Earthquake Geology of the April 14 and 16, 2016 Kumamoto Earthquakes

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[This is a preliminary report based on limited information as of April 28, 2016 and shall be revised and corrected. Click HERE for new version.]

1. Overview

A Mw 7.0 earthquake hit west central Kyushu island in west Japan at 01:25 JST on April 16, 2016. Reportedly 49 were killed, 1 are missing and more than thousand are injured as of April 27. 28 hours before, at 21:26 JST on April 14 another Mw 6.1 had shook the same region severely. Intense ground shaking by two successive earthquakes caused structural damages in an extensive area. The shakings by a large number of aftershocks force 90,000 people to evacuate from their homes no matter the homes were damaged or not. And the extensive damages to infrastructures make their lives more difficult.

Previously mapped and evaluated Futagawa and Hinagu fault zones are the sources of these two earthquakes. The Futagawa fault zone, the northeastern portion of the two fault zones runs about 30 km ENE-WSW. The longest section of the NE portion is called Futagwa fault. The SWS-NEN trending Hinagu fault merges with the Futagawa near its west termination (F and H in figure 1). The Futagawa fault is the source of the Mw 7.0 with 2 m+ right-lateral strike-slip at the surface. The Mw 6.1 ruptured about 15 km long northernmost section of the Hinagu fault without surface ruptures. Minor surface ruptures appeared in this section during the Mw 7.0.

2. Tectonics

The earthquake occurred on the south margin of the Central Kyushu rift. Central Kyushu is the only area of volcanic extensional tectonics in Japan, where EW compression is predominant. Unzen volcano in west of Kumamoto, Aso volcano, and Beppu-Haneyama graben in east are within this NS extending volcanic graben. In southwest, the graben is believed to continue down to the Okinawa trough, the active back-arc spreading center behind the Ryukyu island arc. In northeast, the graben terminates in Beppu bay and the active tectonics shift to strike-slip of the Quaternary Median tectonic line (figure 1).

In west of the Quaternary Median tectonic line, there is a continuous boudary between Mesozoic subduction-related sediments in south and the Neogene volcanics and sediments in north. The Median tectonic line in Shikoku is a very active Quaternary transform, but the activity is replaced with normal faulting on shore Kyushu in most part of the graben. So, the geologic boudary along the south margin of the grabe is mostly inactive except for the Futagawa fault.

The Futagawa-Hinagu fault zone is driven both by the EW compression derived from Philippine Sea plate subduction and by the N-S extension of the Central Kyushu rift. The slip is right-lateral strike-slip with south-side-up normal separation. That means the WSW-ENE strike Futagawa fault is dipping NWN and the NEN-SWS strike Hinagu fault is dipping WNW. The dips are within 60 to 80 degrees. On both faults, right-lateral strike-slip is predominant, but the uplift of the Kyushu mountains in south is due to the normal component of the fault movement.

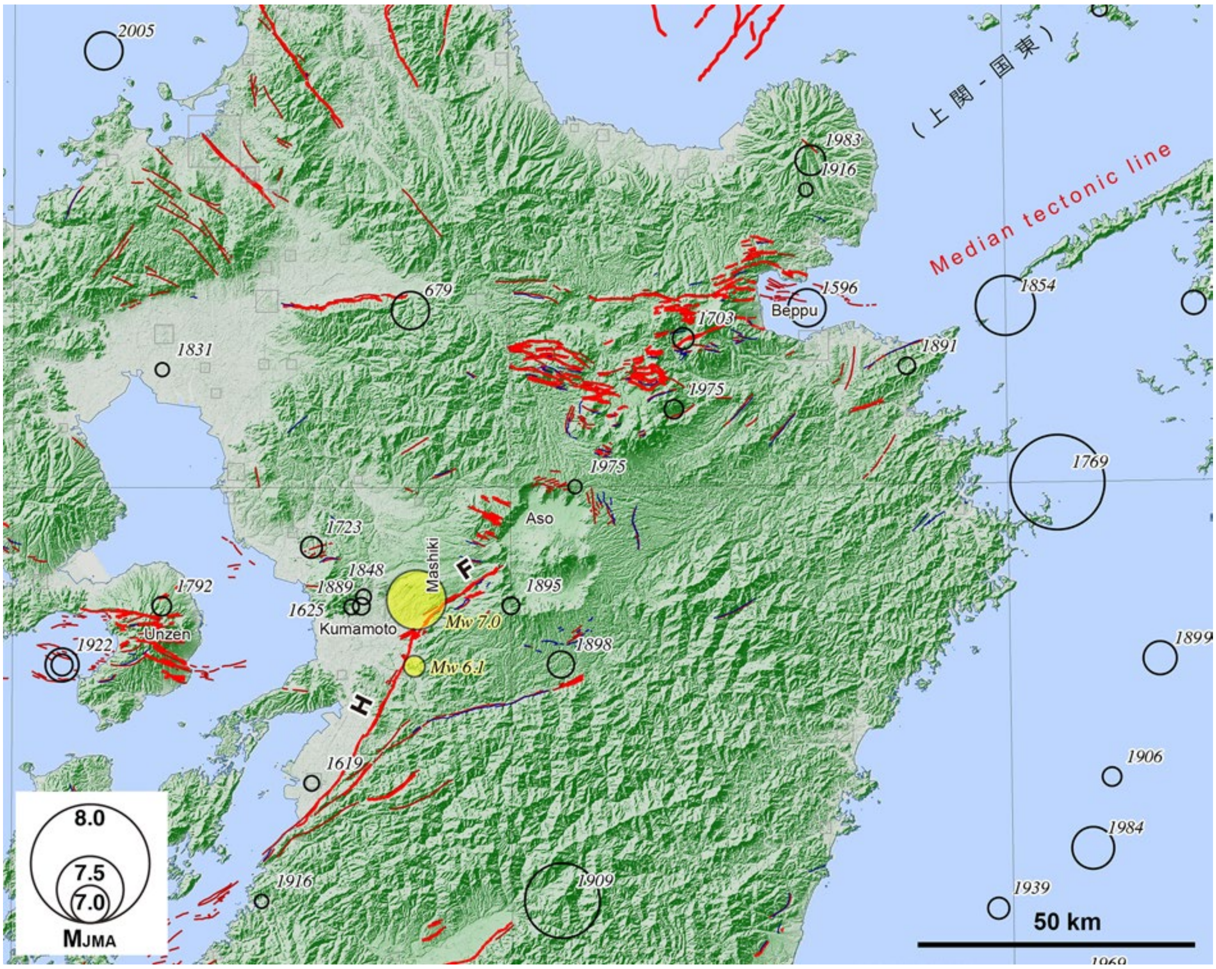

Figure 1 Quaternary faults and earthquakes in Northern Kyushu
Quaternary faults: Nakata and Imaizumi eds. (2002), Research Group for Active Faults of Japan (1995)
Historic earthquakes: Usami (1996)

3. Earthquakes

The April 14 Mw 6.1 recorded the highest JMA intensity scale of 7 at Mashiki JMA (Japan Meteorological Agency) station. The KiK-net (Strong-motion Seismograph Network of the National Research Institute for Earth Science and Disaster Prevention: NIED) maximum peak ground acceleration at Mashiki (KMMH16) was 1580 cm/s^2 in the area of the JMA intensity scale of 7.
http://www.j-risq.bosai.go.jp/report/static/R/20160414212642/0131/00001/R-20160414212642-0131-00001-REPORT_EN.html
http://www.kyoshin.bosai.go.jp/kyoshin/topics/html20160414212621/main_20160414212621.html
http://www.fnet.bosai.go.jp/event/tdmt.php?_id=20160414122500&LANG=en

The Mw 6.1 ruptured the deeper part of the northernmost section of the Hinagu fault. Strong ground motion took place in north and northwest of the epicenter or respectively in Mashiki town and Kumamoto city. The intensity 7 at Mashiki may be due to the directivity effect of the northward rupture propagation on the Hinagu fault. The radiation of strong seismic wave perpendicular to the WNW dipping Hinagu fault plane may be the cause of the strong shaking in Kumamoto.

The Mw 7.0 earthquakes on April 16 occurred during the aftershock sequence of a Mw 6.1 earthquake at 21:26 JST on April 14, 2015. Therefore the Mw 7.0 "aftershock" on April 16 was

immediately redefined as a "mainshock" after the occurrence and the Mw 6.1 "main-shock" was redefined as a "foreshock". The Mashiki JMA station again recorded intensity 7. The Mashiki KiK-net station KMMH16 recorded 1320 cm/s^2 this time, a little smaller than during the Mw 6.1.
http://www.j-risq.bosai.go.jp/report/static/R/20160416012514/0424/00002/R-20160416012514-0424-00002-REPORT_EN.html
http://www.kyoshin.bosai.go.jp/kyoshin/topics/html20160416012405/main_20160416012405.html
http://www.fnet.bosai.go.jp/event/tdmt.php?_id=20160415162400&LANG=en

The main-shock caused extensive structural damages along the Futagawa fault and further east and further west of the fault. The shaking was again the most intensive at Mashiki town. Many houses that were already damaged by the Mw 6.1 collapsed during the Mw 7.0. The extremely strong shaking may be due to the directivity effect of the up-dip propagation of the rupture on the Futagawa fault under Mashiki town, which is located between the epicenter in north and the surface fault in south. Both the epicenter and the fault are two kilometers away from the Mashiki town in opposite directions. The fault plane dips 60° (by GSI: http://www.gsi.go.jp/common/000139798.pdf) to 84° (f-net moment tensor: http://www.fnet.bosai.go.jp/event/tdmt.php?_id=20160415162400&LANG=en) NWN and hypocenter depth is 14 km. The ground acceleration spectra of NIED's KiK-net show significantly larger acceleration at 0.5 to 1.0 Hz by the Mw 7.0 than by the Mw 6.1. Though the peak ground acceleration is smaller by the Mw 7.0, this larger acceleration at 0.5 to 1.0 Hz might account for the heavier damages to Mashiki town by the Mw 7.0.

The rupture propagated toward ENE along the strike of the Futagawa fault. At the end of the rupture is the Minami-Aso village, where 14 were killed and many slope failures occurred. The source fault terminates in the east bank of the Shirakawa barranca where the fault intersects with the Aso caldera rim. In this area, topographic relief is much larger than in other source region for the 300--700 m high caldera walls, 100--150 m deep barranca gorge, and steeply eroded edifices or the central cone volcanoes in east. The steep slopes failed at many locations by the shaking of the mainshock, probably intensified by directivity effects. The Late Quaternary sediments filling the Aso Caldera (95000 years old) also amplified the ground motion to cause many structural damages.

4. Crustal movement and surface faulting

The Geospatial Information Authority of Japan (GSI) published the GEONET (GNSS Earth Observation Network System) observation and model, and SAR (Synthetic Aperture Radar) interferometry results using the ALOS-2 (Daichi-2) satellite together with a lot of low-altitude air-photos and UAV movies.
http://www.gsi.go.jp/BOUSAI/H27-kumamoto-earthquake-index.html
Mw 6.1 foreshock
http://www.gsi.go.jp/common/000139760.png
Mw 7.0 mainshock:
http://www.gsi.go.jp/common/000139809.png
http://www.gsi.go.jp/common/000139905.pdf

The SAR interferometry results clearly demonstrate how faulting occurred and how the surface was deformed. The deformation by the Mw 6.1 is broad and as small as 10 to 20 cm over 10 km wide areas. There was no surface rupture. After the Mw 7.0 more than 10 fringe cycles appeared along the Futagawa fault corresponding to up to 2 m strike-slip offset at the surface on the fault. Along the northernmost

Hinagu fault, the sharp line cutting through frings coincides with the observation of ~25 cm offset by Tohoku University geologists (http://irides.tohoku.ac.jp/irides-news/20160417/289).

According to the preliminary reports from the field and the author's own survey, up to 2.0 m consistent right-lateral strike-slip is observed on the Futagawa fault. The vertical component is usually up to 0.5 m south-side-up, but up to 0.2 m north-side-up deformation is also observed. The offset along the northernmost Hinagu fault is also right-lateral strike-slip. In addition to the slip along the master strands, a 5 km long branch fault of up to 1.2 m right-lateral strike-slip appeared in the east of and under Mashiki town (Kumahara et al.: http://jsaf.info/jishin/items/docs/20160420164714.pdf). There also appeared a conjugate fault with left-lateral strike-slip. These branch faults appeared on modern alluvial plain and there was no remnant of previous slips. The field report of Geological Survey of Japan by Shirahama et al. (http://g-ever.org/updates/?p=334) shows many offset features in the central section of the Futagawa fault. Geospatial Information Authority of Japan (GSI) report (http://www.gsi.go.jp/common/000139911.pdf) based on UAV survey (https://www.youtube.com/watch?v=bS6ftodIHeI&feature=youtu.be) shows the surface rupture near the ENE termination of the Mw 7.0 fault inside the Aso caldera just east of the barranca. The 5 km section of the ENE termination has not been mapped previously.

Most of the Mw 7.0 surface rupture appeared along the previously mapped ~30 km strands of the Futagawa and Hinagu fault. However, the occurrence of the branch faults, south-side down dip-slip, as well as the unmapped termination section presented much more complicated faulting took place in longer than expected source fault.

5. Soil condition in Kumamoto--Mashiki area

Kumamoto city and Mashiki town are located north of Kumamoto alluvial plain (Heiya). Look at the area in the seamless geologic map by the Geological Survey of Japan at https://gbank.gsj.jp/seamless/seamless2015/2d/index.html?lang=en. Kumamoto Heiya is a Holocene alluvial plain (unit 1). The alluvial plain, especially in its southern and eastern parts are mostly too wet for developing and used as paddy fields. Northern half of Kumamoto city and Mashiki town are located north of the plain on Pleistocene fluvial terraces (170 and 171) and on early Late Pleistocene pyroclastic flow (95 and 83). The Futagawa fault cuts the lava plateau (83) and continues along the boundary between the Kumamoto Heiya (1) and Cretaceous rocks. The Hinagu fault in south juxtaposes alluvial plain (1) with bedrocks and run north through bedrocks to merge with the Futagawa fault.

According to Ishizaka et al. (1975: The Quaternary Research [Tokyo], vol. 34: https://www.jstage.jst.go.jp/article/jaqua1957/34/5/34_5_335/_pdf), the Kumamoto Heiya is an area of active subsidence at a rate of 0.90 mm/yr near the coast and 0.45 mm/yr in south of Kumamoto city. With this subsidence rate, 900 m to 450 m sediments are to be accumulated in a million years under the Kumamoto plain. It is very likely this zone of subsidence continues toward east along the Futagawa fault in south and Mashiki town in north.

In the J-SHIS Japan Seismic Hazard Map (http://www.j-shis.bosai.go.jp/map/?lang=en) large site amplification is expected in Kumamoto plain and intensity 6+ to 7 is forecasted in case of Futagawa-Hinagu fault zone earthquake. The Kyushu Express way (right green line) got severe damage on this alluvial plain and is closed now. An express way bridge in the middle of the plain barely survived from collapsing with structural damages. However, the eastern part of the plain is so wet for developing there were no house to be damaged.

Mashiki town, where the severest structural damages took place, is located across the plain from the unit 100 isolated volcanic hill in the geologic map. The center of the town is on the south-facing slope above 11 m high alluvial plain and below 40 to 50 meter high upland consists of Late Quaternary sediments and pyroclastic flows. Subsurface geology is not known yet, but there should be a few hundred meters of sediments that were laid down in pace with the subsidence in south. The sediments may be deposited above south facing bed rock slope as there are hill of Cretaceous rocks several kilometers north.

The KiK-net 1580 cm/s^2 and 1328 cm/s^2 peak ground acceleration, as well as intensity 7 were recorded on the flat top of the upland away from the slope and the alluvial plain. The very strong ground shaking here even destroyed rather new houses on the flat top of the upland where no amplification by surface soil is expected. Therefore the effect of the deeper subsurface sediments and structures on the ground shaking are to be investigated. The significant thickness of Late Quaternary sediments as well as the shape of the basin may have affected the ground shaking on the Mashiki upland.

The author also observed a lot of gravitational slides and lateral spreading on the south-facing slope and on the slopes along incising creeks. There are many collapsed houses owing to this geotechnical causes in addition to the vibration effects. At the foot of the slope, a river runs along the boundary between the upland and the alluvial lowland. The river erodes the upland and fill its course with soft sedmients. There is no clear erosional scarp along the bank, but the sediments of the upland should contact with the alluvial sediment with buried scarps. This situation may be the cause of lateral spreading and sliding in the lower part of the slope. 8 fatalities by the Mw 6.1 foreshocks were reported along the foot of the scarp.

The most intense ground shaking at Mashiki town is presumably due to the effects of seismic wave radiation and of rupture directivity both for the Mw 6.1 and the Mw 7.0. The failure of slopes and possible lateral spreading are the additional cause to the shaking of the severest structural damages. Some researchers claim the branch fault in east and under the town is the cause of the localized damages. It is not likely because the ruptures in the sediments and shallow bedrocks generate neither strong ground motion nor directivity effect. There is no significant concentration of damages by shaking along the master strand of the Futagawa fault. This is clear and strong evidence that ruptures at and near surface have nothing to do with strong vibratory motions.

In Kumamoto city, moderate structural damages took place extensively. The southern half of the city has expanded into the Kumamoto Plain above hundreds of meter thick sediments. The northern half of the city is on Late Pleistocene terraces on Quaternary volcanics. Thick soft sediments and rocks may have amplified the ground motion. Detailed investigation on the soil condition and damages should be carried out to understand seismic risks in the cities on soft sediments.

6. Past earthquakes and earthquake forecast

No historic earthquake larger than M 6.5 was recorded in the source area (figure 1). In Kumamoto, M 6.0 to M 6.5 earthquake occurred every 50 to 100 years. These earthquakes killed 10s of people and damaged Kumamoto castle repeatedly. So, the 2016 shaking in Kumamoto is not an unusual event. Earthquakes larger than M 7.0 were inferred only by paleoseismological excavations on the Futagawa-Hinagu fault zone.

HERP, the Headquarter for Earthquake Research Promotion of the government of Japan, had evaluated long-term seismic potential of the Futagawa-Hinagu fault zone in 2002 and revised it in 2013. The seismic risks of the Futagawa-Hinagu fault zone was evaluated by rather limited geologic information of recurring earthquakes. For the Futagawa segment of the fault zone, an earthquake around M 7.0 with 2 m surface offset on a 19 km long rupture was forecasted. A M 6.8 earthquake was forecasted for the 16 km segment of northernmost section of the Hinagu fault, on which the Mw 6.1 occurred at depth and surface ruptured during the Mw 7.1.

The conditional probability of the earthquake in 30 years was estimated as 0 to 0.9 %. This estimate is based on two past earthquakes in paleoseismological excavations. The timing of the two events are 2200 to 6900 years before present and 23000 to 26000 years before present. One or more events were supposed to have been missing in the geologic records. Assuming 2 or 3 events since 26000 years ago, recurrence interval was estimated as 8100 to 26000 years. The large uncertainty and long interval made the probability less than 1 %. But 0.9 % 30-year probability is rather high for slow-moving intra-plate faults in Japan and the highest possible ratio between the elapsed time and the recurrence time was 0.9 at the highest.

Figure 2 Surface rupture at Shimojin (N32.49519° E 130.84871°)
The rupture offsets the southeast corner of a paddy by 1.2 m right-lateral strike-slip (east edge of the paddy) and 0.4 m south-side-up. The slope to the left is a fault scarp of the Futagawa fault. It seems farmers cut into the scarp to make the paddy wider and the scarp steeper. The fault passes just in front on left hand side of the upper-right house. The house is almost intact.