Overview of the 2016 Kumamoto eathquake

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On April 16th, 2016 a devastating earthquake with Mj=7.3 occurred in Kummoto, Kyushu, Japan. The earthquake was associated with prominent forechks.

Urgent joint seismic observation of the 2016 Kumamoto earthquake - Seismic activities and their background -

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Large earthquakes of M6.5 and M7.3 occurred in April, 2016, in the Kumamoto prefecture, Kyushu, Japan. We are carrying out an urgent joint seismic observation by several universities and institutes in Japan in order to investigate the detailed feature of seismic activity of the Kumamoto erathquakes. In this observation, we installed more than sixty temporary seismic stations including eleven online telemetered stations in the inland area of middle Kyushu, which enable us to determine the space-time distribution of hypocenters and focal mechanism solutions.
The hypocenter of the M6.5 earthquake of April 14 locates beneath the northeastern end of the Hinagu fault zone. The aftershocks occurring before the M7.3 of April 16 were mainly aligned along an approximately 20 km long NE-SW trend, which roughly corresponds with the trace of the Futagawa-Hinagu fault zone. The hypocenters of the aftershock region were distributed on a nearly vertical plane at depths of 5 - 15 km, deeper at the central part and shallower at both NE and SW sides. The M6.5 was located near the central part of the aftershock region at a depth of approximately 13 km. The large aftershock of M6.4 occurred at the southwestern part of the aftershock region. The focal mechanism solution of the M6.5 is strike-slip fault type with N-S tension. These suggest the M6.5 earthquake was generated by a right-lateral strike slip of the nearly vertical Hinagu fault. However, both detailed hypocenter distribution and a nodal plane of the focal mechanism solution indicate the strike of the M6.5 fault is oblique to the trace of Hinagu fault.
The hypocenter of the M7.3 earthquake of April 16 locates about 5km WNW of the M6.5, and beneath the Futagawa fault zone. The aftershocks were roughly along the Futagawa-Hinagu fault zone, and induced earthquakes were activated along the Beppu-Shimabara graben. The hypocenters of the aftershock region were distributed at depths of 3 - 17 km dipping NW direction. The hypocenters at

both NE and SW sides of aftershock region are shallower, however, the NE and SW extention of aftershock region become relatively deeper again. The focal mechanism solution of the M7.3 is strike-slip fault type with NW-SE tension, and its nodal planes are not consistent with the trace of both Futagawa and Hinagu fault. These suggest the initial rupture of M7.3 earthquake occurred on the different plane from the main rupture. In the period between M6.5 and M7.3, the migration of seismicity was recognized from the hypocenter of M6.5 to that of M7.3, which may be related with a trigger mechanism of M7.3 earthquake.
The Futagawa-Hinagu fault zone was a seismically active region since the seismic network was established in this area. In June 2000, the M4.8 earthquake occurred at almost the same place of M6.5 of April 14, and the focal mechanism was very similar to that of M6.5. These suggest that the stress level on the fault in this area has been high until the outbreak of the 2016 Kumamoto earthquake.
Acknowledgements:
This work is partly supported by MEXT KAKENHI Grant Number 16H06298, the Ministry of Education, Culture, Sports, Science and Technology of Japan under its Earthquake and Volcano Hazards Observation and Research Program, and Earthquake Research Institute, The University of Tokyo under Joint Usage Program.

Keywords: the 2016 Kumamoto Earthquake, urgent joint seismic observation, hypocenter distribution, seismic activity, Futagawa-Hinagu fault

Crustal deformation of the 2016 Kumamoto Earthquake

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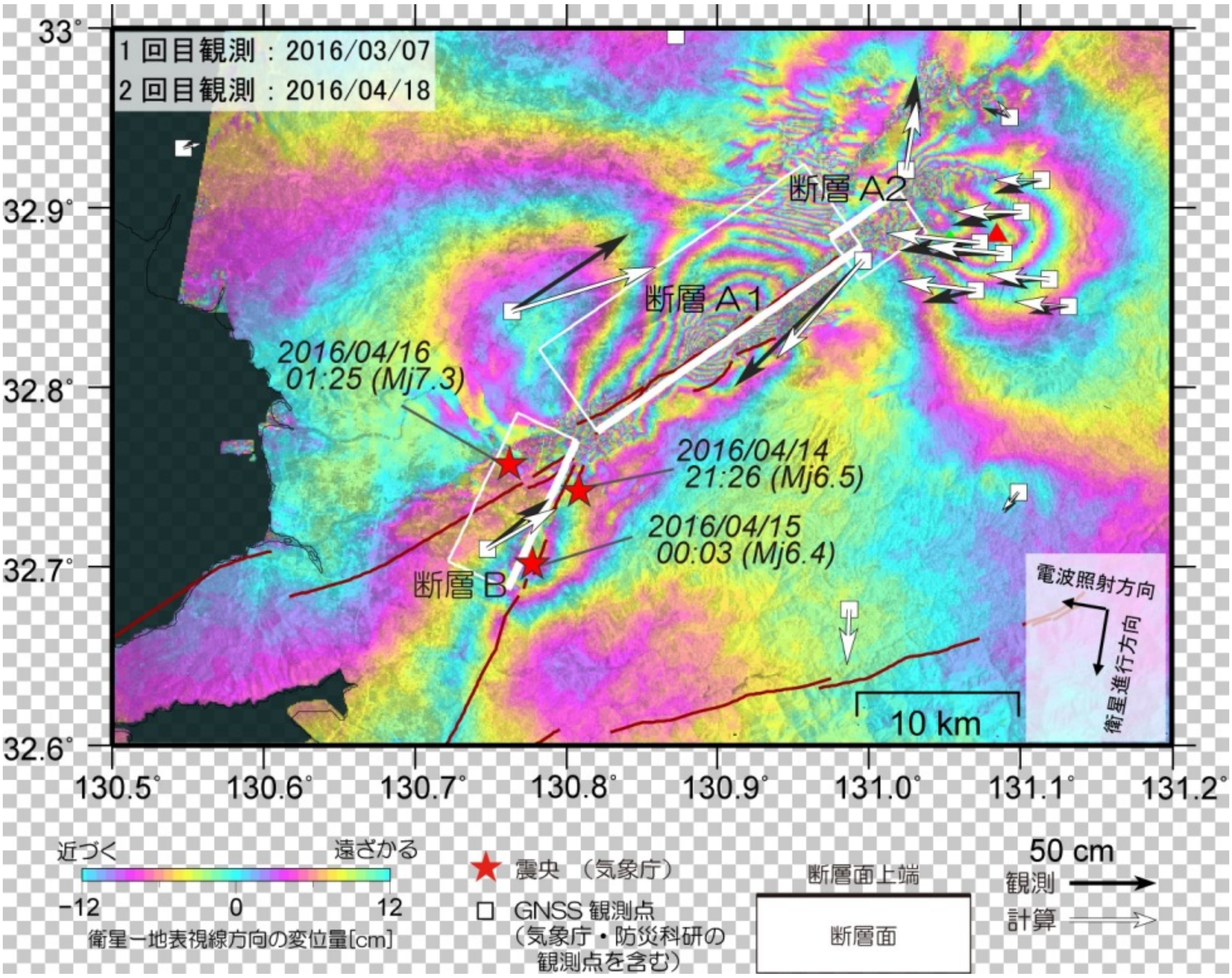
Coseismic deformation derived from the 2016 Kumamoto Earthquake was observed by GNSS stations of the permanent GPS Earth Observation Network system (GEONET) and ALOS-2/PALSAR-2 interferometric SAR.
Clear coseismic displacements due to the Kumamoto earthquake were observed by GEONET. NE displacement of 75 cm and subsidence of 20 cm and SW displacement of 97 cm and uplift of 28 cm were detected at sites 0465 and 0701, which are located near the Futagawa fault zone, respectively.
We have also successfully detected distributed ground displacements for the Kumamoto Earthquake by applying a SAR interferometry analysis of Advanced Land Observing Satellite 2 (ALOS-2) L-band data. The interferograms suggest that fault motion of the main shock has right-lateral motion on the Futagawa fault and the Hinagu fault.

We invert the InSAR results with GNSS data to construct a fault model of the earthquake. A fault model consists of 3 rectangular faults with a uniform slip in an elastic half-space. The fault model shows that: a total major rupture length is about 35 km; a total moment magnitude is 7.07.

Postseismic deformation following the Kumamoto earthquake was detected by GEONET and ALOS-2 InSAR. Postseismic deformation up to 3 cm also has been observed by GEONET, showing a roughly similar deformation pattern to those associated with the mainshock. ALOS-2 interferograms show that subsidence about ~5 cm along the Futagwa fault zone.

Acknowledgements.
The PALSAR-2 data obtained by the ALOS-2 were provided by the Japan Aerospace Exploration Agency (JAXA) through the Agreement between GSI and JAXA. The ownership of PALSAR-2 data belongs to JAXA.

Keywords: The 2016 Kumamoto Earthquake, crustal deformation, GNSS, SAR



1 回目観測 : 2016/03/07
2 回目観測 : 2016/04/18
断層 A2
断層 A1
断層 B
2016/04/16 01:25 (Mj7.3)
2016/04/14 21:26 (Mj6.5)
2016/04/15 00:03 (Mj6.4)
電波照射方向
衛星進行方向
10 km
33°
32.9°
32.8°
32.7°
32.6°
130.5°
130.6°
130.7°
130.8°
130.9°
131.0°
131.1°
131.2°
近づく
遠ざかる
-12
0
12
衛星ー地表視線方向の変位量[cm]
震央 (気象庁)
GNSS 観測点 (気象庁・防災科研の観測点を含む)
断層面上端
断層面
50 cm
観測
計算

Strain concentration zone based on GNSS data in southwest Japan and its possible application to a long-term forecast of inland earthquakes

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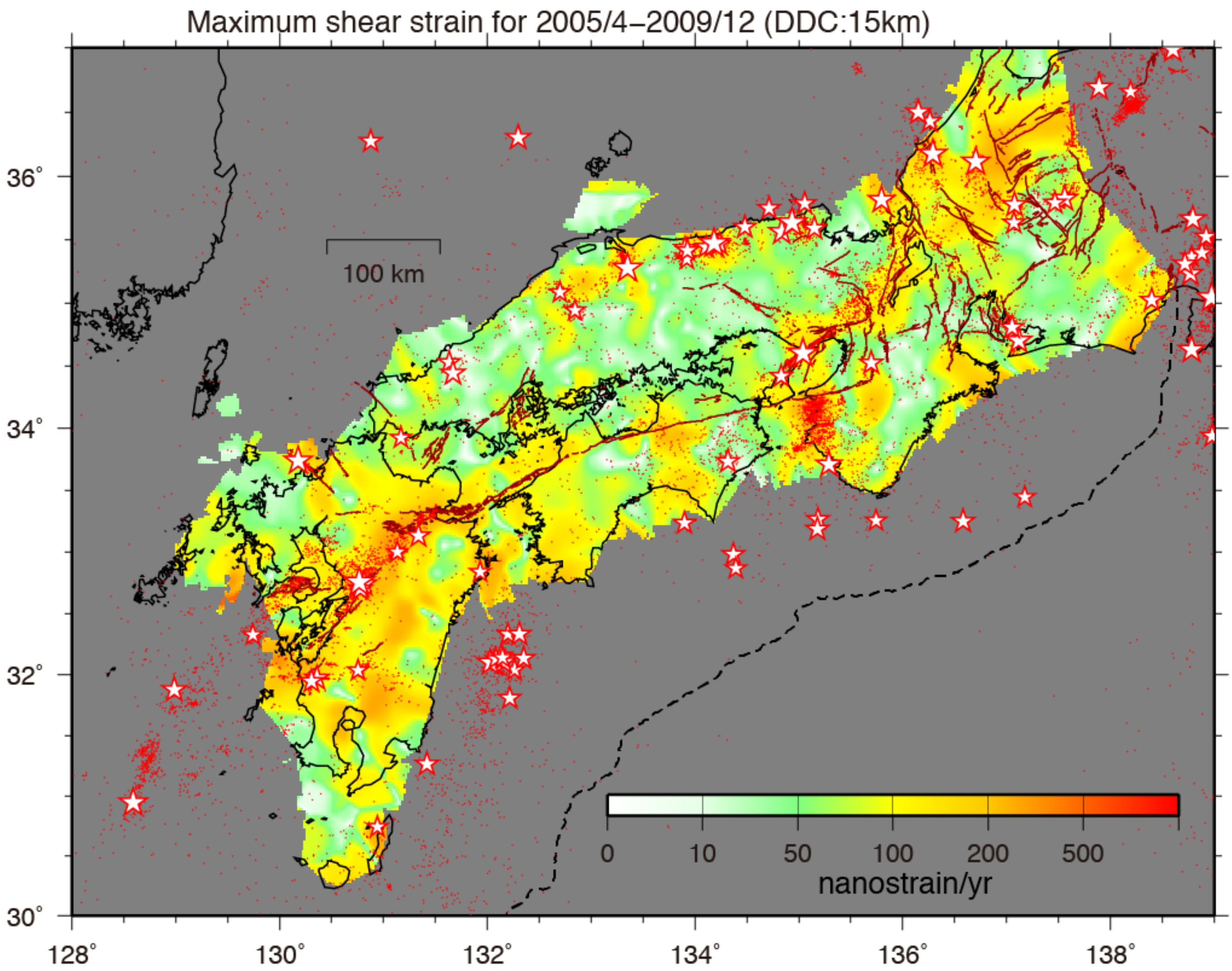
Two-decades GNSS observations have clarified strain concentration zones including the Niigata-Kobe Tectonic Zone in an inland area of the Japanese Islands. We removed elastic deformation due to interplate coupling along the Nankai Trough from the GNSS velocity data observed from April 2005 to December 2009 and calculated distribution of areal and maximum shear strain rate to clarify strain concentration zones in the inland area. We compared the strain-rate distribution with epicenters of shallow inland large earthquakes with M ≥6.
Most large earthquakes including the 2016 Kumamoto earthquake occur in the area of high rate of the maximum shear strain rate (Figure). Because the geodetically observed strain rate includes both elastic and inelastic strain, the strain rate is not directly related with an occurrence rate of earthquakes. However, the geodetic strain rate is an important data apparently related with earthquakes. It should be used as one of datasets to evaluate a long-term forecasting model of large earthquakes in the Japanese Islands.

Keywords: Strain concentration zone, GNSS, Inland earthquake


Maximum shear strain for 2005/4–2009/12 (DDC:15km)
100 km
0
10
50
100
200
500
nanostrain/yr
36°
34°
32°
30°
128°
130°
132°
134°
136°
138°

Distribution of surface rupture associated the 2016 Kumamoto earthquake and its significance

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A Mj 6.5 earthquake hit Kumamoto prefecture, central Kyushu, southwest Japan at 21:26 JST on April 14th. 28 hours after, another Mj 7.3 at 01:25 JST on April 16 generated severe shaking in the same region (JMA, 2016). It is well know previously mapped the ~100-km-long active fault called Futagawa-Hinagu fault zone (FHFZ) (Watanabe et al., 1979; RGATK, 1989; Ikeda et al., 2001; Nakata and Imaizumi ed, 2002) runs in the epicentral area, we considered the northeastern portion of the FHFZ could be responsible to two earthquakes and started to do a field reconnaissance along the fault zone after the Mj 6.5 event.According to 3 weeks field survey by our team, we found the 31-km-length successive surface rupture close to the traces of the northeastern portion of the FHFZ and another the 5-km-length rupture on a part of Denokuchi fault and some possible surface ruptures in the epicentral area. The rupture along the FHFZ shows right-lateral strike-slip mainly (~ 2 m in maximum between Dozon in Mashiki city and Nishihara village) with down-thrown to northwest. The rupture on the Denokuchi fault, far from 1 to 2km east of the FHFZ, is normal component with down to northwest. These coseismic ruptures of the Mj 7.3 earthquake represented a characteristic movement of the northeastern portion of the FHFZ.A series of the open cracks with NW-SE-trending were traceable for a distance of 5.4 km from Kengun to Shirakawa River in Kumamoto city. Those features followed on tectonic landform by possible active fault and on the line of the fringe abnormal in InSAR image, and may represent minor surface rupture.The local eyewitness and our observation revealed that the coseismic minor rupture of the Mj 6.5 earthquake prior to the Mj 7.3 earthquake were emerged on the some trace of the rupture of the Mj 7.3 earthquake in Mifune town and South of Mashiki town.Seismic inversion theory by DPRI, Kyoto Univ (2016) showed that the coseismic rupture propagated toward ENE along the strike of the FHFZ, and asperity on surface was recognized 10 km far from the epicenter, where we surveyed the maximum displacement of right lateral strike slip close to Nishihara village. JMA (2016): http://www.jma.go.jp/jma/press/1604/16a/201604160330.htmlThe Research Group for Active Tectonics in Kyushu ed. (1989): Active tectonics in Kyushu, Tokyo University Press.Ikeda et. al., (2001): Active fault map in urban area [Kumamoto]. GSINakata and Imaizumi ed. (2002): Digital active fault map of Japan. Tokyo University Press.DPRI, Kyoto Univ. (2016): This work was supported by JSPS KAKENHI Grant Number 16H06298.

Keywords: Surface rupture, 2016 Kumamoto earthquake, Active fault

Strong motion and source processes of the 2016 Kumamoto earthquake sequence

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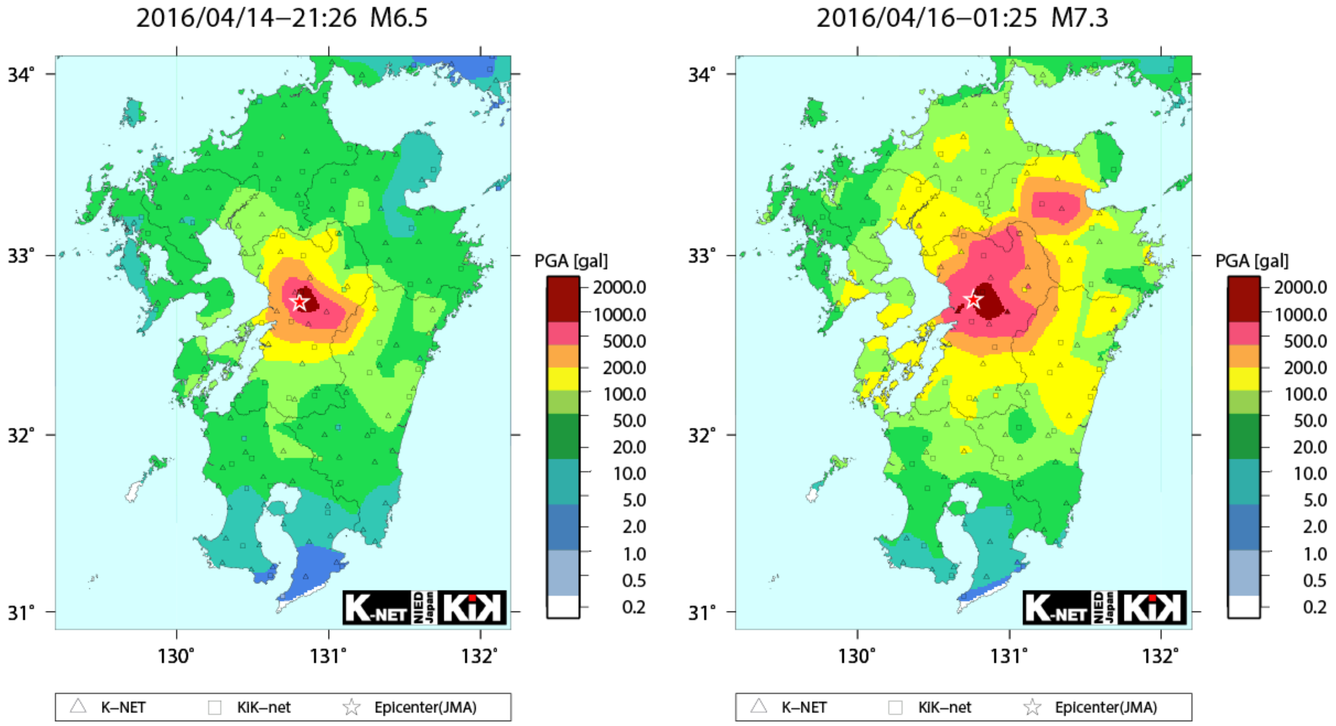
M6.5 (Mw 6.1) and M7.2 (Mw 7.1) earthquakes respectively attacked the Kumamoto region at 21:26 on April 14 and 28 hours later at 1:25 on April 16, 2016. Strong shaking with JMA seismic intensity (INT) 7 were observed for the both earthquakes at the Mashiki town of the Kumamoto prefecture. These earthquakes are considered to rupture mainly the Hinagu fault zone (Takano-Shirahata part) and the Futagawa fault zone (Futagawa part). The Headquarter for Earthquake Research Promotion performed the long-term evaluation of the fault zones with M7-calss potentials, and seismic hazard assessment estimated more than INT 6+. We here call the M6.5 event and the M7.3 event that occurred on the individual fault zones.
KiK-net Mashiki (KMMH16) recorded PGA more than 1000 gal, and ground motions were observed wider area for the 7.3 event than the M6.5 event. PGAs and PGVs of K-NET/KiK-net stations are consistent with the empirical attenuation relationship of Si and Midorikawa (1999). PGVs at longer distance than 200 km attenuate slowly, indicating the effect of Lg wave of western Japan. 5% pSv of the Mashiki town in Kumamoto shows a peak of 1-2 s that exceeds ground motion response of JR Takatori of the 1995 Kobe earthquake and the Kawaguchi town in Niigata of the 2004 Chuetsu earthquake. KiK-net Mashiki that locates 640 m apart from the Mashiki town observed large ground motion with a peak of 1 s. 5% pSv of the Nishihara village in Kumamoto shows 350 cm/s peal at 3-4 s. Ground motions at several stations in Oita exceed the attenuation relationship due to a triggered earthquake by the M7.3 event. PGAs of K-NET Yufuin (OIT009) records 90 gal for the M7.3 event and 723 gal for the near-by triggered event.
Source processes are analyzed using 16 and 27 K-NET/KiK-net/F-net strong motion stations located within an epicenter distance of 50 km and 100 km for the M6.5 and M7.3 events, respectively. Two pulses are observed at many station for the M6.5 event, and corresponding two slips near the hypocenter with a peak of 0.7 m and at north-northeastern with 0.6 m. As for the M7.3 event, large slip does not inverted for around 5 s after the earthquake initiation, then rupture propagated toward the northeastern shallow part reaching near the caldera of the Aso volcano with large slip with a peak of 4.6 m. The shallow slip is consistent with active fault surveys.

Keywords: the 2016 Kumamoto earthquake, strong motion, source process


2016/04/14–21:26 M6.5
2016/04/16–01:25 M7.3
34°
33°
32°
31°
130°
131°
132°
PGA [gal]
2000.0
1000.0
500.0
200.0
100.0
50.0
20.0
10.0
5.0
2.0
1.0
0.5
0.2
K-NET
KiK-net
Epicenter(JMA)

Rupture process of the 2016 Kumamoto earthquake based on waveform inversion with empirical Green's functions

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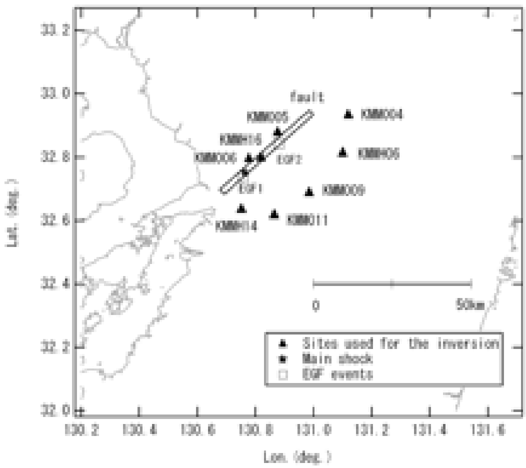
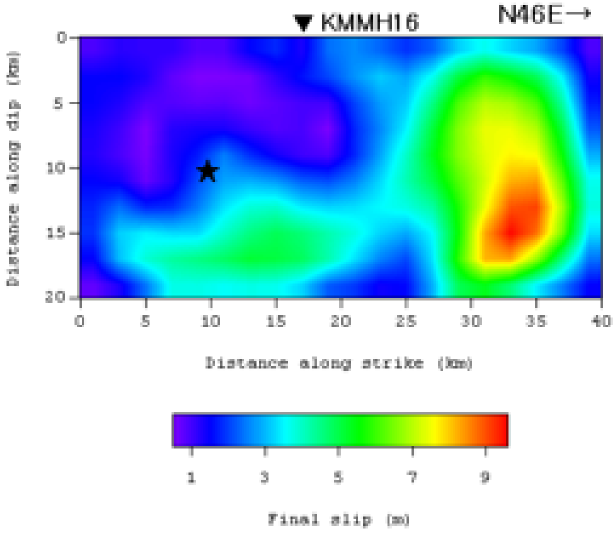
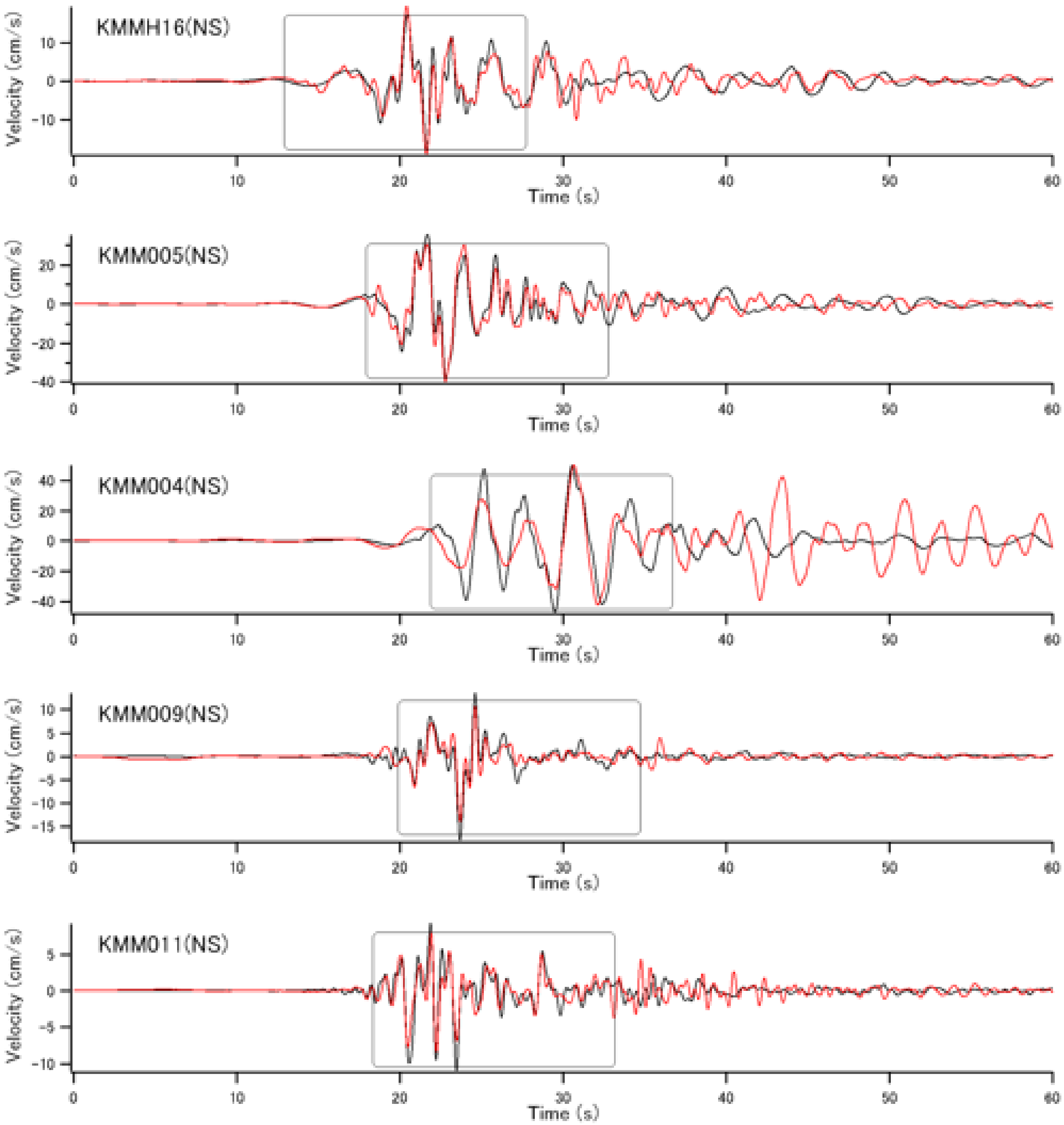
Rupture process of the 2016 Kumamoto earthquake was estimated based on waveform inversion with empirical Green's functions. Records from two small events, namely, the April 15 0:50 event (M_J =4.2) and the April 15 15:27 event (M_J=4.2) were used as empirical Green's functions. The conventional least-squares linear waveform inversion (Hartzell and Heaton, 1983) was adopted.
A fault plane with a dimension of 40 km times 20 km was assumed, whose strike and dip angles were set to be 46 and 96 degrees, respectively. The fault was divided into 20 times 10 fault elements. The rupture front is assumed to start at the JMA hypocentral time and to propagate radially at a constant velocity of 2.5 km/s. The moment rate function at each fault element after passage of the rupture front was assumed to be a convolution of the moment rate function of the small event and an impulse train. The impulse train is composed of 12 impulses at equal time intervals of 0.25 s. The height of each impulse was determined through the inversion. Conventional corrections for the geometrical spreading and time shifts (Irikura, 1983) were applied to the empirical Green's functions to represent arrivals from each fault element. The shear wave velocity in the source region was assumed to be 3.55km/s. Absolute time information for both the main shock and small event recordings was used.
The result indicates that both slip and slip-velocity were small in the west of the hypocenter. Between the hypocenter and KMMH16 (Mashiki), a large slip and slip-velocity region existed but it was restricted at the deeper part of the fault, indicating that the large amplitude ground motion in Mashiki was not a result of a forward directivity effect. A region of significantly large slip and slip-velocity existed about 20 to 25 km east of the hypocenter.

Keywords: 2016 Kumamoto earthquake , rupture process, empirical Green's funcion, waveform inversion, strong ground motion


fault
KMM005
KMM004
KMMH16
KMMH06
KMM006
EGF2
EGF1
KMM009
KMMH14
KMM011
0
50km
Sites used for the inversion
Main shock
EGF events
Lat. (deg.)
Lon. (deg.)


KMMH16
N46E→
Distance along dip (km)
Distance along strike (km)
Final slip (m)


KMMH16(NS)
KMM005(NS)
KMM004(NS)
KMM009(NS)
KMM011(NS)
Velocity (cm/s)
Time (s)

The cause of heavy damage concentration in downtown Mashiki-cho inferred from observed data and field survey

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To understand the cause of the damage during the mainshock of the 2016 Kumamoto earthquake sequence, we carried out field survey from 29 April through May 1, in Mashiki Town, including microtremor observation. We have extracted sufficient information from which we can infer the cause of the heavy damage concentrated in Downtown Mashiki, where strong motions with JMA seismic intensity of 7 were observed.

First the fundamental features of the structural damage in the damage concentrated area (DCA) in Downtown Mashiki were summarized. The damage concentration starts from the west of the National Highway R.443 and extends to the east of the Prefectural Road R.235, about 1.5km to 2km in the east-west direction. In the north-south direction it spreads about plus/minus 300m on both sides of the Prefectural Road R.28. The main features need to report are as follows:
1) inside DCA, not only old (and so weak) wooden houses but also new and reinforced houses were damaged;
2) there are many old buildings that have successfully survived outside of the heavy damage lines in the east-west (EW) direction;
3) the damaged houses look aligned to some lateral extent (50 to 100 m) in EW direction;
4) The deformed direction of the collapsed or heavily inclined houses were mostly in EW direction (attached photo). Overturning direction of tombstones were also in EW direction;
5) Almost always significant ground deformation, failure, and cracks can be seen in the paved roads crossing the above damage lines.

Next, inside DCA we measured microtremors covering about 700m by 1km with about 100m intervals. Horizontal-to-Vertical Spectral Ratio of Microtremors (MHVRs) at three selected sites deployed at the northern end, in the center, and at the southern end of DCA were compared. The observed MHVRs share the common peak in the vicinity of 2 to 3Hz, with the level of 4 to 5. This MHVR characteristics suggest that the subsurface structure may have moderate impedance contrast at certain depths but that the differences in MHVRs at these three stations are so small that it is impossible to explain DCA creation by the spatial difference of soil structures below.

Finally by using the observed strong motion records at the Mashiki Town Office and a nonlinear response analysis model, which was calibrated to reproduce observed damage ratios of wooden houses during the 1995 Kobe earthquake, we calculated the estimated damage ratios at the Mashiki Town Office. We found that more damage would have occurred in the EW component than in the NS component. We also found that the calculated damage ratio was only 30% at most. This means that the observed ground motions in DCA were not surprisingly strong to wooden houses.

Based on these survey results, the mainshock hypocenter location, and AIST GSJ information on mapped active faults and InSAR on their web site, we may conclude that DCA in Mashiki was created by the complex interaction of both strong ground motions and crustal deformation associated with the fault movement and subsequent ground failures, rather than the simple strong shaking alone. The

reason for this conjecture is as follows:
1) The ground motion there was not strong enough to create such a large damage as had been observed.
2) The damage in the fault-parallel direction was dominant, rather than the fault-normal direction which is supposedly stronger.
3) The damage lines were continuous in the EW direction only. Ground deformation, failure, and cracks were observed in the roads across these damaged lines.
4) Inside of the damage lines some newly-constructed houses were damaged, while outside of the damage lines even old houses could sometimes survive with the minor damage.
5) It is not likely to have strong velocity variations beneath DCA.
6) The active fault map by GSJ shows a branching fault along the Prefectural Road R.28 (Kiyama fault). The western end of Kijima fault is the eastern end of DCA. This is so because in DCA the fault displacements associated with the earthquake have been distributed in a wide area. Variation of crustal movement in InSAR contours also shows spreading motions there including DCA.
7) The mainshock hypocenter seems to be on the far western extension of Kijima fault. We can confirm from the InSAR contours that Kijima fault actually corresponds to the northern end of the crustal deformation there.

Keywords: microtremors, damage in wooden houses, crustal deformation

Characteristics of landslide disaster induced by the 2016 Kumamoto earthquake in and around Minamiaso Village, southwestern Japan

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The Kumamoto earthquake (Mj7.3) on April 16, 2016 triggered numerous landslides in and around Minamiaso Village, the western part of Aso caldera, central Kyushu, southwestern Japan. The landslides were divided into two types: landslides occurring at steep caldera walls and landslides generated on the slopes of the post-caldera central cones of Aso Volcano. Several landslides occurred on slopes steeper than 25° at the northwestern to western caldera walls, which comprise pre-Aso volcanic rocks (lavas and pyroclastics). The largest landslide (ca. 300 m high, 130-200 m wide) occurred on the western caldera wall, and damaged the National Route 57 and the Hohi line of the Japan Railway. Because any clear rupture surface could not be observed, unstable blocks which had been divided by cracks were likely to be collapsed due to the intense earthquake on April 16. At the post-caldera central cones of Aso Volcano, the April 16, 2016 earthquake-induced landslides occurred not only on steep slopes but also on slopes gentler than 10°. They occurred in unconsolidated superficial tephra deposits overlying lavas and agglutinates, and the thickness of the slides usually ranged from 4 to 8 m. The sliding masses traveled long distances (<600 m), comparing to small differences in elevation. The deposits were composed of tephra blocks of a few meters and there was no evidence that they were transported by water. These facts suggest that some landslides mobilized rapidly into debris avalanches, traveling a few hundred meters. The associated debris avalanche resulted in five casualties and severe damages of houses at the foot of Takanoobane lava dome.
The characteristics of the April 16, 2016 earthquake-induced landslides are different from those of rainfall-induced landslides in July 2012, June 2001 and July 1990 at Aso Volcano, and provide important information for preventing or mitigating future landslide disasters in the Aso caldera region.

Keywords: the 2016 Kumamoto earthquake, landslides, debris avalanches, tephra deposits

Problems associated with the active fault assessments and analyses of the destructive 2016 Kumamoto earthquake

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The 2016 Kumamoto earthquake occurred with the activity of a known active fault. Although it could be possible that the latest long-term predictions by the Headquarters for Earthquake Research Promotion are correct, there are still unresolved problems regarding 1) the earthquake mechanism itself, 2) the extent of damages caused by strong ground motion, and 3) the emergence of unknown earthquake faults.

The active fault was assessed two times in 2002 and 2013. According to the evaluation in 2002, the faults extending from Aso to the Yatsushiro Sea were regarded as a series of active faults, which were collectively referred to as the Futagawa-Hinagu fault. In contrast, the evaluation in 2013 divided the Futagawa and Hinagu faults into separate systems by taking into account underground geology within the Kumamoto plane. This later assessment concluded that the Futagawa fault extends from Aso toward the Uto Peninsula, and furthermore, that the Hinagu fault extends from Togawa in Mashiki to the Yatsushiro Sea. However, the “Active Fault Map in Urban Area” regards the Futagawa fault as continuing further south of Togawa because the tectonic landforms were smoothly traced. Among the several estimations mentioned above, we should check which one is more appropriate. On the basis of the 2002 evaluation, it is possible to say that the earthquakes on April 14th and 16th occurred continuously along the northeastern part of the Futagawa-Hinagu fault. On the other hand, based on the 2013 evaluation, the two earthquakes appear to have occurred irregularly on different parts of the different faults. According to the 2002 evaluation, the former earthquake on April 14th should be regarded as a “one size smaller earthquake” than the expectations, whereby the possible occurrence of a bigger one was mentioned.

The locality of the Futagawa-Hinagu fault had already been indicated on the large-scale active fault map, and the earthquake faults appeared on the fault line. However, several secondary faults emerged at other places. In particular, an earthquake fault with a total length of 4 km appeared, and it produced extensive damage in the town of Mashiki. We should thus carefully check the reason why this fault was not identified prior to the 2016 earthquakes.

Within the vicinity of the Futagawa fault, severe damage occurred. Especially, in the town of Mashiki where high seismic intensities were recorded on April 14th and 16th, numerous buildings collapsed during the earthquake on April 16th. The “severely damaged zone,” which was approximately 1 km in width, trended in the east-west direction. In the village of Minami-Aso, several traces of earthquake faults were discovered, and almost all of the buildings located on these faults collapsed. At least five cars overturned onto their sides in the northward direction. Such phenomenon had not been observed before in Japan. These events are estimated to have been the result of an S wave in the orthogonal direction along strike-slip faults.

There is a need to re-examine the segmentation and groupings of the faults. The 2016 earthquakes indicate that the fault should not be divided if the tectonic landform is smoothly continued. There is also a need to explain why such high seismic intensity of 7 occurred along the Futagawa-Hinagu fault. Although the present theory of strong ground motion postulates that a shallow portion of the crust never generated strong motion, the narrow distribution of damage seems to imply some contribution from breaks at the shallow portion of the crust. In regard to this issue, the distribution of seismic intensity of 7 will need to be officially mapped by the Japan Meteorological Agency. In the field of disaster prevention awareness, it is often heard that strong earthquakes can happen anywhere, but this could misleading. It will be necessary to specify the areas where the seismic intensity could reach 7 for disaster prevention. It will also be important to verify the reason why the branch faults could not be identified before the 2016 earthquakes. Needless to say, active fault assessments for regions harboring nuclear power plants require further rigor. Although the Nuclear Regulation Authority may say that they can identify the potential active branch faults prior to the earthquake, it is essential to verify this assessment.

Keywords: Active fault, Earthquake disaster prevention, Earthquake fault, Strong ground motion

