudline on a wall (inside a building)
5	IAIN Palu campus, Palu	0°53′03.1″	119°50′43.7″	I	1.75	0.95	Mudline on a wall (inside a building)
6	Talise, Palu	0°53′07.2″	119°51′42.7″	I	2.74	3.26	Broken branches
7	Talise, Palu	0°52′42.2″	119°52′19.2″	I	3.29	1.99	Debris on a net (inside a building)
8	TV office, Palu	0°53′12.5″	119°51′46.0″	I	2.28	1.05	Mudline on a wall (inside a building)
9	TV office, Palu	0°53′12.1″	119°51′46.1″	I	4.56	4.08	Broken branches
10	Buluri, Palu	0°50′54.8″	119°49′22.7″	I	6.77	0.22	Local residents witnessed
11	Buluri, Palu	0°50′37.6″	119°49′04.3″	R	6.02	–	Debris on a slope
12	Loli, Donggala	0°46′46.0″	119°47′36.1″	R	4.13	–	Debris on a slope
13	Labuan Bajo, Donggala	0°39′56.5″	119°44′30.5″	I	1.71	0.91	Mudline on a wall (inside a building)
14	Labuan Bajo, Donggala	0°39′56.1″	119°44′29.3″	I	1.59	0.53	Mudline on a wall (inside a building)
15	Mamboro, Palu	0°49′00.8″	119°52′48.1″	I	5.07	0.25	Mudline on a wall (outside a building)
16	Mamboro, Palu	0°49′00.5″	119°52′49.1″	R	5.26	–	Local residents witnessed
17	Mamboro, Palu	0°48′00.7″	119°52′34.2″	I	4.70	2.01	Mudline on a wall (inside a building)
18	Wani2, Donggala	0°41′39.4″	119°50′26.5″	I	1.68	0.80	Mudline on a wall (inside a building)
19	Kavaya, Donggala	0°34′01.7″	119°47′16.1″	R	2.49	–	Debris on a slope
20	Kaliburu, Donggala	0°28′42.7″	119°45′52.2″	R	2.16	–	Local residents witnessed
21	Tompe, Donggala	0°12′10.9″	119°48′56.3″	I	0.90	0.81	Local residents witnessed
22	Lombonga, Donggala	0°08′09.0″	119°48′36.3″	R	1.51	–	Local residents witnessed

earthquake, so that they did not actually witness the tsunami waves. However, in two of the locations residents did describe the tsunami arrival time. At Wani2, the wave apparently arrived 4 min after the earthquake (it is not clear whether this first wave was the highest wave). At Silae, the first wave arrived 10 min after the earthquake, with the highest wave arriving 15-20 min after the first one. In addition, Muhari et al. (2018) mentioned that a tide gauge at the port of Pantoloan, which is located inside Palu Bay, recorded the peak water level 8 min after the earthquake. Based on the above evidence, the measured heights were corrected to the heights above the estimated tide level at 18:20 local time on the 28th of September, 2018 (taking an average of the arrival time of the highest waves, 8 min and 25–30 min after the earthquake at Pantoloan and Silae, respectively). The tide level was estimated by using the WXTide32 software (which can calculate tide levels at more than 9500 stations worldwide and is available at http://www.wxtide32.com/). The reference location was Donggala (the closest station among those included in the software), which has a tidal range of around 2 m. At the time of the tsunami's arrival it was close to high tide. All the heights shown in Table 2 refer to this corrected dataset.

The traces of tsunami inundation and run-up heights were identified by broken branches, debris, mudlines left on walls, and the descriptions by residents who witnessed the event. It should be noted that a mudline left on a wall inside a building probably indicates the inundation level inside it during the passage of the tsunami, though this might be lower than the high energy flows outside.

In addition to the survey of tsunami inundation and run-up heights, an aerial photographic survey using an unmanned aerial vehicle (UAV) was carried out to capture the spatial distribution of tsunami damage to buildings and infrastructure. Recently, aerial photographic surveys using UAVs have been widely applied to evaluate the changes in land surface as a consequence of geo-hazards (Niethammer et al. 2010; Chen et al. 2016). Given time constraints, the area covered by this aerial photographic survey was limited to the south area of Palu Bay. For this survey a Phantom 4 Pro+ (Da-Jiang Innovations Science and Technology Co. Ltd.) was used, with an overlap

between the pictures parallel and perpendicular to the coastline being roughly 70–90% and 50–70%, respectively. A digital elevation model (DEM) was then constructed using Metashape 1.5.0 Professional Edition (AgiSoft).

Figure 2 shows a map of the locations surveyed, with their corresponding tsunami inundation or run-up heights. In total, approximately 100 km of the coastline was covered by the field survey. In the remainder of this section the results will be summarized by dividing the locations visited into four geographical areas (south, west, east, and north of the bay), as shown in Fig. 2a. Among these four, the south, west, and east areas are located inside Palu Bay, whereas the north area lies to the north of the bay.

3.1. South Area

Palu City is situated to the south of Palu Bay, with Palu River (which arrives from the south direction) dividing this area into two, as shown in Fig. 2b. Several locations were surveyed on each side of the river mouth, namely: Silae, Taman Ria, and the campus of IAIN Palu (State Institute for Islamic Studies Palu) to the west part of the river, and Talise and a TV station office to the east of the river.

In Silae the inundation heights measured at two different locations were 4.4 m and 4.6 m. Severe damage to houses due to the tsunami was observed within 100 m of the shoreline. Local residents described how the first wave arrived 10 min after the earthquake, as explained earlier.

In Taman Ria a coastal road suffered severe damage, probably due to both the earthquake and tsunami. All of the houses, cafes and shops that were located seaward from the road were washed away due to the tsunami flow (see Fig. 3a). The measured inundation height in this area was 5.2 m. A multi-story shopping mall and parking garage are located about 500 m east of the point where the inundation height was measured. These structures served as a vertical evacuation destination for many people during the event. A spiral ramp providing vehicle access to the upper levels of the parking garage (see Fig. 3b) helped people to climb easily to the higher levels (a video posted by Channel NewsAsia (2018)
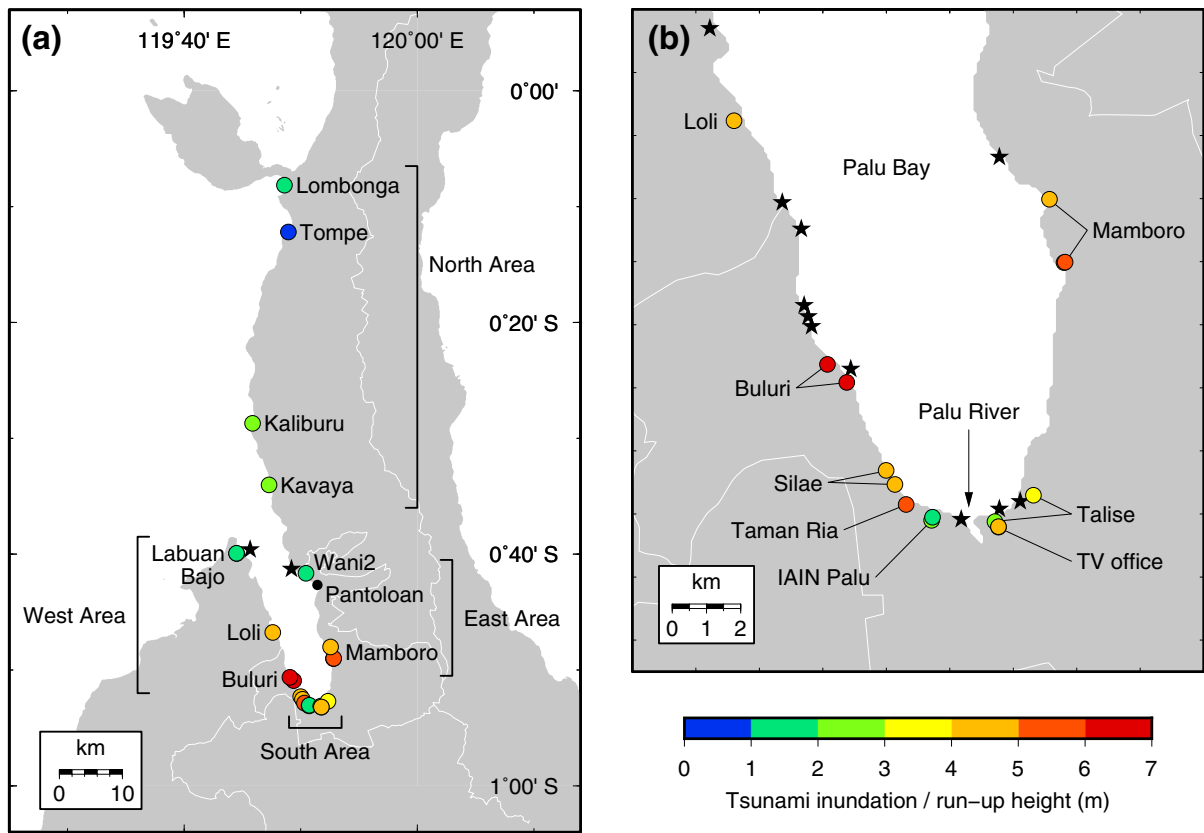
Figure 2
Map of the locations surveyed (circles), with their corresponding tsunami inundation or run-up heights. Also shown are the locations of suspected landslides (stars) based on the information in Robertson (2019) and Takagi et al. (2019): **a** all locations surveyed, **b** inner part of Palu Bay

shows the reaction of people at this location to the arrival of the tsunami).

The campus of IAIN Palu is located just east of the aforementioned shopping mall. In the campus there were several two-story buildings, with the tsunami causing severe damage to the first floor. Inundation heights of 1.8 and 3.0 m were measured at two of these buildings, which were located 100 m and 200 m from the shoreline, respectively. It should be noted that since the inundation height was measured according to mudlines found inside the buildings (see Fig. 3c), the maximum water level outside might have been higher. The flow depth at the latter building (200 m from the shoreline) was 1.61 m, indicating how the tsunami at this point had enough energy to reach further inland.

Talise had a seaside park along its coast. A large part of the seaside grounds of the park collapsed into

the bay, probably by a combination of return flows and localized land subsidence (possibly indirectly caused by submarine landslides and/or liquefaction) at the coast (see Fig. 3d). Several broken trees were also found near the coast. They were folded toward the west, suggesting that there was a strong tsunami flow from east to west (which corroborates witnesses' reports of the direction of the incoming wave). A 2.7 m inundation height was measured at a tree in this park. It is important to note that the ground level at the location of this tree was 1.0 m above sea level at the time of the survey, but this level is 0.5 m below the estimated tidal level at the time of tsunami arrival, providing further evidence that localized land subsidence took place in this area. Another example of a part of the coastline that collapsed into the water was found about 1 km northeast from the park, where an inundation height of 3.3 m was measured.
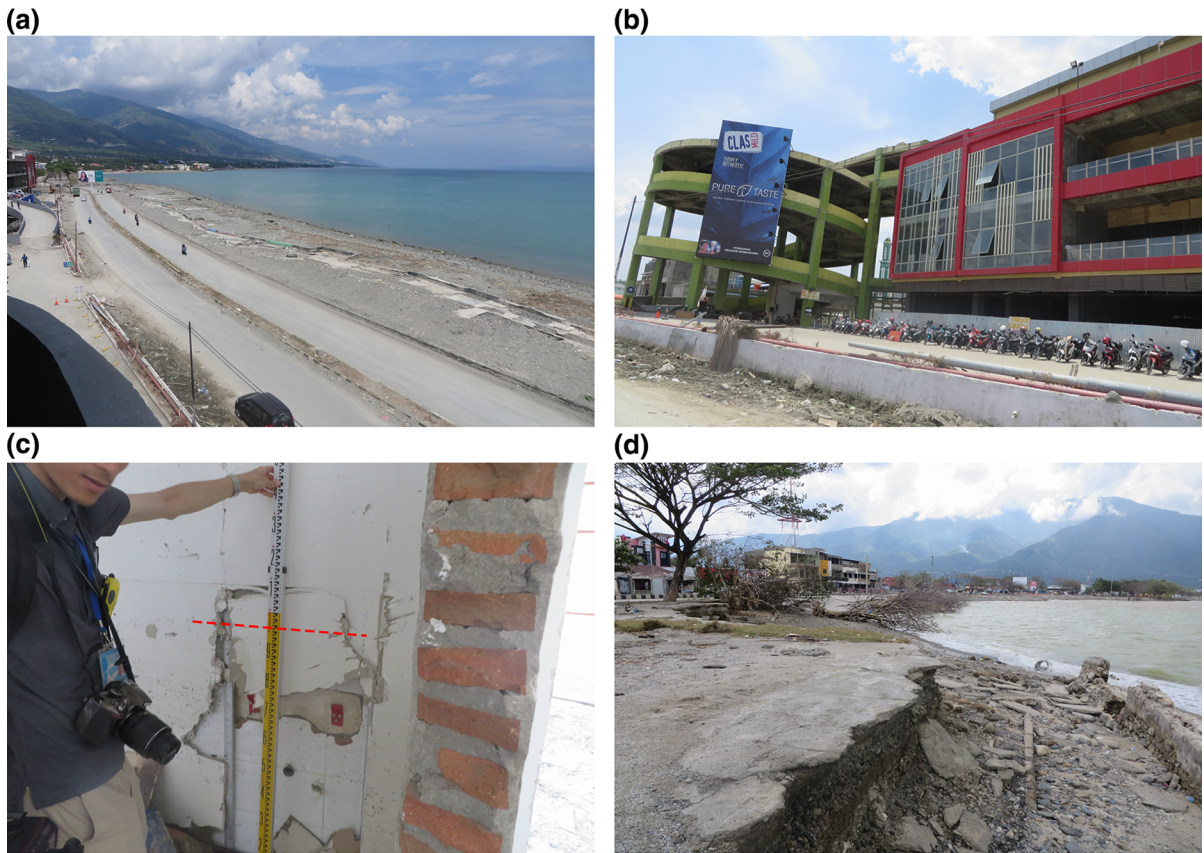
Figure 3
Tsunami survey in the south area: **a** coastal area of Taman Ria, **b** spiral ramp at a shopping mall in Taman Ria, **c** mudline found inside a building on the campus of IAIN Palu, **d** part of the coast that collapsed into the water at Talise

A TV station office building is located just behind the aforementioned seaside park. The distance from the shoreline to this building was about 120 m, and an inundation height of 2.3 m was measured inside the building. Some walls and windows in this building were damaged by the tsunami. The inundation height around this area was measured as 4.6 m on a tree in front of the building.

In some parts of the south area an aerial photographic survey was conducted, as mentioned earlier. Figure 4 shows the aerial image and DEM obtained from this survey. After analyzing the results, it would appear that the most severe damage was concentrated within 100–200 m from the shoreline, with hardly any structural damage observed after 200 m (it should be noted that in the most severely inundated areas some buildings had already been removed by cleaning efforts before the survey began, so it was

difficult to fully corroborate this observation). Considering the relatively flat ground elevation in this area, the rapid decrease in the degree of damage with distance indicates that the wavelength of the tsunami generated in Palu Bay was probably not as large as that of events generated by co-seismic vertical deformation.

3.2. West Area

In the west area three communities (Buluri, Loli, and Labuan Bajo) were surveyed. The coastal land in this area is relatively narrow before reaching the foothill of the mountains, where a number of gravel quarries are located (see Fig. 5a). At the mouths of the rivers coming from these mountains a large amount of gravel and sand had accumulated, indicating that the nearshore area probably also contained a
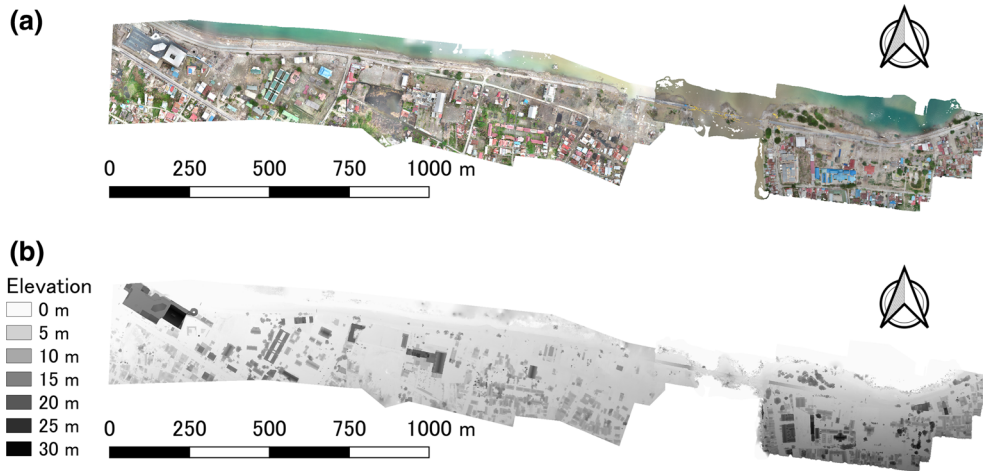
Figure 4
Results of an aerial photographic survey of the south area: **a** aerial image, **b** digital elevation model (DEM)
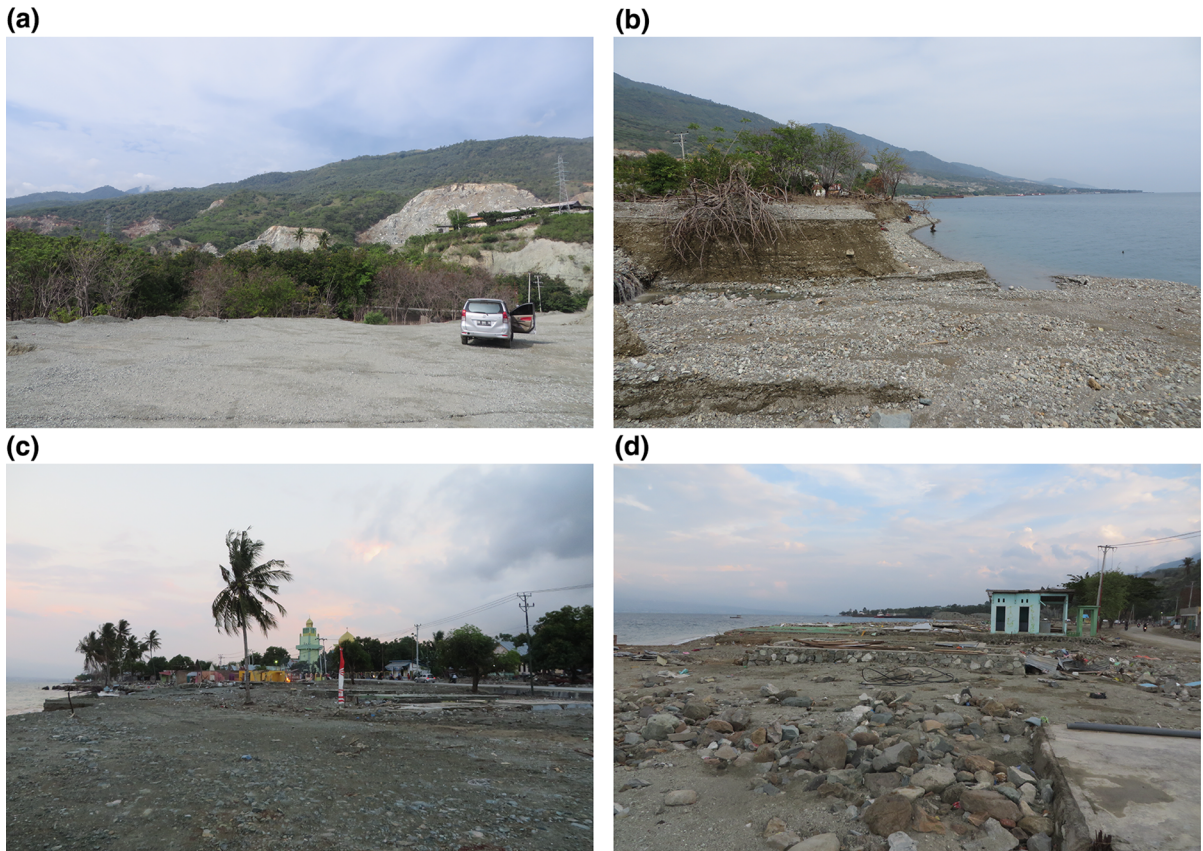

Figure 5
Tsunami survey in the west area: **a** gravel quarries, **b** reclaimed land, **c** tsunami damage in Buluri, **d** tsunami damage in Loli

large amount of these materials. It was also noted that the mining companies had created some areas of reclaimed land to store gravel and then load it onto barges (see Fig. 5b). The location of the river mouths and barge loading areas were often the same as the origin points of the waveforms filmed by Mr.

Ricosetta Mafella, the pilot of the Batik 6321, the last flight to leave Palu moments before the earthquake (see Takagi et al. (2019) for a detailed description of the location of these points). The pilot was interviewed by the authors, and confirmed that he saw several waveforms, radiating from points at the west side of the bay, that went on to cover the entire bay. The shape of these waveforms at the surface were also filmed by the operator of one of the gravel barges (Hasrul Saputra 2018), showing an expanding waveform that originated close to the coastline (probably a combination of a small portion of material above ground and a much larger submarine landslide component).

In Buluri two locations were surveyed. At one of the locations residents described that the water level reached the floor of their house, which was located around 100 m from the shoreline. The inundation height at this house was 6.8 m. The house was almost intact, but other houses located within 80 m of the shoreline were washed away. At another location in this area the tsunami reached a steep slope located around 70 m from the shoreline, where the run-up height was measured to be 6.0 m. From the shoreline to this point nothing was left except for the foundations of houses (see Fig. 5c). A similar scene of devastation was observed at Loli (see Fig. 5d). The tsunami reached a steep slope located around 90 m from the shoreline, where the run-up height was measured to be 4.1 m.

In Labuan Bajo, which is located at the tip of the western shore of Palu Bay, inundation heights of less than 2 m (1.7 m and 1.6 m) were measured at two different houses located at the shoreline. Otherwise, damage to houses due to the tsunami in this settlement was limited (compared to that found in Buluri and Loli).

3.3. East Area

In the east area two coastal communities (Mamboro and Wani2) were surveyed. The port of Pantoloan, which is located around 2 km south of Wani2 and has a tide gauge record [see Muhari et al. (2018)], was also visited, but it was difficult to find any clear evidence of the tsunami inundation height, as the port area had already been cleaned. Compared to the west area this part of the bay shoreline is relatively flat and densely populated.

In Mamboro, severe damage was observed to structures in the low-lying coastal ground (within 50-150 m from the shoreline). Almost all houses and trees located seaward from the main road were washed away (see Fig. 6a). Inundation heights at two different houses in Mamboro were measured to be 4.7 m and 5.1 m. Both of the houses were located landward from the main road, and damage was rather limited (though some walls and fences were damaged) compared to houses located on the seaward

Figure 6
Tsunami survey in the east area: **a** tsunami damage in Mamboro, **b** grounded ship in Wani2

side. A run-up height measured close to one of these houses (around 190 m from the shoreline) was 5.3 m.

Wani2 has a small port, and several ships that were docked there were left stranded on the ground close to the pier (see Fig. 6b). A house located around 80 m from the quay of the port was surveyed, and the inundation height according to a mudline left on a window on the first floor was 1.7 m. The residents of this house mentioned that the highest water level they had observed had been higher than that mudline, though lower than the second floor of the house (the level of the second floor was 1.5 m higher than the level of the mudline). This indicates that the maximum inundation height at this house was between 1.7 m and 3.2 m. According to residents, the tsunami arrived 4 min after the earthquake.

3.4. North Area

In the north area, closer to the epicenter of the earthquake, four coastal communities (Kavaya, Kaliburu, Tompe, and Lombonga) were surveyed. The inundation and run-up heights measured in this area were less than 3 m (2.5 m in Kavaya, 2.2 m in Kaliburu, 0.9 m in Tompe, and 1.5 m in Lombonga). Houses located seaward from the main road that runs along the shoreline were found to have suffered slight damage. Some of the beaches in this area had seawalls or wave dissipating concrete blocks along the shoreline (probably because the wind-driven wave conditions in this area are more severe than inside Palu Bay). In one location 650 m north of Kavaya, residents indicated that the sea water had not overtopped the concrete blocks placed along the shoreline, explaining why no damage took place in this area.

Residents in Kavaya, Tompe, and Lombonga reported that they evacuated to the mountains immediately after feeling the ground motion. When they returned they found debris along the beach and streets. It is interesting to note that one fisherman in Lombonga, who was offshore during the event, saw a huge wave propagating towards Palu Bay. Residents in Kaliburu described their experiences, and recounted how first a small earthquake took place, then the tide rose, and finally a big earthquake occurred. A translator explained that they did not use the term "tsunami", but referred to the wave as a "tide". This description provides further evidence that the tsunami in this area was not strong and arrived almost simultaneously with the earthquake. It is likely that a mechanism other than co-seismic seafloor deformation or the landslides in Palu Bay caused the tsunami around this location. It was possibly the result of another small landslide, or the southward movement of the adjacent peninsula as recorded by radar data (Geospatial Information Authority of Japan 2018).

4. Discussion

4.1. Characteristics of the Distribution of Tsunami Inundation and Run-up Heights and Damage

The results of the field survey show that tsunami inundation occurred throughout Palu Bay and also in the areas to its north (towards the epicenter of the earthquake). In the inner part of Palu Bay tsunami inundation and run-up heights were more than 4 m, with a maximum surveyed height of 6.8 m. Severe damage to houses and other structures was found along the low-lying coastal planes. In the north and close to the mouth of the bay, tsunami inundation and run-up heights were less than 3 m, and damage due to the tsunami was not as severe as further south. Thus, the distribution of inundation and run-up heights indicates that the tsunami energy was concentrated in the inner part of the bay.

The tsunami inundation distance from the shoreline varied according to location. Figure 7 shows the profiles of the measured tsunami inundation and run-up heights and ground levels at four different locations. In the west area, as the mountains are located close to the coast, the inundation distance was around 100 m. In the east area the tsunami could travel further inland, as the slope is much milder than in the west area. On the other hand, in the south, which has a wide low-lying coastal plane, the tsunami reached more than 200 m from the shoreline at some locations. The results of an aerial photographic survey using a UAV clearly show that the tsunami reached further inland in this area, compared to the other areas surveyed. However, even in the south area
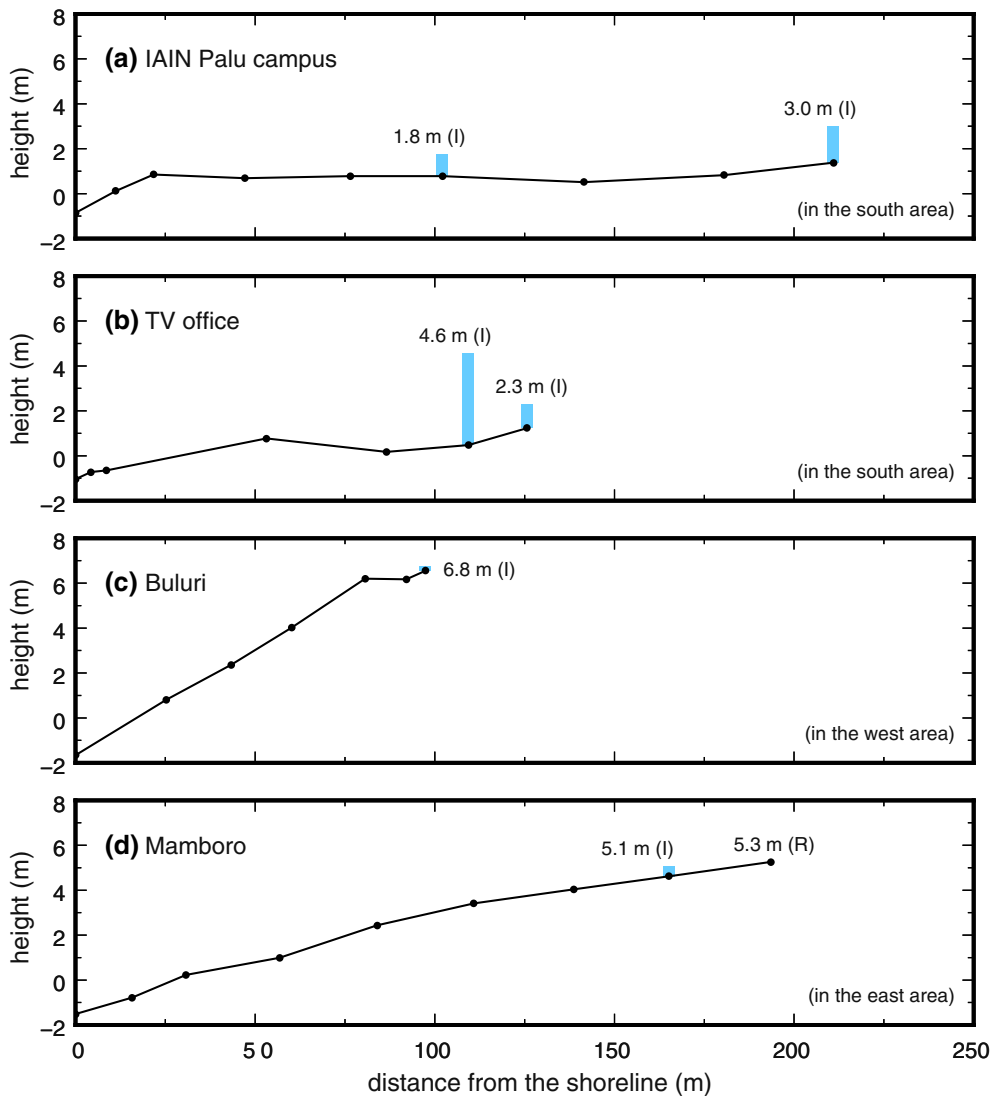
Figure 7
Profiles of measured tsunami inundation and run-up heights and ground levels at the time of the arrival of the tsunami: **a** IAIN Palu campus,
b TV office, Palu, **c** Buluri, Palu, **d** Mamboro, Palu

the inundation distance did not go as far as the authors would have expected and severe damage to houses was found within around 200 m from the shoreline. For example, in the case of the 2010 Mentawai Islands Tsunami, in which the measured tsunami inundation and run-up heights were similar to those in the 2018 Sulawesi event, the inundation distance was longer than 400 m at some of the affected locations (Hill et al. 2012; Satake et al. 2013; Mikami et al. 2014). Although the topographical features varied from place to place (as shown in Fig. 7), overall the damage due to the tsunami in the

Palu Bay coastline was limited to a very narrow coastal area, which implies that the tsunami had a relatively short wavelength compared to that of tsunamis generated by co-seismic vertical deformation. Higman et al. (2018) reported that the period of landslide-generated tsunamis is shorter than that of tectonically generated events, and this could be considered as further evidence that the tsunami in Palu Bay was generated by landslides.

The area surveyed by the authors contained some locations which were not visited by other teams (see Arikawa et al. 2018; Muhari et al. 2018; Omira et al.

2019), and thus by combining these results it is possible to obtain an overall picture of tsunami inundation and run-up heights and damage patterns.

4.2. Lessons Learnt from the Event

In some locations inside Palu Bay, residents described that the first wave arrived soon after the earthquake (4 min in Wani2 and 10 min in Silae). As mentioned in Muhari et al. (2018), Arikawa et al. (2018), Sassa and Takagawa (2019), Takagi et al. (2019) and Omira et al. (2019), the tsunami was caused, at least in part, by earthquake-triggered submarine landslides. In that sense, this event highlights how quickly tsunami waves can inundate coastal areas following nearshore landslides, and it is thus necessary to reconsider the risk of landslide-generated events in many parts of the world (in addition to those caused by co-seismic vertical deformation). During the authors' survey, it was clear that there were a number of unstable coastal areas (river mouths and reclaimed land using gravel and sand) along the western shore of Palu Bay, where the series of landslide-generated tsunamis waveforms could be observed from the pilot's video mentioned earlier. This shows the dangers posed by unstable sediments in coastal areas, and it has been postulated that climate change may increase the risk of landslide-generated tsunami in glaciated regions (Higman et al. 2018). This highlights the necessity to identify sites where landslides could occur, based on topographical and geotechnical surveys at each coastal community, and then disseminate the information to the public (as well as to put in place appropriate land use policies for reducing the risk of landslide events).

According to historical records of past tsunami events on Sulawesi Island there had been no significant events in Palu Bay since 1927. Nevertheless, residents described how they evacuated to the mountains soon after the earthquake. This indicates that they possessed some knowledge and awareness about tsunamis, which might be based on lessons from recent major tsunami events in the world, such as the 2004 Indian Ocean Tsunami and the 2011 Tohoku Tsunami (Esteban et al. 2013, 2017a). When a similar type of event occurs, namely a tsunami that arrives soon after an earthquake, it is difficult to warn people by means of a tsunami warning system, given the short window of time before the arrival of the wave (Takabatake et al. 2018). Therefore, in order to reduce the loss of life in a future event it is important to maintain a high level of knowledge and awareness in places where local residents already possess them, and start to create awareness in places where local residents do not have any (Esteban et al. 2018). In this sense, further research to investigate the current level of tsunami knowledge and awareness in each coastal community is needed. Also, placing tsunami warning/evacuation signs [which can be found in other places in Indonesia, see Mikami et al. (2014)] may contribute to improving people's awareness.

In addition, it is also important to make sure that each coastal community is aware of appropriate evacuation routes and destinations. Along the western shore of Palu Bay, as the mountains and hills are close to the coastline, it is easy to evacuate to high ground. Thus, each coastal community should be required to prepare an evacuation route (preferably a paved one) to high ground so that residents can quickly evacuate. Along the eastern and southern shores of Palu Bay there is a wide low-lying coastal area which is more densely populated than the other places surveyed. Thus, in such areas it is necessary to have a sufficient number of buildings which are high and strong enough so that residents can evacuate vertically within a short period of time (such as what happened in the shopping mall described earlier). Evacuation simulations can enable disaster risk managers to investigate the appropriate locations of evacuation destinations and the time it would take for all residents to reach them [e.g. Takabatake et al. (2018) and Mostafizi et al. (2017)]. Using such state-of-the-art techniques, it is possible to develop a good evacuation plan for future tsunamis, which should increase the overall resilience of human settlements against these events.

5. Conclusions

The authors conducted a field survey of the coastline affected by the tsunami caused by the 2018 Sulawesi Earthquake, in order to clarify tsunami

inundation and run-up heights and damage patterns. In the inner part of Palu Bay, and particularly around Palu City, tsunami inundation and run-up heights of more than 4 m were measured at many locations, and severe damage to coastal low-lying settlements was observed. The area to the north of Palu Bay, and that in the actual entrance of the bay, experienced tsunami inundation and run-up heights of less than 3 m, with limited damage being observed. The results of the field survey also showed that the tsunami inundation distance depended on the topographical features of coastal areas and was longer in the southern portion of the bay. However, even in the southern part of the bay severe damage was limited to around 200 m from the shoreline.

This event highlights the necessity to re-assess the risk of landslide-generated tsunamis triggered by earthquakes throughout the world, and highlights a number of lessons that can be learnt for future risk reduction strategies in the area. Given the number of historical tsunami events recorded on Sulawesi Island and the characteristics of the present tsunami, it is clear that the settlements around Palu Bay are at a high risk of experiencing such events. Thus, it is important for local residents and authorities to prepare for these hazards by carefully considering the topographical features and the current levels of tsunami knowledge and awareness of each settlement, and developing appropriate countermeasures.

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