SEISMIC DISPLACEMENTS IN THE ASO CALDERA DEPRESSION ZONE, 2016 M7 KUMAMOTO, JAPAN EARTHQUAKE

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ABSTRACT

A zone of ground deformation in the Aso Caldera triggered during the main shock of the 2016 M7 Kumamoto earthquake formed a graben-structure approximately 10-km-long. This ‘depression’-zone projects northeastward from near where the Futagawa Fault ruptured into the Aso caldera to the northern end of the caldera. Several competing models for the cause of the graben-structure have been proposed, including vertical fault offset (Lin et al. 2016) and horizontal sliding (Tsuji et al., 2016). Our original interpretation was that this depression zone was likely caused by normal faulting on the caldera ring fault. In this paper, we explore the alternative hypothesis, that it is the extensional boundary of a large seismic displacement. Toward that end, we investigated the area north and downslope of the graben for evidence of compression and modeled the potential for large displacements on gentle slopes within a multidirectional compliant seismic displacement analysis. Compression occurred continuously near the Kurogawa river, north of the graben. Ground motions recorded near the graben indicate directivity effects that create a large velocity pulse capable of driving ground displacements toward the north, consistent with field observations.

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A zone of ground deformation in the Aso Caldera triggered during the main shock of the 2016 M7 Kumamoto earthquake formed a graben-structure approximately 10-km-long. This ‘depression’-zone projects northeastward from near where the Futagawa Fault ruptured into the Aso caldera to the northern end of the caldera. Several competing models for the cause of the graben-structure have been proposed, including vertical fault offset (Lin et al. 2016) and horizontal sliding (Tsuji et al., 2016). Our original interpretation was that this depression zone was likely caused by normal faulting on the caldera ring fault. In this paper, we explore the alternative hypothesis, that it is the extensional boundary of a large seismic displacement. Toward that end, we investigated the area north and downslope of the graben for evidence of compression and modeled the potential for large displacements on gentle slopes within a multidirectional compliant seismic displacement analysis. Compression occurred continuously near the Kurogawa river, north of the graben. Ground motions recorded near the graben indicate directivity effects that create a large velocity pulse capable of driving ground displacements toward the north, consistent with field observations.

Introduction

The 2016 Kumamoto earthquakes are a series of events that began with an earthquake of moment magnitude 6.2 on the Hinagu Fault on April 14, 2016, followed by another foreshock of moment magnitude 6.0 on the Hinagu Fault on April 15, 2016, and a larger moment magnitude 7.0 event

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on the Futagawa Fault on April 16, 2016 beneath Kumamoto City, Kumamoto Prefecture on Kyushu, Japan. These events are the strongest earthquakes recorded in Kyushu during the modern instrumental era and produced both seismically-induced landslides and surface fault rupture offsets that damaged roads, bridges, buildings, river levees, and critically damaged an agricultural dam (Kayen et al. 2016; Kayen et al. 2017).

This paper focuses on a zone of ground deformation that occurred in the Aso Caldera and formed a graben-structure approximately 10-km-long and 1-km wide projecting northeastward from near the point at which the Futagawa Fault ruptured into the Aso caldera. The graben-feature damaged ground continuously up and to the northern end of the caldera (Figure 1). This so-called “depression”-zone (Konagai et al., 2016) ranged from 30-m to 110-m in width through the zone. Several groups, including the GEER team, collected LIDAR and Structure-From-Motion imagery to measure vertical displacements that typically varied from 0.5-m to 1.25-m, but were at their greatest more than 2 meters.

Figure 1. Map of central Kyushu with Futagawa fault Hinagawa fault, Aso Caldera, and depression zone. Multiple Aperture Interferometry (MAI) processed from ALOS-2 provided by the Geospatial Information Authority of Japan (GSI). The red lines are mapped active faults. Seismometer stations KMM004 and KMM007 are located in Aso Caldera, as is the 10-km depression zone. JMA magnitudes are different from moment magnitudes reported above.
Our original interpretation was that this depression zone was likely caused by nearly vertical normal faulting on the Aso caldera ring fault, with a secondary sympathetic normal fault creating a graben as a result of the deep soil profile in the caldera. In this paper, we explore an alternative explanation for the graben structure, which is likely due to the extensional boundary of a large horizontal-seismic displacement of the ground.

**Kumamoto Earthquake**

The 2016 Kumamoto earthquakes are a series of earthquakes including the magnitude 7.0 mainshock, which struck at 01:25 JST on April 16, 2016 beneath Kumamoto City, Kumamoto Prefecture on Kyushu, Japan, at an epicentral depth of about 10 kilometers and a MW 6.2 foreshock earthquake at 21:26 JST on April 14, 2016, at an epicentral depth of about 11 kilometers. This chain of events, along with another foreshock of MW 6.0 on April 15th, occurred within 28 hours and is called the 2016 Kumamoto Earthquakes. This was the strongest earthquake ever recorded in Kyushu (since the JMA was established). The epicenter of the mainshock and the distribution of aftershocks are plotted on Fig. 1. More than 1,400 aftershocks have been recorded by the Meteorological Agency of Japan since April 14. The earthquakes resulted in substantial damage to infrastructure including buildings, the cultural heritage of Kumamoto castle, roads and highways, slopes and river embankments due to earthquake induced landslides, debris flows, and ground subsidence. At a surprisingly limited extent, liquefaction occurred only in a few districts of Kumamoto City and in the port areas.

**Aso Caldera and the Fault Surface Rupture**

Aso San Caldera formed 95 kya and as a result, a crater lake filled in with many tens of meters of sediment. A soil boring near the Aso San depression zone indicates nearly 70 meters of fine sediment with void ratios ranging from 5 to 7. The central cone of the caldera broke through this crater lake and deposited upwards of 10 meters of additional pyroclastic sediment near the modern surface. A late Pleistocene/Holocene outburst event(s) drained the crater lake through a western passage dissecting the Aso Caldera rim wall, flooding the Kumamoto plain. The fault rupture in the foreshocks and mainshock occurred along the Hinagu and Futagawa Faults. The Hinagu Fault is the southernmost fault in the Kumamoto area and intersects the Futagawa Fault southeast of Kumamoto. The Futagawa Fault projects from that intersection point both to the west (the Uto Segment) and to the northeast (the Futagawa Segment) (GSJ, 2016a). Each of these faults was previously mapped by the Geological Society of Japan Sources vary as to whether the foreshocks ruptured the ground surface, but if they did, it would have been on the Hinagu Fault.

In the mainshock, both faults and both segments of the Futagawa Fault appear to have ruptured, although most of the rupture, and the largest surface displacements, were on the Futagawa Segment of the Futagawa Fault. In total, about 28 km of the Futagawa Fault had surface fault rupture and about 6 km of the Hinagu Fault (GSJ, 2016b). Both of these faults are oblique right-lateral strike-slip faults. Peak surface movements reported are about 2.2-m right-lateral strike slip (GSJ, 2016b) with up to 0.35-m vertical offset (GSJ, 2016b), occurring on the Futagawa Fault. The surface trace of the Futagawa Fault extended northeast into the southwestern corner of the Aso Caldera, a region of active volcanism. An approximately 10-km long, sub-linear graben-structure occurred as a result of the earthquake parallel to but offset to the north of the trend of the Futagawa segment of the fault.
Aso Caldera Depression Zone

The Futagawa Fault surface fault rupture extended northeast into the southwestern corner of the Aso Caldera, a region of active volcanism. An approximately 10-km-long “depression zone”, occurred coseismically according to the observation of a resident who witnessed the earthquake (Konagai, et al. 2016), projecting along the trend but offset to the north from the point at which the Futagawa Fault ruptured into the caldera, up and to the north-inner edge of the caldera. This depression zone is a 30-m-to-110-m wide trough with near vertical offsets on each side of the trough and vertical movement typically between 0.5 m to 1.25 m zone” (Figure 2).

The ground supporting the depression zone dips northward on slopes less than 1° throughout the entire 10 km of the feature. The base of the slope is defined by the small Kurogawa river that runs along the north margin of the caldera, roughly parallel to the crater wall. At the time of the 2016 GEER investigation, we had three field days, and in retrospect, this area at the base of the slope was not adequately investigated due to time constraints of the team.

Figure 2. Graben feature of the Aso depression zone viewed in agricultural fields at 32.951°, 131.027° (Kayen, et al. 2016)

Interpretations of the Aso Depression Zone

Several competing models for the cause of the graben-structure have been proposed:

Lin, et al. 2016: The authors describe the graben feature on the north side of Aso Caldera to be the northeast-most approximately 34 km extension of the surface rupture zone along the NE striking strike-slip Hinagu–Futagawa Fault Zone and ‘newly identified faults’ on the western side of Aso caldera. The authors propose that the coseismic surface ruptures terminated in Aso caldera due to the presence of magma beneath the central Aso volcano group. The segment of what the authors call the ‘rupture zone’ inside Aso crater was found to be more complex than the defined a narrow strike-slip zone outside the caldera, towards the southwest. This graben-zone is in a region not previously reported for having faults. The graben zone extends for ~10 km along the northwestern edge of Aso caldera and consists mainly of normal displacements and extensional cracks. The authors report normal displacements that strike N50°–70°E that form a graben structure that varies in width from 20 to 100 m, with vertical offsets of up to 1.3 m on both sides of the graben, the dips of south side of the graben are 75°–85° to NW, and the dips on the north side of the graben are similarly angled toward the SE.
**GEER, 2016 Report:** In the original report of the GEER team (Kayen, et al. 2016) it was also our interpretation that the depression zone was likely caused by near vertical normal faulting on the caldera’s ring fault, with the second, antithetic fault and graben created as a result of the deep, soft soil profile in the caldera or as a result of underlying interaction of a ring dike, a sub-circular dike of igneous rock created along a ring fault, or other deeper geological structure. Ring faults typically encircle the caldera of a volcano, allowing the caldera to collapse relative to the caldera walls as magma is released (Fichtner and Tkalcic, 2010, Goldman et al., 2015, Geyer and Marti, 2014). The type of ground movement observed in the Kumamoto earthquakes is similar to the layout of the fault structure of the California Long Valley Caldera, where the strike-slip Hilton Creek Fault enters the caldera near, but not entirely coincident, with the caldera’s ring fault (e.g., Chen et al., 2014). Therefore, the initial interpretation of the GEER team was consistent with the model of Lin, et al. 2016. In figure 3, a drawing of the type of graben structure and offset expected during normal-displacement of a ring fault is presented Bray et al. 1994.

**Tsuji, et al. 2016:** In contrast to the two interpretations above, Tsuji, et al. (2016) argue that nearly horizontal sliding of a 50-meter thick block of ground under seismic loads led to the formation of the graben and compressional features at the perimeter of the slide to the north. The authors note physical damage to a suite of sheared water pipes feeding water to ‘Onsen’-hot spring resort spas and video camera imagery of offsets in these boreholes at approximately 50 m depth. They argue that horizontal sliding more than 1 m toward the northwest created an extensional graben on the south side of the slide in the vicinity of the head scarp. They also noted compressional deformation and spontaneous water emission from wells at the northwestern edge of the block. Speculation about the mechanics of horizontal sliding includes either an anomalously low-frictional layer, or seismic-soil liquefaction to weaken the sliding surface to achieve 1-2 meters of displacement on the ground with less than one-degree of slope.

![Figure 3](image.png)

**Figure 3.** Possible mechanism of the depression zone formation, showing steepening of a normal ring fault through soil causing the formation of secondary, antithetic faults and a drop-down graben structure (from Bray et al., 1994).

**NSF Rapid – GEER Phase 2 (2017) investigation of the Aso Depression Zone**

The two competing models for the depression zone are vertical displacement on the ring fault of the Aso Caldera (Lin, et al. 2016; Kayen et al. 2016) and horizontal sliding due to the seismic displacement of the 50-m thick block (Tsuji et al. 2016). In June, 2017, with support from the US
National Science Foundation, we also returned to the crater to explore for more evidence in the hopes of resolving which of these two competing models is the likely principal cause of the observed displacement. The two elements needed to support the model of seismic-block displacement of the ground are [1] evidence of compression near the toe of the slide, and [2] recorded strong motion adequate to drive a sliding block presumably downslope. The lack of these elements would be consistent with observations associated with the ring fault vertical offset, in that the graben feature would be independent of horizontal sliding or strong earthquake shaking needed to induce this type of a feature. Of course, it is possible that vertical offsets of a ring fault could occur simultaneously with the horizontal seismically induced sliding of the northern side of potential fault due to strong motion, but we would also then expect sliding on the south side of the graben with material moving into the depressed ground.

Along the 10-km depression zone, we explored every road and crossing to the north of the graben zone in the direction of the Kurogawa river. Though not as dramatic as the graben, at every crossing near the river we found evidence of compression ranging from [a] tens of centimeters of compression distributed over several hundred meters at the far northeastern end of the feature evidenced in thrusting of small open agricultural drainage culverts and compression of asphalt roadway, [b] nearly 1.8-meters of compression at a large box culvert of the Kurogawa river in the central portion of the ground north of the graben feature, to [c] approximately 1+ meter of compression at a bridge crossing the Kurogawa river on the southwestern end of the graben zone. At this site, ground on the south side of the bridge pushed the structure partially off its foundation resulting in severe bending distortion on the southwestern abutment. Examples of these features are presented in Figure 4.

**Ground Motions in Aso Crater**

Several KIK-net stations recorded ground motions of the M7.0 mainshock, on April 16, 2016. The largest recorded three component-composed peak ground acceleration was 1.362 g observed at KIK-net station KMMH16 (PGA of 0.653g N-S, 1.157g E-W, 0.873g U-D) located 7 km from the epicenter. The station closest to the graben feature is KMM004 (32.932°N, 131.121E, 33-km ENE of the epicenter), just beyond the end of the ground deformation features. This record had a three component-composed peak ground acceleration of 0.403g (PGA of 0.261g N-S, .347g E-W, 0.268g U-D). The ground motions from station KMM004 of acceleration, integrated velocity, and double-integrated elastic displacement are plotted below in Figure 5a. The ground motions are rotated from N-S and E-W into the strike and dip orientation of the slope. Here, the dip direction is taken as 000° to the north, so that the strike and dip motions are the same as N-S and E-W.

It can be seen in Figure 5a that there are pronounced asymmetries in the acceleration record for both the strike and dip records that result in strong velocity pulses in the record at 25-26-s and 28-29-s. Forward directivity associated with the propagation of rupture of the Futagawa fault towards the northeast is the likely cause of the asymmetry in the acceleration pulses, that lead to large velocity pulses in the record.

In contrast, on the far south side of the Aso caldera is station KMM007 (32.827°N, 131.123°E, 30-km E of the epicenter), that is 11.5 km south of KMM004 and off the trend of the Futagawa fault.
This station had motions slightly stronger in maximum amplitude than KMM004, with a three component-composed peak ground acceleration of 0.451g (PGA of 0.279g N-S, 0.420g E-W, 0.302g U-D), as can be seen in Figure 5b. Though these PGA values are higher, it can be seen in Figure 5b that there is no asymmetry in the acceleration record and no clear evidence of forward directivity. As a result, the velocity record is significantly smaller in amplitude than the velocity record at KMM004.

Figure 4. Compression near the Kurogawa river, north of the depression zone (a) small decimeter distributed compression in agricultural culvert, (b) bridge crossing pushed 60 cm off the south pier by compression, (c) decimeter distributed compression in drainage culvert, (d) 1.8 meters of compression of Kurogawa river culvert, (e) Bridge crossing, restraining bearing fully loaded

Seismic displacement modeling

A recent paper by Kayen (2017) explores the combined effects of multidirectional earthquake motions and soil compliance of gently sloping ground like the graben-area of the north side of Aso caldera on seismic displacements. On low angle-environments, strike-directed earthquake motions contribute significantly to dip-directed displacements due to the anisotropic gravitational shear stress of the sloping ground. On level- and gently sloping-ground, including the strike component of motion results in a larger and more accurate shear stress vector than is computed using only the dip-direction of motion. One of the aspects explored in the paper was the characterization of yield acceleration regarding the Normalized Soil Parameter framework of Ladd and Foott (1974), adjusted for dynamic loading and strain-dependent sensitivity. As such, we can test what kind of displacements are possible for normal values of an NSP-type soil.

For our study of the potential seismic-displacements resulting from ground motions (KMM004 and KMM007) recorded in the Aso Caldera, we use the geometry identified by Tsuji et al. (2016) of the soil block 47 meters thick underlain by a 3-meter thick shear zone. The declivity of the sloping ground was estimated to be 1°. For both ground motions, a scaling factor was used to reduce the ground motions to estimates at a depth of burial. We do not have any geotechnical measurements of the potential slide zone, so we used normal NSP values of 0.3 (30% of the effective overburden stress), and over consolidation ratio of 1, and a sensitivity of 3 achievable at
20% rotational strain of the critical later in the shear zone. These values are typical of soils of moderate sensitivity, normal consolidation, and effective stress normalized shear strength. To account for compliance effects of the slide block, we directly measured shear wave velocity at 5 locations north of the Aso depression zone using MASW and SASW. From these data, we estimate the average shear wave velocity of the 50-m soil profile to be 310 m/s.

For the analysis, these soil properties were kept identical for loading under KMM004 and KMM007 ground motions. Details of the multi-directional and compliant seismic displacement model can be found in Kayen (2017). Figure 6 shows the strike and dip displacements of the ground under loading from (6a) KMM004 and (6b) KMM007. The amplitude of plastic downslope seismic displacements for the ground motion recorded along the trend of the Futagawa fault is approximately five-fold greater than those recorded off the trend of the fault. What is dramatic about the results of seismic displacement modeling under loading from the earthquake motions recorded at KM M004 is that the displacements range between 1.5 and 2.5 m depending on parameter adjustments. These displacements are occurring in the soil modeled to be normal and typical, not susceptible to liquefaction or somehow exposed to transiently elevated pore pressures. By combining the strike and dip directed seismic displacements we compute seismic trajectories for the sliding mass. The sliding trajectories for the soil block exposed to KMM004 or dramatically greater in amplitude than those for KMM007. These trajectories can be seen in Figure 7a for KMM004 and Figure 7b for KMM007. In general, the contribution of compliance to the observed displacements is minimal in all modeled cases using the shear wave velocities we measured at the site.

**Conclusions**

Several competing models have been proposed to describe ground deformations at Aso Caldera. Lin et al. (2016) proposed fault movement as a means of achieving the features observed in depressions zone. The initial GEER team report (Kayen et al. 2016) offered offset of the caldera ring-fault as a mechanism to produce the observed features. Tsuji et al. 2016 proposed a different model for the observed features. They describe the sliding block to be approximately 50 m in thickness that opened in an extensional zone near the head scarp of a slide, the graben forming in this 1-to-2 m of extension. On the north side of the sliding block, they present evidence of soil
compression. The depth of the sliding is controlled by dislocation of water pipes throughout the Aso Hot Springs area, consistently found at 50 meters.

![Figure 6. Dip- and strike-directed seismic displacements for a 47 m thick block loaded by the KMM004 and KMM007 motions, for a rigid block and compliant block with Vs=310 m/s.](image)

Members of the GEER team revisited the site in 2017 specifically to address the competing models presented in the literature. Our team found clear evidence of compression on the north side of a potential slide block in the vicinity of the Kurogawa River. Our team also recorded surface wave dispersion data that were used to invert shear wave velocities for the site. Modeling the seismic displacements using a multidirectional sliding block model that incorporates compliance (Kayen, 2017) led to the following observations.

- Ground motion KMM004 shows clear evidence of forward directivity not observed in the other strong motion record at KIK-net station KMM007 in the southern end of Aso Caldera.
- Seismic displacement in the range of 1.5 to 2.5 m is easily achievable when a sliding block with normal NSP soil properties is loaded with the ground motion recorded at KMM004.
- Seismic displacements estimated using KMM004 are approximately 500% of those estimated using KMM007, and consistently reach 1.5-2.5 meters on nearly level ground, consistent with field observations.

We must conclude that it is entirely possible for the feature observed in the depression zone of Aso crater to be the result of Newmark-type seismic displacements of the ground. Indeed, supporting evidence of the compression zone near the Kurogawa River, dislocation of water pipes at ~50m throughout the Aso/Uchinomaki hot spring spa area, and the anomalous character of ground
motions recorded at KMM004, when all combined, indicate that offset of the caldera ring fault is not needed to achieve the observed features.

Figure 7. Trajectory of plastic seismic displacements for a 47 m thick block loaded KMM004 and KMM007 motions computed for a rigid- and a compliant-block (Vs=310 m/s). Northward dip is toward the bottom of the figure.

References


