The Kumamoto, Japan, earthquakes of April 2016

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Abstract

The April 2016 Kumamoto earthquake series started with an M_{JMA} 6.5 (Mw 6.2) foreshock, followed by an M_{JMA} 6.4 (Mw 6.1) event a few hours later. The mainshock with M_{JMA} 7.3 (Mw 7.1) occurred ~28 hours after the first foreshock. The foreshocks occurred on Hinagu fault, where a possibility of an M 6.8 earthquake was forecasted. The mainshock occurred on Futagawa fault, where an M 7.0 earthquake was forecasted with 0–1 % probability in the next 30 years. The mainshock triggered earthquakes with M~6 in Aso (~50 km from the epicenter) and Beppu (~80 km) regions. The aftershock activity as well as triggered seismicity were very high, nearly 250 earthquakes with M > 3.5 occurred within 30 days. While the location and size of foreshock and mainshock were similar to the forecast, forecasting the timing, including the identification of foreshock is still difficult.

Keywords: Kumamoto earthquake, foreshock, aftershocks, forecast, active fault

1. INTRODUCTION

The April 2016 Kumamoto earthquakes occurred in the Beppu-Shimabara rift, running east-west direction through central Kyushu. This rift is a westward extension of Median Tectonic Line, a major geological boundary in western Japan. The rift is characterized by north-south extension, and Aso volcano with one of the largest caldera is located in it (Figure 1). The rift extends in the southwest direction toward Okinawa Trough, a backarc of Ryukyu Trough. On November 14, 2015, an M 7.1 earthquake with strike-slip fault mechanism occurred in Okinawa Trough, about 300 km SW of the Kumamoto earthquake, and many aftershocks followed.

The Kumamoto earthquake series started with an M_{JMA} 6.5 (Japan Meteorological Agency scale) event in the evening at 21:26 on April 14 (Japan Time: UTC+9). About 2.5 hours later, at 00:03 on April 15, an M_{JMA} 6.4 earthquake occurred, which was thought as an aftershock of the first event. Then, about 28 hours after the first event, at 01:25 on April 16, the largest earthquake with M_{JMA} 7.3 occurred (JMA, 2016). This is considered as the mainshock, and all the previous earthquakes became foreshocks. Because of such unusual and active foreshock activity, we call the entire sequence as the Kumamoto earthquake series, or simply Kumamoto earthquakes.

The Kumamoto earthquakes caused 50 casualties and 1,800 injured. Soon after the mainshock, nearly 200,000 people were evacuated to shelters. The housing damage includes 8,300 total collapse, 26,000 half collapse and 236,000 partial collapse (Cabinet Office, 2016). Most of casualties and house collapse occurred along active faults extending from the epicenter in Mashiki Town to Aso caldera.

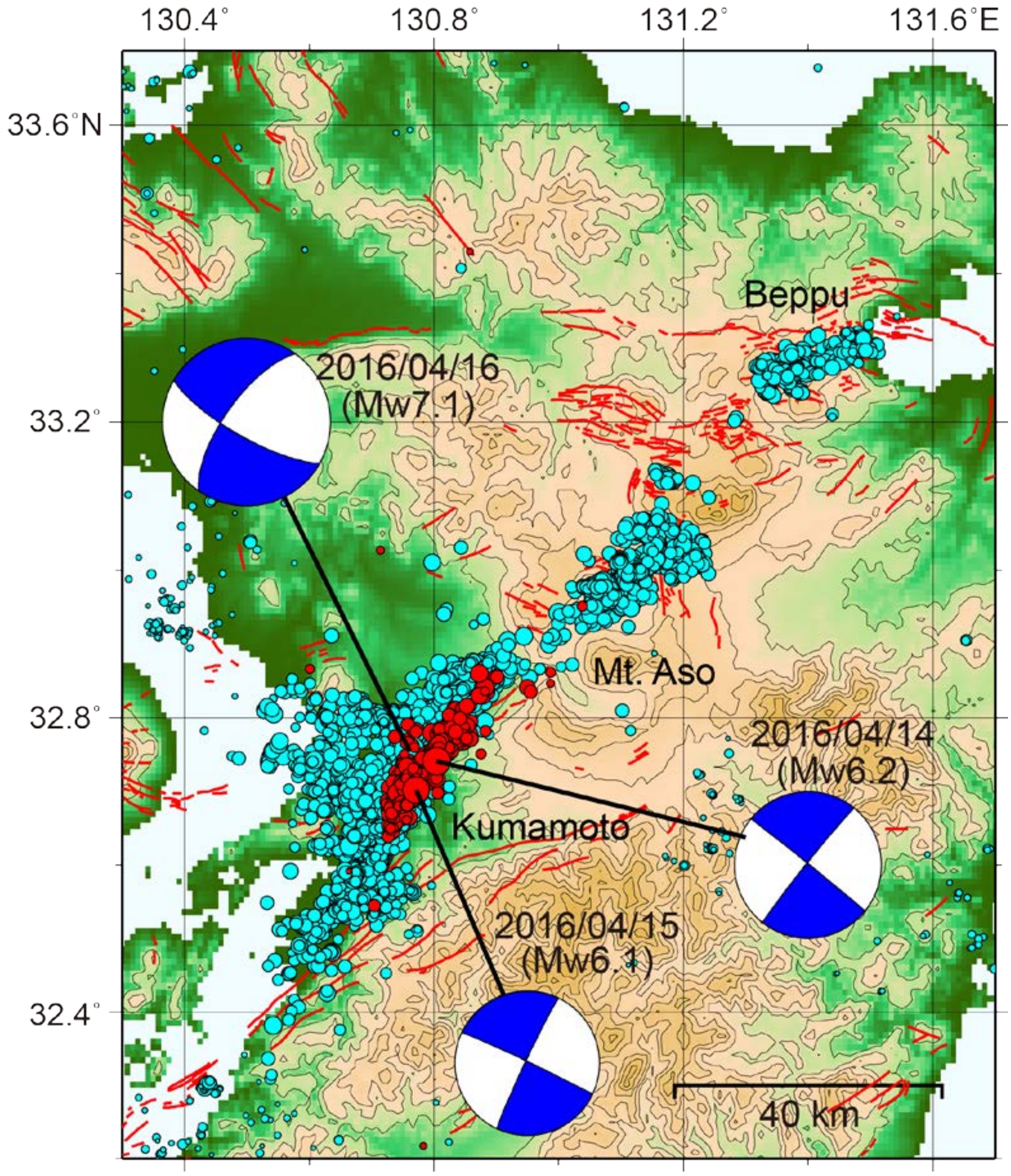

Figure 1. Focal mechanism solutions of the foreshocks and mainshock. Relocated earthquakes before and after the mainshock (April 14 to April 16: red and April 16 to May 31: blue) are shown.

2. HINAGU AND FUTAGWA FAULTS AND PREVIOUS EARTHQUAKES

After the 1995 Kobe earthquake, which caused more than 6,000 casualties, the Japanese government set up Headquarters of Earthquake Research Promotion (HERP), and deployed networks of seismograph, strong-motion and GPS, each consists of ~1,000 stations in Japanese Islands. In addition, HERP started mapping and paleoseismological studies of active faults. Based on available data on these observation networks, the Earthquake Research Committee (ERC) evaluates the seismicity around Japan at their monthly meetings as well as emergency meetings after damaging earthquakes. The ERC also makes long-term forecast of earthquakes, evaluates the size and 30-year probability of occurrence, on major (~100) active faults in Japan.

In the source area of the Kumamoto earthquakes, two fault systems, the Futagawa fault zone and the Hinagu fault zone, were mapped and evaluated by Earthquake Research Committee (2013a) (Figure 2). The Futagawa fault zone consists of three segments; only the eastern segment, the 19 km long Futagawa section, is mapped on ground surface, and the western two segments, 20 km long Uto section and > 27 km long Uto Hantou Hokugan (northern coast of Uto peninsula) section, are inferred from subsurface structure, mostly the Bouguer gravity data. The Hinagu fault zone also consists of northern segment (16 km long Takano-Shiharata section), central segment (40 km long Hinagu section), and southern segment (30 km long Yatsushiro-kai section). It should be noted that the ERC's earlier (2002) evaluation, as well as other mapping (e.g., by Geospatial Information Authorities, 2001) identified, mostly based on aerial photographs, the Futagawa-Hinagu fault zone as a continuous active fault system.

Paleoseismological investigations have been made on the four sections these fault zones. On the Futagawa section of the Futagawa fault zone, two past earthquakes were identified in 6.9–2.2 thousand years (ka) before present (BP) and 28–23 ka BP. The recurrence interval was estimated as 8.1–26 ka (ERC, 2013a). On the northern (Takagi-Shirahata) section of the Hinagu fault zone, only one event, dated at 1.6–1.2 ka BP was identified.

Size and occurrence probabilities of future earthquakes on each segment were estimated from the fault mapping and paleoseismological data. On the Futagawa section (19 km long with strike of N55°E), the earthquake size was estimated as M 7.0 with fault slip of 2 m, and the 30-year probability of occurrence was estimated as 0–0.9 %, which belongs to a group of high probability of active faults. On the Takagi-Shirahata section of Hinagu fault zone (16 km long with strike of N23°E), the earthquake size was estimated as M 6.8 with 2 m slip, but the probability of occurrence was not estimated because only one past event was dated. Larger magnitude was estimated for a possible rupture extending to neighboring sections, and the maximum size of earthquake was estimated as 8.2 if both Futagawa and Hinagu fault zones were ruptured in a single event.

In addition to the evaluation of individual faults, ERC (2013b) made regional evaluation of entire Kyushu. They estimated occurrence probabilities of an M 6.8 or larger earthquake as 18–27 % in central Kyushu (including the Futagawa fault zone) and 7–18 % in southern Kyushu (including the Hinagu fault zone). They also estimated the 30-year probability of an earthquake from the current seismicity data; they are 11 % and 19 % for the central and southern Kyushu, respectively.

In Kumamoto prefecture, several damaging earthquakes have been recorded in historical documents. The oldest one on June 26, 744 (M~7.0) may have occurred on the southern segment of Hinagu fault zone. Another earthquake on May 1, 1619 (M ~ 6) might have been on Hinagu fault zone, though it is less certain. At least three earthquakes have caused damage in Kumamoto city, including Kumamoto castle, as in the 2016 earthquakes. They are: July 21, 1625 (M ~5 to 6) with 50 casualties, December 19, 1723 (M ~ 6.5) with two casualties, and July 28, 1889 (M 6.3) with 20 casualties. The last earthquake was studied in details, such as damage distribution and photograph, as well as seismograph recording of the aftershocks.

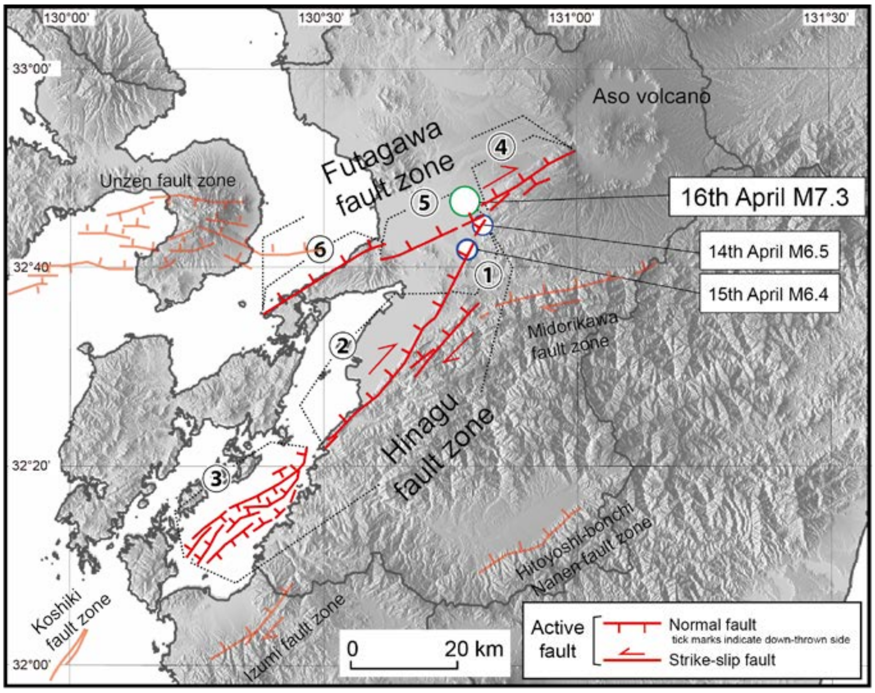

Figure 2. Locations of Futagawa and Hinagu fault zones based on ERC (2013a). The Figure courtesy of Dr. Hisao Kondo at HERP.

3. FORESHOCKS ON APRIL 14 AND 15

The first foreshock (M_{JMA} 6.5) on April 14 registered the maximum seismic intensity of 7 on the JMA scale (composite PGA of 1580 gal at KiK-net Mashiki station; NIED, 2016) and caused damage including nine casualties. The moment magnitude based on USGS W-phase inversion is Mw 6.2. Another large earthquake (M_{JMA} 6.4) occurred several km SW of the first event on April 15 at 2.5 hours later at 0:03, which caused maximum seismic intensity of 6+, was considered the largest aftershock of the first event. The moment magnitude based on USGS W-phase inversion is Mw 6.0.

The focal mechanism of these earthquakes is strike-slip type with T-axis in NNW-SSE direction. The gCMT (Global Centroid Moment Tensor) solutions are strike: 32°, dip: 82°, rake: -165° with Mw 6.2 for the first event and strike: 30°, dip: 83°, rake: -175° with Mw 6.0 for the second event. The strikes are similar to that of Hinagau fault, which indicates a right-lateral fault. Their depths were ~10 km. The "aftershocks" were distributed for ~20 km in the NNE-SSW direction.

On April 15, the following day of the first foreshock, the ERC held an emergency meeting (ERC, 2016). They compiled the available data, and concluded that the "mainshock" occurred on the Takanao-Shirahata section of the Higanu fault zone. The committee recognized that the total size of "mainshock" and the "largest aftershock" was similar to the characteristic earthquake evaluated by the ERC. The report also says 'At this point, the seismicity follows mainshock-aftershock type. Although the number of aftershocks is decreasing, they are still active, occurring on a 20 km segment extending NE-SW direction'. At the time of meeting, the number of "aftershocks" were relatively high (67 earthquakes with M 3.5 or larger within 16.5 hours from the first event).

4. MAINSHOCK ON APRIL 16

Several hours after the ERC evaluation, a larger (M_{JMA} 7.3 and Mw 7.0 by USGS) earthquake (mainshock) occurred, and all the earthquakes before then became foreshocks. The epicenter of this earthquake was located ~7 km NW of the first foreshock at the depth of 12 km. The mainshock also registered the maximum seismic intensity of 7, and caused more widespread damage than the foreshock. The composite PGA at the same station at the Mashiki station was 1362 gal, somewhat smaller than the foreshock (NIED, 2016).

The focal mechanism of this earthquake is also strike-slip type with T-axis in N-S direction. The gCMT solution of the mainshock is strike: 222°, dip: 77°, rake: -163°. Mw = 7.0. The strike direction is rotated about 20° clockwise from the foreshocks, but closer to that of Futagawa fault.

The aftershocks were located along 30 km long segment in NE-SW direction. The aftershocks and triggered seismicity expanded toward NE direction in the Beppu-Shimabara Rift. In Aso region, about 50 km from the mainshock epicenter, two earthquakes with M_{JMA} 5.8 occurred at 03:03 and 03:55, a few hours after the mainshock. In Beppu region, ~80 km from the mainshock epicenter, an earthquake occurred immediately after the mainshock. The signal from this earthquake was mostly masked by the later phase of the mainshock at many stations, but the size was estimated as 5.6. This is a typical dynamic triggering. Another earthquake with M_{JMA} 5.3 occurred 07:11, nearly 6 hours after the mainshock.

The ERC held another emergency meeting in the morning of April 17 (ERC, 2016). They evaluated that the mainshock mainly occurred on the Futagawa section of Futagawa fault zone. By the time of the meeting, the field survey teams confirmed that surface rupture appeared along the Futagawa section of Futagawa fault zone.

5. CHARACTERISTICS OF THE EARTHQUAKE SERIES

The foreshocks and mainshock seem to have occurred on different faults. The largest surface displacement of the foreshocks, ~20 cm in NE direction, was recorded at Jonan station near Hinagu fault zone. The largest displacement from the mainshock was 97 cm in SW direction at Choyo station within Aso caldera, and the displacement at Jonan was 25 cm (Geospatial Information Authorities, 2001). These GNSS observations indicate that the main movement for the foreshocks occurred on the Hinagu fault zone, and the main slip of the mainshock occurred on the Futagawa fault zone. A fault model of the foreshock and mainshock proposed by Geospatial Information Authorities of Japan, based on GNSS and InSAR data, consists of three faults, Hinagu fault, Futagawa fault, and an additional fault in Aso caldera.

Relocated earthquakes by Double Difference method (Figure 1) showed that the foreshocks extended ~30 km mostly along the Hinagau fault zone, while aftershock distribution extends ~60 km, mostly along the Futagawa fault zone but extending in both NE and SW directions. Vertical distributions of earthquakes are also different before and after the mainshock, supporting that they occurred on different faults. There are additional clusters in Aso and Beppu regions.

Inversion of teleseismic body waves indicate that the slip is concentrated near the hypocenters with the maximum slip of 0.76 m and 0.15 m, respectively for the two foreshocks on April 14 and 15. The seismic moments are 3.0 x 10^{18} Nm (Mw 6.3) and

1.6 x 10^{18} Nm (Mw 6.1). For the mainshock, the large slip extends ~30 km toward NE and ~10 km toward SW along the fault plane. The largest slip of 5.6 m was located at ~20 km from the hypocenter along Futagawa fault, and the slip extended beyond the mapped Futagawa fault zone (19 km long) into Aso caldera. The seismic moment of the mainshock is 6.7 x 10^{19} Nm (Mw 7.1), more than an order of magnitude larger than the foreshocks.

Surface mapping indicate that surface rupture, mostly right-lateral slip, appeared for more than 20 km (Geological Survey of Japan, 2016). They were mostly along previously mapped fault traces, but extended into caldera of Aso volcano. Near the fault traces appeared in Aso volcano, large-scale landslide occurred, which collapsed the bridge (Aso-Ohashi), a university campus and many student housings.

The seismicity was very high. Number of earthquakes with M 3.5 or larger, including foreshocks and aftershocks exceeded 200 within 30 days from the first foreshock (April 14). This is the largest number compared to other earthquakes occurred Japanese inland in the last 20 years.

6. CONCLUSIONS

The source characteristics of the Kumamoto earthquakes may be summarized as follows.

(1) The 2016 Kumamoto earthquakes are crustal strike-slip events in Beppu-Shimabara rift.
(2) The mainshock (M_{JMA} 7.3, Mw 7.1) was preceded by two foreshocks with M_{JMA} of 6.5 (Mw 6.2) and M_{JMA} of 6.4 (Mw 6.1) about a day.
(3) Thanks to the high-density seismograph and GNSS network, as well as recent space technology, the source processes were modelled and evaluated within a day of earthquakes.
(4) The earthquakes occurred on mapped faults. The foreshocks occurred on Hinagu fault zone, while the mainshock mainly occurred on Futagawa fault zone. The location and size of earthquakes were roughly forecasted.
(5) The mainshock rupture was ~30 km long and reached the rim of Aso caldera, beyond the mapped length (~20 km) of Futagawa fault zone. It further triggered earthquakes on in Aso and Beppu regions.
(6) Seismicity was very high. Number of earthquakes is the largest compared to other earthquakes occurred Japanese inland in the last 20 years.
(7) Forecasting the timing of earthquakes, both foreshock and mainshock, as well as triggering event, is still difficult.

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