EERI Preliminary Notes on Tsunami Information and Response:

Tsunami Generated by M$_w$7.5 Sulawesi, Indonesia Earthquake on 28 September 2018

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I. Executive Summary and Key Recommendations

On 28 September 2018 an earthquake with magnitude (M) 7.5 occurred in the Sulawesi region of Indonesia. Minutes after the earthquake, a tsunami hit the coasts within Palu Bay. The tsunami, which was generated immediately after the earthquake, caused significant loss of life in the area. The tsunami was captured in a number of videos, was measured on tide gauges, and appeared to have run-up elevations up to 9 meters (the elevation of the ground surface at the position of maximum inundation distance). During the earthquake, landslides up to several square-kilometers in size were triggered by soil liquefaction along the floor of Palu Valley on gently sloping alluvial fans. There is also extensive evidence for landslides along the coastline of Palu Bay. All earthquake- and tsunami-related hazards contributed to the significant structure and infrastructure damage and casualties in the area.

Although scientific and engineering analyses are still on-going, initial evaluations were completed and summarized in this report. The following studies and information contributed to the content of this report:

- Pre- and post-earthquake remote sensing data have been used to estimate the ground deformation from the earthquake.
- A collaboration between the Indonesian Government and Japanese tsunami experts (from a variety of universities) have produced a summary report from their field investigation of tsunami inundation and size.
- Landslide experts produced initial assessments and interpretations of the landslides in Palu Valley.

To date, there are multiple hypotheses that attempt to explain the triggering source for the multiple tsunamis observed in Palu Bay:

- The strike-slip fault motion on the seafloor could have caused horizontal and vertical offsets of submarine bathymetric features, leading to displacement of the water in the Bay.
- The coseismic vertical land motions from the earthquake could have displaced land around the bay.
- Multiple slope failures (landslides) along the coastline could have generated direct tsunami waves.
- Large submarine landslides could have caused significant seafloor displacement.

From initial evaluations, it appears that all of these features could have contributed to tsunami generation, with the subaerial and submarine landslides being the major contributors. The linear shape of Palu Bay likely also contributed to amplification of tsunami waves, especially at the far south end of the bay (Palu City) where there was a higher number of casualties.

From a notification standpoint, Indonesia has a large network of tide gauges which are telemetered (e.g. connected via radio or cell communication protocols) and post the data online in real time. If these gauges were incorporated into a tsunami early warning system, it is possible that some people could be notified in advance of tsunami inundation.

As with most tsunami events, the significant natural tsunami warning sign is the earthquake shaking itself. This event demonstrates that no matter the perceived tsunami threat, educating coastal populations (residents and visitors) about tsunami hazards should be a priority. These two tsunamis (28 September 2018 Donggala-Palu and this 21 December 2018 Sunda Strait event) in Indonesia causing significant casualties demonstrate a need to address non-subduction-earthquake-caused tsunami education and alert/notification solutions.
II. Purpose of Report

The 28 September 2018 Mₗ7.5 Sulawesi, Indonesia earthquake, landslides, and tsunami have caused over 2,100 fatalities, 680 missing people, 4,600 injuries, and about 79,000 internally displaced persons according to the International Tsunami Survey Team Palu (ITST, 2018).

The Earthquake Engineering Research Institute (EERI) supports gathering and sharing information about the effects and damage caused by tsunamis as well as the lessons learned about tsunami notification, evacuation and response activities. This report summarizes the initial observations and response outcomes of the tsunami generated by the Mₗ7.5 Sulawesi, Indonesia earthquake on September 28, 2018 (Figure 1). Although EERI-related field teams were not deployed specifically for the tsunami, this report provides information compiled by the authors from various references, colleagues, and their own personal experiences during and after the event. The information presented should be considered preliminary; for updates, the authors recommend readers visit the scientific and emergency management websites discussed herein.

Figure 1. Plate tectonic map of central Sulawesi, Indonesia. The Palu-Koro and Matano faults are shown on the left (Bellier et al., 2001), as they may be related to several other fault systems trending from the southeast of this region. The USGS epicenter is shown as a red star. On the right is a larger scale map from Watkinson and Hall (2017) that shows some details of the faulting in the Palu Valley. Note their interpretation that includes strike-slip and normal faulting.
The authors who compiled this information include:

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The authors’ objectives for this paper include:

1. Summarizing the background on the earthquake and the characteristics of the tsunami that was produced.
2. Discussing potential lessons learned and future improvements for tsunami-related scientific research, engineering, notification and response (NOTE: discussion about lessons learned represent the opinions of the authors).

III. Earthquake Rupture, Landslides, and Tsunami Effects

The Mw 7.5 earthquake occurred on 28 September 2018 at 10:02:45 UTC near Palu, Sulawesi, Indonesia. This event had extensive effects including ground shaking, landslides, liquefaction, and tsunami inundation. The earthquake was the result of slip on the Palu-Koro fault, a sinistral (left-lateral) strike-slip plate boundary fault system (Figure 1). Sulawesi is bisected by the Palu-Kola / Matano fault system. These faults appear to be an extension of the Sorong fault, the sinistral strike-slip fault that cuts across the northern part of New Guinea.

GPS and block modeling data suggest that the fault in this area has a slip rate of 42 mm/yr (Socquet et al., 2006).
However, analysis of offset stream channels provides evidence of a lower slip rate for the Holocene (last 12,000 years), a rate of about 35 mm/yr (Bellier et al., 2001). Given the short time period for GPS observations, the GPS rate may include postseismic motion from earlier earthquakes.

The seismic hazard associated with this fault was well evidenced prior to the earthquake (Cipta et al., 2016). Using empirical relations for historic earthquakes compiled by Wells and Coppersmith (1994), Socquet et al. (2016) suggest that the Palu-Koro fault system could produce a magnitude M7 earthquake once per century. However, studies of prehistoric earthquakes along this fault system suggest that, over the past 2000 years, this fault produces a magnitude M7-to-M8 earthquake every 700 years (Bellier et al., 2006; Watkinson and Hall, 2017). There is also a record of M>7 earthquakes in the 20th century (Gómez et al., 2000). So, it appears that this is the characteristic earthquake we might expect along this fault.

Earthquake Observations

According to the National Disaster Management Authority (Badan Nasional Penanggulangan Bencana, BNPB), there were around 2.4 million people exposed to earthquake intensity MMI V or greater. MMI V is described as, “Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop.” However, the highest intensity was observed near the earthquake source at MMI VIII, which is described as “severe” shaking with potential damage to all types of structures.
**Figure 2** is a map showing the updated USGS model of ground shaking. This updated earthquake fault slip model was additionally informed by post-earthquake analysis of ground deformation.

Soon after the earthquake, Dr. Sotiris Valkaniotis (Aristotle University of Thessaloniki, Greece) performed an optical analysis using pixel matching/change detection techniques and prepared a map that showed large horizontal offsets across the ruptured fault along the entire length of the western margin on Palu Valley (**Figure 3**). This horizontal offset had an estimated ~8 meters (~26 feet) of relative displacement. InSAR analyses confirmed that the coseismic ground deformation extended through Palu Valley and into the mountains to the south of the valley. Note that the fault displacement is greatest along the western Palu Valley where the fault enters Palu Bay. Also note how the inferred location of the fault that slipped is different than the small-scale map of the fault system shown in **Figure 1**.

**Landslide Observations**

The ground shaking from the earthquake led to extensive slope failures in the region. Observations range from “pro-delta” style landslides along the margin of Palu Bay to kilometer-scale liquefaction driven lateral-spread type failures that transformed into liquefied flows.

On 29 September 2018, one day after the event, Carn (2018) presented on social media a pair of pre- and post-event images of the shoreline from Planet Labs (**Figure 4**). He discussed the sections of coastline that were missing following the earthquake. Based on our analysis of satellite aerial imagery, the coast of Palu Bay in this area has numerous anthropogenic gravel deposits that are placed to allow the gravel mines (the lighter colored region on the left of the images) to load gravel on ships. However, some of these failures occurred in areas not currently being used as aggregate loading zones and may be locations of man-made fill or natural deposits.

Following the 28 September earthquake and tsunami, the Copernicus satellite imagery system was activated in the region for emergency response and management. Users were provided with satellite imagery to evaluate the level of damage visible in the imagery, creating products that grade the damage to affected population and assets such as human settlements and critical infrastructure.

**Figure 5.** Grading map from Copernicus. Color represents relative damage assessed by using post-event satellite imagery.
as settlements, transportation networks, industry, and utilities. The mapping products for this event are named AMSR317 and located online here: https://emergency.copernicus.eu/mapping/list-of-components/EMSR317.

**Figure 5** shows a damage grading map for the region of southern Palu Bay following the event. The mouth of Palu River is in the center of the map; note the sediment plume in Palu Bay. Red colors represent observations of assets believed to be destroyed, orange represents assets that sustain damage, and yellow represent assets that are possibly damaged.

In the grading map (**Figure 5**), two significant impacts from this disaster are observed. First, there is damage along the coastline that diminishes with distance inland away from Palu Bay. This damage is most likely associated with the tsunami inundation. Second, note the area in the southwest of the map that is colored red. This is the Balaroa neighborhood where a large landslide caused the lateral displacement of roads and several hundred buildings. Two much larger kilometer-scale slides are located about 8 and 12 km to the southeast in the Petobo sub-district and the Jono Oge village, respectively.

**Tsunami Observations**

Large, damaging tsunamis are typically associated with subduction zone earthquakes because these earthquakes are the type that generate vertical land motion along the sea floor. However, there is historical evidence that strike-slip fault earthquakes can also generate tsunamis. For example, the 1999 Izmit, Turkey earthquake (Altinok et al., 1999; Alpar et al., 2003; Gusman et al., 2017; Heidarzadeh et al., 2017), and the 2010 M7.0 Haiti strike-slip earthquake (Hornbach et al., 2010) generated local tsunamis. However, these types of earthquakes typically generate tsunamis that are smaller in size.

When landslides generate tsunami, they are often localized relative to the location of the landslide. The tsunami size can be rather large near the landslide and the size diminishes rapidly with distance from the landslide. An example of a landslide generated tsunami is the 1998 Papua New Guinea tsunami (an earthquake triggered a landslide) causing a “larger than expected” tsunami to inundate the land there. The size of the tsunami was very large near the landslide. Localized large tsunami run-up elevations from the 1999 Izmit earthquake may also be explained by a submarine landslide source (Altinok et al., 2001).

There are also observations and modeling results that suggest narrow bays can amplify waves. If the bay is v-shaped, waves can be amplified due to the funnel effect (Shimozono et al., 2012; 2014). The funnel effect would affect the size of the tsunami in Palu Bay if the source of the tsunami were outside of the bay mouth. The modeling of waves in narrow water bodies requires special considerations.

<table>
<thead>
<tr>
<th>Date</th>
<th>Location</th>
<th>Magnitude (M)</th>
<th>Intensity (MMI)</th>
<th>Mechanism</th>
<th>Wave Height (m)</th>
<th>Place, Related Phenomena, and Victims</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dec. 1, 1927</td>
<td>0.7 °S, 119.7 °E</td>
<td>6.3</td>
<td>-</td>
<td>-</td>
<td>15</td>
<td>West Cent. Sulawesi, Palu Bay, subsidence 0.5–12 m, 14 deaths, 30 injured</td>
</tr>
<tr>
<td>Apr. 11, 1967</td>
<td>3.3 °S, 119.4 °E, 20 km</td>
<td>5.5-6.3</td>
<td>VII-VIII</td>
<td>Thrust</td>
<td>-</td>
<td>Tinambung, 58 deaths and 100 injured, the water suddenly retreated</td>
</tr>
<tr>
<td>Aug. 14, 1968</td>
<td>0.7 °N, 119.8 °E, 25 km</td>
<td>7.4</td>
<td>VII-VIII</td>
<td>Normal</td>
<td>10</td>
<td>West Cent. Sulawesi, Palu Bay, subsidence 2–3 m (Mapaga villages), 500 m inland inundated. 200 deaths</td>
</tr>
<tr>
<td>Feb. 23, 1969</td>
<td>3.1 °S, 118.5 °E, 13 km</td>
<td>6.1</td>
<td>VIII</td>
<td>Thrust</td>
<td>2-6</td>
<td>South Sulawesi, Majene, 64 deaths</td>
</tr>
<tr>
<td>Jan. 8, 1984</td>
<td>2.77 °S, 118.8 °E, 14.8 km</td>
<td>6.6</td>
<td>VII</td>
<td>Thrust</td>
<td>-</td>
<td>Mamuju, no record (?)</td>
</tr>
<tr>
<td>Jan. 1, 1996</td>
<td>0.83 °N, 120.1 °E, 15 km</td>
<td>7.7</td>
<td>VII-VIII</td>
<td>Thrust</td>
<td>1-3.4</td>
<td>West Coast Central Sulawesi, Simuntu – Pangalseang, Subsidence 0.5—2 m, 9 deaths, 63 injured</td>
</tr>
</tbody>
</table>

¥ Latitude (degrees), Longitude (degrees), and Depth (km)

Modified from Prasetya et al. (2001)
Didenkulova and Pelinovsky (2011) found that narrow u-shaped bays can amplify waves if there is a monotonic shallowing of water depth, but the largest waves are generated where there are steps in decreased depths. The 2011 Tohoku-oki tsunami also resulted in amplified tsunami waves in narrow bays (Mori et al., 2012).

The Makassar Strait, the seaway to the west of Sulawesi and east of Kalimantan, has the highest frequency of historic tsunami in Indonesia (Prasetya et al., 2001). The primary sources are the Palu-Koro and Adang Line-Pasternoster strike-slip fault systems forming the eastern and western boundaries, respectively, of the Makassar Strait. However, most of the tsunamigenic earthquakes in this area are attributed to thrust or normal faulting (but the 1927 earthquake mechanism is not known). Nainggolan et al (2015) show that these fault zones have fault strands that include strike-slip, normal, and thrust segments. There are Prasetya et al. (2001) suggest that some tsunamis associated with the Pasternoster fault are likely a result of coseismic landslides (slumping). Table 1 lists the historic tsunamis observed in the Makassar Strait (Prasetya et al., 2001).

In the days following the earthquake, Andreas Schäfer prepared a numerical simulation of wave amplitude following his methods presented in Schäfer et al. (2017). Bertrand Delouis prepared a slip model, like the initial model developed by the USGS. Schäfer used this slip model as a source of displacement for his tsunami model. Figure 6 shows the results of this tsunami modeling. At the time this information was provided and given the limited knowledge of the tsunami wave height or run-up elevation, this model suggested that the slip on the fault may have been sufficient to explain the size of the tsunami. Note how, in general, the tsunami wave heights increase and appear to be amplified to the south. This may have to do with the geometry of the bay relative to the source model.

In central eastern Palu Bay, there was a tsunami recorded at the Pantoloan Port tide gauge with a wave height of about 2 meters (location: "PP" on Figure 2). The larger waves lasted about an hour, but smaller waves (~10-20 cm wave height) lasted more than 6 hours. Figure 7 shows a 50m-long vessel that was lifted onto a dock at the port. The tsunami arrived 6 minutes after the earthquake and the maximum wave height was measured 2 minutes after that (Muhari et al., 2018). Debris lines (marks of debris that represent localized flow depths and wave run-up elevations) were observed to be over 8 meters in places along the coast and the flow decreased inland (Muhari et al., 2018). Eyewitness accounts inform us that the tsunami wave heights changed significantly over the course of the event.

Table 1 lists the historic tsunamis observed in the Makassar Strait (Prasetya et al., 2001).

Figure 6. The map on the left shows the maximum tsunami wave heights along the coastline of Palu Bay and north of Palu Bay. The color bar shows these heights as color and units are in meters. The plot on the right show the wave heights at the different locations presented on the map. The vertical axis is aligned with the map on the left. The horizontal axis shows the height in meters.

Figure 7. 50 m long vessel uplifted by the tsunami at Pantoloan Port (Muhari et al., 2018).

Figure 8. 1-minute interval tide gage record from the Pantoloan, Sulawesi, Indonesia. The tide gage is located on the east margin of Palu Bay (Badan Informasi Geospasial, 2018).
did not appear to enter Palu Bay from the mouth (e.g. near Donggala), but from within the bay itself.

**Figure 8** shows tide gauge data provided by Balai Layanan Jasa dan Produk Geospasial, who operate the Indonesia tide gauge network (location: “M” on **Figure 2**). This network is presented online at the following website: [http://tides.big.go.id:8888/dash/](http://tides.big.go.id:8888/dash/). The tsunami was also observed at the Mamuju tide gauge located approximately 275 km to the southwest of the epicenter, along the west-facing coastline in the Makassar Strait. The maximum wave height at Mamuju was about 20 cm, an order of magnitude smaller than recorded at Pantoloan.

Sassa and Takagawa (2018) analyzed these tidal data by removing the astronomical tide data. They concluded that the long period component (e.g. attributed to astronomical tides) has a period of about 1 hour and has an amplitude of 0.7 m. The short period component, associated with the tsunami, has a period of a few minutes and has an amplitude of 3.6 m.

**Potential Tsunami Source**

Based on post-earthquake satellite imagery from Digital Globe, Planet Labs, and Copernicus, the overwhelming majority of tsunami damage is localized within Palu Bay. The severity of damage is worse in southern Palu Bay where tsunami inundation is on the order of 200-300 meters inland. While at the northern part of the bay, inundation is on the order of 15 meters inland. In the north, most of the buildings that were destroyed by the tsunami were built over the water, though not entirely. Building damage extends further inland in the south where buildings have...
been heavily damaged or destroyed. North of the mouth of the bay, there is less evidence for tsunami inundation, but there is localized damage in places.

In the weeks following this natural disaster, numerous teams conducted post-tsunami surveys to document the damage from the tsunami. Their observations included debris lines and other information that allowed them to estimate flow depth, run-up heights, and inundation distance. Figure 9 is a summary figure showing a subset of these observations (Arikawa et al., 2018). These authors documented areas of potential coseismic subsidence, cliff collapse, and evidence for tsunami inundation height, run-up height, and splash height (Figure 9). What Arikawa et al. (2018) describe as subsidence is likely their interpretations of the coastline slope failures presented in the satellite imagery earlier in this report. Note how their documented tsunami evidence is localized within Palu Bay and the isthmus near the epicenter. Also, note that the tsunami observations are associated with evidence of subsidence (coastline slope failures).

Figure 10 is another presentation of direct observation of tsunami wave run-up elevations. This map is a summary of direct observations of tsunami flow depths based upon a survey that culminated on 5 October 2018 (Meteorological, Climatological and Geophysical Agency, BMKG). There is evidence that narrow water bodies amplify wave heights and wave run up elevations (e.g. Didenkulova, 2012) and observations such as those shown in Figure 10 support this hypothesis. However, other observations presented later in this report suggest that there are other factors that are controlling the spatial extent of the largest waves.

Between 7 and 11 November 2018, a UNESCO team of international tsunami scientists conducted a post tsunami survey in regions that had not been a focus of earlier post tsunami surveys (Omira et al., 2019). We present their summary of tsunami run-up elevations in Figure 11. Omira et al. (2019) attribute the variation in run-up elevations due to possible localized non-seismic sources in the generation of tsunami waves. These authors also mention

Figure 11. Observations of tsunami run-up elevations (Omira et al., 2019).
that tsunami observations of run-up height were an order of magnitude lower outside of Palu Bay (Table 2 in Omira et al., 2019).

In addition to tsunami and coastal landslide observations made by Omira et al. (2019), they also found evidence for coseismic subsidence. For example, in Balaesang (village located at the isthmus near the epicenter, north of Palu Bay) there was no tsunami damage nor evidence of inundation. However, eyewitnesses noted that there was an increase in relative sea level that led to flooding of their houses. This occurred for 3 successive days following the earthquake. This apparent coseismic subsidence may be evidence for coseismic vertical land motion, but also could be due to slope instability (similar to the pro-delta type slope failures observed along the coastline of Palu Bay). If due to tectonic vertical land motion, this information could be important to unravelling the mystery of the tsunami triggering.

Figure 12, left side, is a map showing the areas where Sassa and Takagawa (2018) have documented coastline slope failures based on pre- and post-earthquake satellite imagery, labeled A-F. Bathymetric map is from Valkaniotis (2018), made from bathymetry data downloaded from the Indonesian Seamless Digital Elevation Model and National Bathymetry (DEMNAS) [http://tides.big.go.id/DEMNAS/]. The shape of the bathymetric contours provide bathymetric evidence for several km-scale landslide scarps, especially on the eastern margin of the Bay (we annotate landslide headscarsps with yellow lines). Two low-angle oblique images (right), taken by passengers on a commercial flight out of Palu City, show tsunami waves propagating from the coastline. Area F is the same area shown in in Figure 4 that experienced shoreline slope failures.
failures using Digital Globe satellite imagery as part of the Open Data Program (Digital Globe, 2018). The coastline slope failures shown on Planet Labs imagery (Carn, 2018; Figure 4) are from the area labeled “F” in Figure 12.

Passengers on the final flight out of the airport in Palu, prior to the airport being closed due to earthquake damage, took photos of the tsunami waves sourced from these coastline slope failures. Sassa and Takagawa (2018) present some annotated low angle oblique images posted on social media as taken from this air flight.

The tsunami waves shown in F may be due to the shoreline slope failures documented by Carn (2018) using Planet Labs imagery and documented by Sassa and Takagawa (2018) using Digital Globe satellite imagery.

Sassa and Takagawa (2018) found that the tsunami inundation height was ~3-4 m on average in Palu Bay and was as high as 6.8 m in localized areas (6.2 m above the astronomical tide at the time of the earthquake). Based on field evidence and their tide gauge analysis, Sassa and Takagawa (2018) find that 16% of the tsunami amplitude may be attributable to large-scale tectonic processes like the earthquake (such as ground shaking induced slope failure, vertical land motion, or fault rupture), while the remaining 84% of the tsunami amplitude is most likely due to the coastline and submarine slope failures mentioned in this report. A similar coastline slope failure occurred in Haiti in 2010, which is thought to be what caused the local tsunami there (Hornbach et al., 2010). However, in Palu Bay, these coastline slope failures are common and evidently triggered numerous tsunamis (Sassa and Takagawa, 2018). However, given the kilometer-scale landslides observed onshore, it should not be ruled out that a larger submarine landslide is the potential trigger for the tsunami that inundated the southern shores of Palu Bay.

Ulrich et al. (2019) conducted a physics-based modeling approach to resolve the spatial distribution of slip including the time history and sense and magnitude of slip on the fault. Their modeling was calibrated using observations from seismic stations, as well as with a comparison with InSAR analysis of surface displacement. Their model incorporates rupture dynamics, seismic wave propagation, and tsunami propagation and inundation. They found that the 65° east-dipping fault slipped 6m in a left lateral sense and included 2m of normal slip. Ulrich et al. (2019) determined that the vertical motion across the fault would have resulted in seafloor displacements of 1.5 m (Figure 13). The wave amplitudes and periods from their tsunami modeling match tide gauge observations at Pantoloan Port. While landslides were observed onshore and along the coastline, Ulrich et al. (2019) suggest that the observed tsunami may have been primarily caused by fault displacement. However, the single largest limitation of the tsunami modeling of Ulrich et al. (2019) is the low resolution of the bathymetry used.

Figure 13 is a figure from Ulrich et al. (2019) that shows their estimate for the surface displacement along the seafloor in Palu Bay.

Figure 14 shows the maximum run-up elevations at selected locations at Palu Bay as modeled by Ulrich et al. (2019). The locations labeled on this map are correlated to the run-up heights bar chart in Figure 15.

![Figure 13](image-url) **Figure 13.** (a) A “snapshot” showing the vertical land motion (Δb in meters) at 50 seconds into their simulation. (b) West-East profiles of the seafloor at -0.7 (red), -0.8 (orange), -0.75 (green), and -0.85 (blue). (c) The step in bathymetry as a function of latitude. The gray dashed line represents the average (from Ulrich et al., 2019).
**Figure 14.** Simulated run-up maxima at various locations where tsunami run-up elevations have been directly observed (from Ulrich et al., 2019).

**Figure 15.** Comparison between maximum run-up observed elevations (blue) with simulation (orange). Locations are shown on map (Figure 14) and, from left to right, encircle the bay from the northwest, to the south, and then to the northeast (from Ulrich et al., 2019).
Figure 15 is a comparison plot showing the simulated run-up elevations and the observations of run-up elevations. There are several limitations to this modeling approach, such as the coarse bathymetry resolution, which greatly reduces the ability to consider local effects like the observed coastline slope failures. Thus, at the time of this publication, there is insufficient information and analysis to be able to resolve the source(s) of the tsunami (Sassa and Takagawa, 2018 versus Ulrich et al., 2019). There does not appear to be a systematic increase in wave size relative to distance from the mouth of the Bay, suggesting the wave size was not amplified significantly by shape of Palu Bay.

IV. Emergency Notification and Response

As previously stated, the tsunami arrived a number of locations within minutes of the earthquake. This allowed very little time for official tsunami alert messages to be received and the public to react. Figure 16 shows the official timeline of the earthquake and tsunami events according to BMKG.

The following is the timeline translated from Indonesian into English (using Google translate to start with):

17:02 The earthquake happened.
17:07 High alert-level tsunami early warning (0.5-3 m high) in Palu (evacuation).
17:10-17:13 Tsunami arrival time. Viral video of the tsunami in Palu at dusk (but still daylight) with duration ± 3 minutes and confirmed with a statement that the tsunami struck shortly after the big earthquake.
17:27 Tsunami observed in Mamuju. The monitored tide gauge results show the tsunami height is 6 cm. The tsunami is not significant.
17:36 The end of the tsunami. The end of the tsunami was completed at 18:36 [17:36] local time.

Below are some questions that we have been unable to answer:

- Did people evacuate the coastal area after they felt the earthquake?
- Did people start to evacuate when they saw the tsunami?
- Were there any sirens or other notification devices that went off/sounded?
- Did electricity or phones work immediately after the earthquake?
- Did people get the message that no tsunami was expected, eight minutes after the earthquake?

Below are some of the bulletins and other informational resources prepared in response to the tsunami.

- Indonesia National Tsunami Warning Center - Meteorological, Climatological and Geophysical Agency of Indonesia (BMKG)
V. Lessons Learned and Future Applications

Observations of damage and response to the M\textsubscript{w} 7.5 28 September 2018 earthquake and tsunami provide lessons for scientists, engineers, planners, and emergency managers. These lessons can improve responses to future disasters. Some of these lessons and some recommendations are provided in this chapter.

It is recommended that potential follow-up actions for federal agencies be addressed through the U.S. National Tsunami Hazard Mitigation Program (NTHMP) Warning and Coordination Subcommittee, which has served as an effective discussion forum to inform the NTWC and PTWC of issues of concern to states and territories following events.

Tsunami Science and Engineering

Potential lessons about tsunami science and engineering from this event:

1. Strike-slip fault systems can produce deadly and devastating tsunamis (e.g. over 2,200 fatalities for the 28 September 2018 M\textsubscript{w} 7.5 earthquake and tsunami).

2. Strike-slip tsunami scenarios for known faults should be incorporated into probabilistic tsunami hazard analyses.

3. Tsunami bulletins should not be cancelled prior to eyewitness observations or some other direct observations can be made in the region of interest.

4. Tsunami Early Warning systems could be tied to tide gauges, especially in places with existing tide gauge infrastructure, like Indonesia.

5. Tsunami traveling through narrow water bodies may have amplified waves and amplified tsunami runup.

Tsunami Warning Notifications

Application of Lessons Learned to Other Regions

The InaTEWS-BMKG public tsunami bulletin (Appendix A) stated, “Based on historical data and tsunami modelling, this earthquake is not capable of generating a tsunami affecting the Indian Ocean region. No further bulletins will be issued unless the situation changes.” The official timeline mentions the tide gauge data from Mamuju, but there is no mention of the tide gauge at Pantoloan Port, which do show a large tsunami wave. It is possible that the tsunami bulletin should not have been cancelled.

The public was possibly the most successful participant in spreading information about a potential tsunami as evidenced by a social media video recording, showing someone atop the Palu Grand Mall (a multi-story structure facing north towards Palu Bay, approximately 1.5 km west of the yellow Palu River Bridge IV) shouting to people below to evacuate to higher ground. There are many additional occurrences of people evacuating in response to the ground shaking from the earthquake.

The nature of the earthquake (strike-slip) was likely the basis of reasoning for the statement, “...this earthquake is not capable of generating a tsunami affecting the Indian Ocean region.” However, strike-slip earthquakes have a history of generating tsunamis. Notable examples include the 1999 M\textsubscript{w} 7.6 Izmit Turkey earthquake, the 2010 M\textsubscript{w} 7.0 Haiti earthquake, the 2012 M\textsubscript{w} 8.6 Wharton Basin earthquake (Duputel et al., 2012; Wang et al., 2012), and the 2016 M\textsubscript{w} 7.8 Wharton Basin earthquake (Heidarzadeh et al., 2017).

Strike-slip earthquakes are often not considered tsunami-generative because the sense of motion generally does not produce much coseismic vertical land motion. For example, we can compare tsunami models produced in real-time following the 2012 M\textsubscript{w} 8.6 Wharton Basin earthquake to see how tsunami size is affected by vertical land motion for
thrust relative to strike-slip earthquake motion. As we continue to learn more about strike-slip earthquakes, we make observations that there is indeed sometimes a portion of slip that produces vertical land motion. This may be the case for the 2018 Sulawesi earthquake, as evidenced by the analysis by Ulrich et al. (2019).

Application of Lessons Learned to the USA

There were no tsunami warning notifications from the NTWC, PTWC, or any other federal or state agency because this event was not within their geographic area or responsibility for notification.

Tsunami Response

Application of Lessons Learned to Other Regions

Following the 2004 Sumatra-Andaman subduction zone $M_W 9.1$ earthquake and tsunami, killing about a quarter of a million people, the nation of Indonesia has made great progress in educating the public about the hazards associated with earthquakes and tsunami. The people along the coast know that tsunamis are associated with earthquakes. Evident on social media postings of videos before, during, and after tsunami inundation, many people knew to evacuate to higher ground. However, there is some video evidence that people, who were safely atop a multi-story building, evacuated downwards to the ground surface. Because the tsunami did not inundate more than 200-300 m in this location, these people probably survived. However, other scenarios might end with different results.

Application of Lessons Learned to the USA

Many people associate tsunami with subduction zones as they cause earthquakes that most commonly trigger tsunami. Given what we have learned since at least 1999, strike-slip earthquakes can produce deadly tsunami. In the case of the 1999 Izmit Turkey earthquake and tsunami, almost 200 fatalities resulted from a tsunami with an average wave height of more than 2 m (Altinok et al., 1999, 2001).

There are also strike-slip earthquakes in the US that have generated tsunami, including the 1906 $M_W 7.9$ San Francisco earthquake (Geist and Zoback, 1999, 2002) and the 23 January 2018 $M_W 7.9$ Gulf of Alaska earthquake (Wilson et al., 2018). The 1906 San Francisco earthquake very likely generated a small-sized tsunami because of a dilatational fault step over along the San Andreas fault caused coseismic subsidence of the seafloor (Geist and Zoback, 2002). Ryan et al. (2008) found sedimentary stratigraphic and structural evidence of a long prehistory of this vertical land motion, inferred from Plio-Pleistocene subsidence rates calculated from offshore seismic reflection data. While coseismic subsidence may not happen during each earthquake in this area, we may surmise that this has happened at least once in the past, so is possible that this may occur again the future.

The 23 January 2018 Gulf of Alaska earthquake is also thought to have produced vertical land motion across multiple faults (Lay et al., 2018). This $M_W 7.9$ earthquake sequence was the result of slip on intraplate faults in the Pacific plate, possibly due to reactivation of spreading ridge and fracture zone structures related to the formation of the oceanic lithosphere. Lay et al. (2018) suggest that there may have been as much as over 2 m of vertical land motion along the northwestern striking fault and about 0.2 m of vertical land motion along the northeast striking faults. Based on their comparison with DART buoy water surface elevation data, the northwestern striking fault appears to be the principal locus of slip and source of vertical land motion responsible for the tsunami waves. However, as they state, there are no direct observations of coseismic ground displacement along the seafloor.

The state of California is traversed by the San Andreas fault, a dextral strike-slip plate boundary fault system. There are several faults that join the SAF to accommodate relative Pacific – North America plate motion. As these faults interact and are oriented oblique to relative plate motion, additional faults form with normal and reverse/thrust motion. Offshore, any of these faults may serve as a potential source for local tsunami hazard along the coastline. Below are some examples.

In northern CA, the San Andreas and San Gregorio are known Holocene (<12,000 years) active faults that strike offshore of the San Francisco Bay area, along Tomales Bay (similar in shape, but not depth, to Palu Bay), and between Point Reyes and Shelter Cove. Recent work from Beeson et al. (2017) has constrained the northern terminus of the San Andreas fault to extend onshore but not offshore, north of Shelter Cove. They also found that there is potential for vertical separation across the fault north of Point Reyes as evidenced by fault bounded sedimentary basins observed in seismic reflection data. Future ruptures on this segment of the San Andreas fault should be considered as potential for tsunamigenesis.

Koehler et al. (2005) found lithostratigraphic and biostratigraphic stratigraphic evidence for prehistoric coseismic vertical land displacement (subsidence) associated with the northern San Gregorio fault in Half Moon Bay, California. These authors found structural evidence of earthquakes in fault trenches that shows these deposits formed synchronously with earthquakes on the San Gregorio fault. It seems reasonable that the offshore sections of this fault
system may also be capable of generating coseismic vertical land displacement.

There are known faults offshore of Monterey Bay that, if displaced, could be sources for tsunami (Greene, 1990). Johnson et al. (2016) show in seismic reflection profiles highly deformed Pleistocene sediments associated with the San Gregorio fault system.

In southern California, there is an extensive network of faults in the California Borderlands. Many of these faults are reverse faults, but there are some notable strike slip systems. The best known is the Rose Canyon / Newport-Inglewood fault, probably responsible for the 1933 Long Beach earthquake. Recently collected seismic reflection data provide details about the geometry of this fault system offshore of San Onofre (Sahakian et al., 2017). These authors interpret that multiple fault strands include several step-overs, which is evidence that these faults could produce vertical ground displacement. These faults need to be considered as potential sources for tsunamigenesis given our knowledge about historic earthquakes, but also evidenced by the 28 September 2018 Donggala-Palu strike-slip earthquake and tsunami.

Tsunami Early Warning and Public Notification

The agencies in Indonesia failed to maintain a warning for people along the coast of central Sulawesi. There was an initial bulletin, but this was canceled due to the nature of the earthquake (strike-slip) and due to the low amplitude wave recorded on the Mamuju tide gauge. However, it is currently unclear why these agencies did not utilize the information from the Pantoloan Port tidal data, was operational at the time (Figure 8). It would have been prudent to extend the time period of the initial tsunami bulletin for a period of several hours.

The nation of Indonesia operates one of the largest systems of tide gauges in the world. Some gauges are already connected to the Indonesian Tsunami Early Warning System (Schöne et al., 2011). These tide gauges provide a unique opportunity to develop a tsunami early warning system to augment the currently inoperable and expensive tsunami buoy system. For example, if a tsunami early warning system (TEW) were tied to these tide gauges, an alert could have been broadcast immediately following when the wave was recorded at the Pantoloan gauge (Wächter et al., 2012). If this TEW system were tied to SMS (mobile phone messaging), it is possible that a notification could have been sent to people in Palu City prior to the arrival of the tsunami (assuming Pantoloan Port was between the tsunami source and Palu City). A recent tsunami in the Sunda Strait, probably a result of the collapse of Anak Krakatau (Patton et al., 2018), is another example where tide gauge based TEW may have helped (especially given the lack of an earthquake that would have produced a natural warning).

VI. Acknowledgements

We would like to thank the people who provided their near-real time evaluations and analyses of this disaster as it was unfolding, largely on social media. This sharing of information was key to our ability to respond to this natural disaster. Hopefully people continue to share their results freely online and that people continue to respect the sources of these analytical results. We have attempted to give credit to the sources we used in this report.

Additional Sources Online:

Discover Magazine:

Temblor Articles:
- 2018.10.03 Tsunami in Sulawesi, Indonesia, triggered by earthquake, landslide, or both http://temblor.net/earthquake-insights/tsunami-in-sulawesi-indonesia-triggered-by-earthquake-landslides-or-both-7825/

Earth Jay Reports:
- 2018.09.28 M 7.5 Sulawesi http://earthjay.com/?p=7793
- 2018.10.16 M 7.5 Sulawesi UPDATE #1 http://earthjay.com/?p=7866
Twitter accounts Involved in the response to this sequence of disasters:

- ASEAN Coordinating Centre for Humanitarian Assistance on disaster management https://twitter.com/AHACentre
- BMKG Indonesia https://twitter.com/infoBMKG
- Simon Carn https://twitter.com/simoncarn
- Andreas M. Schäfer https://twitter.com/CATnews-DE
- Sotiris Valkaniotis https://twitter.com/SotisValkan
- Eric Fielding https://twitter.com/EricFielding
- IRIS Earthquake Science https://twitter.com/IRIS_EPO
- Anthony Lomax https://twitter.com/ALomaxNet
- Sutopo Purwo Nugroho https://twitter.com/Sutopo_PN
- Dave Petley https://twitter.com/davepetley
- Jascha Polet https://twitter.com/CPPGeophysics

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This publication is available in PDF format from http:// 
www.eeri.org.
The following bulletin was published online by the Indonesia Tsunami Early Warning System (InaTEWS) approximately 8 minutes after the earthquake.

http://rtsp.bmkg.go.id/publicdetail.php?eventid=20180928171136

TSP-InaTEWS-20180928-1011-001

PUBLIC TSUNAMI BULLETIN NUMBER 1
IOTWMS TSUNAMI SERVICE PROVIDER INDONESIA (InaTEWS-BMKG)
issued at 1011 UTC, Friday, 28 September 2018

... EARTHQUAKE BULLETIN ...

This bulletin applies to areas within and bordering the Indian Ocean and is issued by Tsunami Service Provider INDONESIA in support of the UNESCO/IOC Indian Ocean Tsunami Warning and Mitigation System (IOTWMS).

For information applying to areas outside the Indian Ocean refer to the relevant Tsunami Warning and Mitigation Systems listed in section 6 below.

1. EARTHQUAKE INFORMATION
IOTWMS-TSP INDONESIA has detected an earthquake with the following preliminary information:

Magnitude : 7.7 Mwp
Depth     : 10km
Date      : 28 Sep 2018
Origin Time: 10:02:44 UTC
Latitude  : 0.18S
Longitude : 119.85E
Location  : Minahassa Peninsula, Sulawesi

2. EVALUATION
Based on historical data and tsunami modelling, this earthquake is not capable of generating a tsunami affecting the Indian Ocean.
region. No further bulletins will be issued unless the situation changes.

Further information on this event will be available at:
http://rtsp.bmkg.go.id

3. ADVICE
This bulletin is being issued as advice. Only national/state/local authorities and disaster management officers have the authority to make decisions regarding the official threat and warning status in their coastal areas and any action to be taken in response.

For more detailed information, please refer to the tsunami advisory bulletins issued by the National Tsunami Warning Centres (NTWCs) of Indian Ocean countries. The tsunami warning status reported by NTWCs for their countries can be found at:
http://www.incois.gov.in/Incois/tsunami/NTWCFeedbackStatus.jsp

4. OTHER INDIAN OCEAN TSUNAMI SERVICE PROVIDERS:
Other IOTWMS-TSPs may issue additional information at:
IOTWMS-TSP INDIA: http://www.incois.gov.in/Incois/tsunami/eqevents.jsp

5. CONTACT INFORMATION
IOTWMS-TSP INDONESIA:
THE AGENCY FOR METEOROLOGY CLIMATOLOGY AND GEOPHYSICS (BMKG)
InaTEWS - Indonesian Tsunami Early Warning System
Address: Jl. Angkasa I no.2 Kemayoran, Jakarta, Indonesia, 10720
Tel.: +62 (21) 4246321/6546316
Fax: +62 (21) 6546316/4246703
P.O. Box 3540 Jakarta
Website: http://rtsp.bmkg.go.id/publicbull.php
E-Mail: inartsp@bmkg.go.id
monitrtwp@bmkg.go.id

6. TSUNAMI WARNING SYSTEMS OUTSIDE THE INDIAN OCEAN
Pacific Tsunami Warning and Mitigation System (PTWS):
Pacific Tsunami Warning Centre (PTWC)
http://ptwc.weather.gov/

North West Pacific Tsunami Advisory Centre (NWPTAC)

US National Tsunami Warning Centre (US NTWC)
http://wcatwc.arh.noaa.gov/

Joint Australian Tsunami Warning Centre (JATWC)

Northeast Atlantic, Mediterranean and Connected Seas (NEAMTWS):
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French National Tsunami Warning Centre (CENALT)
http://www.info-tsunami.fr

Institute of Geodynamics, National Observatory of Athens
http://www.gein.noa.gr/en/

Kandilli Observatory and Earthquake Research Institute, Turkey
http://www.koeri.boun.edu.tr/2/en/

Caribbean and Adjacent Regions (CARIBE EWS):
---------------------------------------------

Pacific Tsunami Warning Centre (PTWC)
http://ptwc.weather.gov/

END OF BULLETIN