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((to IUGS E-Bulletin))
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Introduction:

Just one day after the Myanmar Earthquake that occurred on 13th of April, 2016, 13:55:17 (GMT) 180 km NW from Mandalay, two more large earthquakes occurred, one in Kumamoto, Japan, and another in Ecuador. As for the 2016 Kumamoto Earthquake, more than one month has passed since the major earthquakes, and many new types of phenomena are known. This report first describes some geological aspects of the Kumamoto earthquake, Japan; reviews some of the tectonic, social and human results; and also provides brief accounts of the within subducting slab-type Myanmar quake, and the subduction-type Ecuador Earthquake (M 7.9) that occurred 26th April, 2016 (local time) close to the Ecuadorian coast. The basic information of seismological aspects on the 2016 Kumamoto Earthquake are from http://www.hinet.bosai.go.jp/topics/nw-kumamoto160416/?LANG=en http://www.jma.go.jp/en/quake/ and so on.

2016 Kumamoto Earthquake:

A series of inland earthquakes occurred in Kumamoto, middle Kyushu, Japan (Figs. 1, 2, and 3), close to the active volcano Mt Aso (Aso Volcano), which has the largest on-land caldera in Japan (24 km diameter). The first major shock occurred on 21:26 of JMT (+9 hours of GMT: 12:26) of 14th April, 2016, M 6.5 (6.1 and 6.4 were also reported) at a depth of 18 km (11 km or 15 km was also reported). The intensity was 7 on the Japan Meteorological Agency Intensity scale (hereafter, JMAI scale) (which in this case corresponds to 10...
on the Modified Mercalli Intensity scale; hereafter MMI scale (Fig. 4). The earthquake epicenter was located in the local town of Mashiki of Kumamoto Prefecture (Fig. 2). The historically and culturally famous and important capital of the prefecture, Kumamoto City (population of 740,000), lies only 20 km west of the epicenter.

Fig. 2. Index map of Kyushu Island and surrounding area, showing some tectonic features (the base map is adopted from USGS HP with topographic names added by authors). White dashed line is the Southwest Japan volcanic front, which passes through the Aso Volcano. The epicenter lies just on the E of Kumamoto. See Fig. 3.
Fig. 3. Epicenter of large earthquakes of the 2016 Kumamoto earthquake (red X). Yellow-red lines are active faults, and double dashed lines are grabens or back arc basins (both are horizontally stretched). Black lines are possible transform faults or fracture zones. The Ryukyu arc’s back arc basin may be entering Kyushu, extending the Beppu-Shimabara graben that crosscuts the volcanic front.

+ and - for column A correspond 強 and 弱 in Chinese characters, respectively.
Fig. 4. Correlation between different intensity scales. At left, column (A) is Japanese (JMAI scale), and column (B) is the Modified Mercalli (MMI scale). At right, column (E) is acceleration in mgal. This table indicates JMAI 7 of the Kumamoto event ranges from MMI 10 to 12, but due to the record, the maximum shake of 16th of April must be of 12, because it is reported that the maximum acceleration attained 1580 mgal (see in text). As for the MMI scale, see https://en.wikipedia.org/wiki/Mercalli_intensity_scale

A second strong shock hit nearby again on 16th of April (at 01:26 of JMT; 28 hours later after the 14th shock), M 7.3 (Mw 7.1 after Prof. Y. Yagi HP as shown later) (Fig. 4). Most researchers consider the second earthquake to be the main shock and the April 14th event as a foreshock. The JMAI scale of the second event attained 7 (its MMI scale reached 12), and the maximum acceleration of the shake was recorded as 1580 mgal at Mashiki Town and Nishihara Village, far larger than the gravitational acceleration. Such continuous or chained (or some researchers use “connected” or “induced”) large in-land earthquakes within two days of one another is rare. The number of aftershocks topped 900 by the 27th of April and 1400 for one month (for JMAI scale larger than 1, roughly MMI scale larger than 4) (Fig. 5). Shaking attributable to the two large earthquakes caused many topographic changes along previously mapped active faults. Significant topographic impacts also occurred along the Hinagu and Futagawa fault zones, and away from known structures. Many (81 places in all) slope failures (sliding, rock fall, collapse of banks and roads, cracks and so on) occurred as shown below.

Fig. 5. Cumulative curves of shocks in red (larger than M 3.5) for the first two days after the April 14th and April 16th shocks. Adopted from NHK-TV based on JMA data. This diagram indicates that many more aftershocks accompanied the Kumamoto compared to other inland earthquakes, including the Niigata-Chuetsu (2004), Iwate-Miyagi (2008), and Kobe (1995) events. By April 27th the number of aftershocks was greater than 900.
By April 27th, 49 fatalities had been reported (mostly by house collapse and debris bury) with 1 missing, and 1500 injured (many serious). Refugees numbered more than 160,000. In total, more than 26,000 houses and buildings collapsed including 15,000 total failures (those numbers are likely to increase over time). Most people who sought refuge on April 14th to 15th of April now live in designated shelters (mostly city or school gymnasiums). Unfortunately, some people who returned home after the first shock were subsequently killed during the second shock on the 16th.

The aftershocks extended to the east, up to the Aso volcano area. The Aso volcanic region, with its large caldera, is known to be of high heat flow, and has been the focus of geomagnetic and gravitational studies (Okubo, 1997; Okubo and Shibuya 1993). Different types of aftershocks were recorded in other areas of Kyushu. For example, shallow earthquakes with normal slip occurred along E-W striking faults in the eastern part of the E-W trending Beppu-Shimabara graben. The maximum magnitude of aftershocks outside the main earthquake areas has been 6.5 (Fig. 6).

Fig. 6. Main shock (No. 4) and pre-main shocks (Nos. 1 to 3), and post-main shocks (Nos. 5 to 12) from April 14th to 19th. Adopted from Yomiuri-Shimbun Newspaper. Earthquakes Nos. 4 to 9 (except 8) are on the Futagawa fault zone, and some others (Nos. 1 to 3, and Nos.11 and 12) are on the Hinagu fault zone. Nos. 6
and 7 are on the extension of the Futagawa fault zone in the Aso Volcano area. No. 8 is, in a large sense, located on an extension of the Futagawa fault, but JMA has interpreted it as an independent earthquake, induced by the main shock (No. 4), on the Beppu-Haneyama fault zone (BHFZ). The BHFZ is known to be an E-W striking normal fault that accommodates N-S stretching in the Beppu-Shimabara graben (Fig. 3).

**Earthquake focal mechanism, seismicity and active fault zones:**

Prof. Y. Yagi utilized a waveform inversion wave of tele-seismic body waves (Yagi and Fukahata, 2011) ([http://www.geol.tsukuba.ac.jp/~yagi-y/EQ/20160416/index.html](http://www.geol.tsukuba.ac.jp/~yagi-y/EQ/20160416/index.html)) to study the largest (main) earthquake of April 16th. During the early morning 0:26 JMT, M 7.3 earthquake, the fracture started at the hypocenter on the SW part of the fault plane, and propagated to the E for 20 km in 20 seconds with a maximum dislocation of 1.8 m along the eastern part of the fault plane (Fig. 7; Y. Yagi personal communication; the values reported here may increase with the collection of additional data (Yagi et al., submitted to EPS)). Thus, the focal mechanism indicates that the slip vector was NE-SW trending and sub-horizontal, yielding a NW-ward, highly inclined, dextral (right-lateral) strike-slip event. The depth to the hypocenter was 15 km. The moment magnitude (Mw) was 7.1 and the strike-slip hypocenter lay on the Futagawa fault zone. Displacement increased to the east and climbed to shallower crustal levels.

![Fig. 7. Focal mechanism with slip model and shake continuation, after Prof. Y. Yagi (University of Tsukuba)’ Farfield analysis after Yagi and Fukahata (2011). As in this figure, focal plane (dislocated area) is 50 km NE trend with 20 km width along the Futagawa active fault, with 1.8 m dislocation maximum for 20 seconds. See text, and](http://www.geol.tsukuba.ac.jp/~yagi-y/EQ/20160416/index.html)
From Y. Yagi’s analysis, and NIED’s Hi-net system (www.hinet.bosai.go.jp), it is known that the large earthquakes in the region are in response to an E-W sigma 1 (maximum compressional stress). Strike-slip faulting is common, but E-W striking normal faults also occur. These normal faults are also a response to the E-W compression but yield smaller magnitude earthquakes (Fig. 8). In the wider region, the stress system varies from place to place, and through time (probably the latter in response to stress release attending earthquake events). On 12th of May, Prof. M. Miyazawa, Kyoto University, reported in NHK TV that the main shock on 16th of April in Kyushu involved double instantaneous quakes, during which the Masihki Town’s quake (M 7.3) induced another quake (M 6.0, at Yufu Town, 80 km NE within Beppu-Haneyama fault zone, location No. 8 of Fig. 6), 32 second later, during the passage of the major seismic wave. Induced quakes are also known in various other places, some 800 km and even 1400 km ENE from the first earthquake. This is the first time that such a series of induced type earthquakes have been analyzed.
Fig. 8. Normal fault type earthquakes of E-W sigma 2 in Kyushu. From web site of NIED (Tsukuba, Japan) www.hinet.bosai.go.jp

Fig. 9. Epicenters with magnitude and depth during one month from 20th of March to 19th of April, 2016. Most of these along the Japan trench are routine ones with certain aftershocks of 2011 Tohoku earthquakes, while most in Kyushu are of the present Kumamoto earthquakes.

As shown in Fig. 7, epicenters extend from SW to NE, along a zone within which the collapse of buildings, houses, roads, and slopes and river banks were concentrated. These epicenters are along three active fault zones: the Futagawa, Hinagu, and Beppu-Haneyama fault zones.
**Surface appearances:**

**Surface fault ruptures:**
A fault that appeared on the earth’s surface during an earthquake is called a surface fault rupture. Some are on previously known active faults or fault zones, but some are on unknown or hidden zones (as described below). Unknown or hidden fault zones can be due to change of the surface by rapid sedimentation or erosion by rivers and related debris or slope failure in active volcanic area.

Geologists that surveyed the Kumamoto area after the April 16th quake found several dislocations and earthquake faults. The Futagawa and Hinagu fault zones (WSW and SW trending, respectively) merge near the main earthquake epicenter, and dislocations were located nearby in fields and on roads. The maximum dislocation observed in Mashiki Town was 2 m of dextral (right-lateral) strike slip with a small vertical component of slip (Fig. 10)

A dextral dislocation along a NE-striking strike-slip fault appeared in a wheat field near Mashiki Town (epicenter area), during the 16th April earthquake (M 7.3). A clear dextral dislocation appeared in another wheat field along the easternmost part of the Futagawa and Hinagu fault zones, showing a 2 m wide *en echelon* pattern of left-stepping ruptures (Fig. 10). Along this fault zone almost 50% of the houses collapsed. Almost all the buildings and houses constructed before the introduction strict building codes collapsed. Buildings constructed according to new regulations survived.

![Fig. 10](image)
Pressure ridge-like straight mound along the faults, suggesting some tens of cm uplifting on the SE side. Two photos on top are by Prof. T. Nakada (Hiroshima University), looking toward NE. See also https://www.gsj.jp/en/index.html (Chishitsu News No.5 (5)) for Kumamoto earthquake surface ruptures.

Fig. 11. Fractures of echelon pattern of Ridel shears are lined by authors on Google Earth views of Minami-Aso Village from the videos of Geographical Research Institute of Japan.

(http://www.asahi.com/articles/photo/AS201604190003872.html).
As shown by pictures taken from a drone (Fig. 11), some fractures appeared along strike to the NE of the previously known Futagawa and Hinagu fault zones. Some normal-type faults were found on the south side of Aso Volcano by Prof. S. Toda (Tohoku University).

**Slope failure:**
Several types of slope failures were recognized. Some representative examples are discussed below. Most slope failures occurred in and around the active Aso Volcano. Steep and even shallowly dipping slopes failed. A sudden slide occurred just north of the active faults at Minami-Aso Village during the second large shock on the morning of April 16th (Fig. 12). A 700 m long, 200 m wide rapid collapse of the scoriaceous deposits flowed down to the Kurokawa River, pushing away the railroad and bridge. One car is still buried on the road.

Fig. 12. Large scale slope failures on the Kurokawa River, around the Aso Volcano soma, Minami-Aso Village, looking NW. Active fault of the Futagawa fault zone runs from Top to center bottom along the greenish slope. (Right is the enlargement of the left). From the Yomiuri-Shimbun HP.

Aso Volcano is located 20 km east of the main shock epicenter, on the extension of the Futagawa fault zone, and is covered with thick, soft scoriaceous deposits. During the April 16th shock, some steep slopes collapsed, feeding debris flows that washed away railroads, roads, bridges, and houses (Fig. 12). Many local apartments for Tokai University collapsed, burying tens of students. Several students and visiting and local people (30 in all) were killed. Aso volcano erupted one day after the first shock, but authorities do not think that the eruption was related to the earthquake. The eruption may be ordinary activity, and no expansion due to magma intrusion was detected.
Another example of slope failure, a landslide, occurred on a shallowly dipping slope at Minami-Aso village. A scoriaceous surface layer above a clay-rich sublayer (after Prof. T. Kamai, Kyoto University) slipped downhill. The fluidized scoriaceous debris flow (Fig. 13) buried many houses.

Fig. 13. Land sliding of the central cone part of Aso Volcano at the Kayo area of Minami-Aso Village. Right is the lower stream of the left. Several people were buried and were killed. Even though the slope was shallow of inclination, a large amount of failures occurred in three directions, as reported by two researchers, Prof. K. Fukuoka (Kyushu University) and Prof. T. Kamai (Kyoto University). The latter considered that the sliding occurred just above the altered clayey ash layers below the young surface scoriaceous deposits. From the Yomiuri-Shimbun HP.

Fig. 14. Slope failure on the freeway in Yufuin Town, Oita Prefecture, also in the Quaternary volcanic area. From Asahi-Shimbun HP.

Liquefaction and other hydrogeologic phenomena:
According to the reports of Prof. S. Yasuda (Tokyo University of Electricity), and Prof. Hazama Hemanta (Kyushu University), liquefaction occurred in up to 20 locations. The Kumamoto area has a shallow ground water level due to the Aso volcanic rocks and sediments, particularly those on the old river channel zones, which are largely sand and gravel-sized and which are prone to liquifaction during shaking.
Some local ponds dried up and debris flows formed natural dams in the nearby rivers. The Aso Volcano area is popular resort and agricultural area, but it was heavily damaged. Some hot springs have stopped flowing. This is the site of the proposed Aso Global GeoParks of Global GeoParks Network (UNESCO), but most of the area was heavily damaged.

Fig. 15. Largely liquefied part shown by brown in color in the parking lot of a super market, Kashima Town. From Asahi-Shimbun HP.

**Crustal movement:**

The wide aperture radar observations from satellite of “Daichi 2”, Geographycal Research Institute of Japan, have been used to measure vertical changes of the surface of the earth (Fig. 16., www.gri.go.jp). The observed changes are well explained as the result of dextral dislocation during faulting, with some cm of sinking around the Aso Volcano area.

Fig. 16. Vertical change of the surface due to wide aperture radar by Geographical Research Institute of Japan.
10 years (from 2006 to 2016, just before the earthquake) of GPS data constraining surface displacements of the surface in and around Kyushu (Fig. 17) are available. Displacements are shown relative to a reference point at Yukuhashi City, NE Kyushu. The relative motion between any two points can be determined by subtracting the two relative vectors.

According to these maps, Shikoku Island displacement is due to the subducting Philippine Sea plate, but Kyushu Island’s horizontal and vertical motion is different. It is extending in a N-S direction, and sinking in the middle. The horizontal movement coincides well the strain map based on triangle survey results for the past 103 years (Fig. 18) (Research Group of Active Faults of Kyushu, 1997). As discussed in other sections, Kyushu may be pushed from the E by Shikoku (Prof. Y. Kobayashi, 1990s personal communication).
Seno (1979) suggested the general stress pattern in Japan, in which he showed the westward dislocation on the south of the Medium Tectonic Line in Shikoku (an active, forearc sliver fault) might push Kyushu from E to W. We now further suggest that the negative gravitational anomaly and seismicity of the SE off Kyushu between Shikoku to the N (Figs. 19 and 20) may support that Shikoku in general pushes Kyushu to produce the N-S extension as verified by the GPS and triangle survey results as in Figs. 17 and 18.

Fig. 18. Horizontal strain map by 90 year results of triangle survey by Tada (1984) (Adopted from Research Group of Active Faults of Kyushu, 1997). This map shows remarkable N-S stretching in a zone of E-W in the central part of Kyushu.

Seismicity maps for the past 103 years until 1988 are consistent with Shikoko Island pushing west into Kyushu. These maps show that seismicity is not along the Nankai trough but instead extends to the N and E between Kyushu and Shikoku (into the Bungo straits to the Seto Inland Sea (Suo-nada). The seismicity is also remarkable in the middle-west part of Kyushu along the present Futgawa-Hinagu two fault zones (Research Group of Active Fault in Kyushu, 1989).
Fig. 19. Seismicity maps for 5710 earthquakes for 103 years until 1988 (left), and large ones (right), indicating they are not along the Nankai trough but extend straight to the N by E between Kyushu and Shikoku (into the Bungo straits to the Seto Inland Sea (Suo-nada). Also attention the seismicity in the Middle-west part of Kyushu along the present Futgawa-Hinagu two fault zones. After Research Group of Active Fault in Kyushu (1989). See also the present seismicity map of Fig. 9.

Fig. 20. Gravity anomaly map (Free air in the sea, Bougue in land (specific gravity 2.67), suggesting the negative anomaly SE off Kyushu is N by E to the Bungo straits, and the present earthquakes in middle Kyushu occur along anomaly zones. After Research Group of Active Fault in Kyushu (1989).
Recently, Matsumoto et al. (2015) have summarized a new dataset of seismic and geodesic activities and movement based on recently developed networks, including GPS and gravity anomaly, seismicity and stress field for 18 years before 2011. According to them, the general situation before the 2016 Kumamoto earthquake and related crustal movement was similar to the situation that we reviewed above. They indicated that a strong sheared zone in Kyushu is not along the Futagawa-Hinagu fault zone but along the western extension of the Medium Tectonic Line in Shikoku (Fig. 21). We now know the seismic activities are along the Futagawa-Hinagu zone and Beppu-Haneyama zone. Even though the actual seismicities are slightly different, the N-S geodetic stretching with E-W horizontal compressive axis (P-axis) are same before the 2016 earthquake (Fig. 22).

![Fig. 21. Strong shear zone along the NE-SW extension of the Medium Tectonic Line (MTL) of Shikoku Island (left) after Matsumoto et al. (2015). Data from January 1993 to August 2011. This paper was published just before the 2016 Kumamoto Earthquake, and we now noticed that the major epicenters are concentrated not with the shear zone but other zones to the north as shown in the text above.](image-url)
Fig. 22. Horizontal P- and T-axes adopted in the stress-tensor inversion, indicating the strong N-S stretching along the 2016 seismically active zone along the Futagawa-Hinagu fault zones, and Haneyama fault zone. See text. After Matsumoto et al. (2015).

**Relation to Aso volcano and other area:**

Aso volcano has not had a huge eruption since the caldera forming event at ca. 85-90 ka. The central Takadake cone has been continuously erupting, but these minor eruptions have not been accompanied by expansion of the underlying magma chamber as detected by GPS and tilt meter observation. However, further attention is required as the volcano has become slightly more active since the earthquakes (Fig. 23).

Fig. 23. The central cone active eruption just after the main shock on 16th April. After Asahi-Shimbun HP.
Another concern is that most of the large inland earthquakes have been temporally-related to subduction megaquakes. They are related, but it is unclear which induces the other (Seno, 1993; Ishibashi, 2015).

**Social damages:**

Large scale damage occurred during the first shock on the 14th and particularly the second one on the 16th. Damage includes the loss of human life line and harm to the economy through impaired transportation and industry. During the first shake on the 14th (they felt a strong lateral shake first), buildings, houses and walls along streets collapsed, as well as tombstones. By the MMI scale the earthquake was a 10 at the maximum at Mashiki Town. The damage of the second shock was stronger (MMI scale 12). During the second shock, already damaged houses which were still standing, collapsed completely (Fig. 24). The two main earthquakes occurred at night, so that the people in the collapsed houses on the epicenter zones were buried. However, if the earthquakes had occurred during the day time, many streets would have had large numbers of people and pupils in locations where walls, glass from buildings, and houses would have fallen, and more losses and damages might have occurred. The Kumamoto Castle of the 16th Century had its stony walls partly collapse during the first quake, and largely collapse during the second quake (Fig. 24). It was also feared that the Shinkaisen (Bullet train) and local trains in Kumamoto City or surroundings were derailed, but fortunately the trains were vacant during transportation to the train bases without any loss of life (Fig. 25).

There was a maximum of ca. 37,000 refugees, whose numbers gradually decreased, but rainfall events caused short-term increases in refugee numbers. More than 1,500 people were injured and this number is increasing. The injured and dispossessed were helped by police, firemen, and defense forces as well as many governmental people. However, people who took shelter in their own cars suffered so-called economy-class deaths, and more than 20 people died. Governments, prefectures, cities and towns tried to prepare temporary housing.

As of April 28th, 300 bridges were reported damaged, among them 16 having suffered serious damage. The Kumamoto castle (one of the most famous ones in Japan, constructed in the 17th C as a symbol of the Kumamoto citizens) was partly damaged by the first shock, but suffered considerable additional damage during the second shock (Fig. 25). Industrial, agricultural and economic losses were large, including closure of some automobile company factories, and shutting down of the transportation network for two weeks. However, things are improving.

On 23rd of May, the Japanese government made a tentative calculation on the economic loss of infrastructures, including buildings, roads, railroads, electricity and so on, excluding industrial and agricultural loss, to range US$ 2.2 to 4.4 x 10^10. This value may increase in future.
Fig. 24. Collapsed houses in Mashiki Town (top and left bottom), the Uto City hall building (right bottom). Those cities and towns are just on the Futagawa fault zone. From Jiji-News and Yomiuri-Shimbun HP.
Earthquake anticipation:

These earthquakes were not anticipated. There was no information pointing to an increase in shear strain prior to the earthquakes, nor any other earthquake-related phenomena. Only the shear strain, which is in general known to be N-S stretching by triangle method and modern GPS survey as mentioned above, implied strain accumulation. According to earthquake probability maps produced by the governmental earthquake research committee (Fig. 26), the Futagawa and Hinagu fault zones were included within a list of 98 dangerous active faults considered to have a 16% probability of producing a M 7.3 size earthquake within the next 30 years. These calculations are based on several stochastic assumptions, including in some cases the Brownian Passage Time model (BPT), and in other cases by the Poisson process (PP), depending upon the paleoseismically acceptable assumption. For BPT modeling, the periodical rupture with a certain recurrence years is known, whereas for PP modeling, it is not. In the Kumamoto area, they adopted the BPT model (http://www.jishin.go.jp/main/index-e.html).

Fig. 25. (Left) Collapse of the Kumamoto castle at the first shock. It was damaged much more at the second shock. From Yomiuri NHK-TV. (Right) Hohi line of Japan Rail Kyushu was derailed. From Yomiuri-Shimbun HP.

Fig. 26. Probability maps issued from The Headquarters for Earthquake Research Promotion of Japan
in 2010, (left), and the Newspaper’s information to citizens by Yomiuri-Shimbun (right). As shown on the right, the Hinagu fault zone has 16% probability of M 7.3 earthquake within 30 years.

A probability map for the next 30 years, issued from The Headquarters for Earthquake Research Promotion of Japan is shown in Fig. 26. The general percentile for the whole of Japan is shown on the left, and the maximum probability of each area depending on the different stochastic assumptions is shown on the right (red parts show the present Futagawa and Hinagu fault zones, the maximum probability in each area is 0.9, 6 to 16%, respectively).

Although the strain field is constrained by survey results, the probability of an actual rupture is difficult to constrain. Around 15 inland earthquakes larger than M 7 or so have occurred. Some earthquakes occurred by the dislocation of unknown active faults (e.g. 2010 West Tottori earthquake), and some occurred as very low probability ones. Therefore, earthquake prediction has not been successful. In any areas of such mobile crust, such as above subduction zones like Japan, inland earthquakes might occur suddenly without any notice. Of course in Japan already 2,000 to 3,000 faults are listed as mapped, and around 100 ones have been studied by observations including trench cuts (Fig. 27).

Fig. 27. Major 98 active faults that are pointed out in near future motion by Government. The present two active fault zones are Nos. 91 and 92, the Beppu-Haneyama fault zone and Futagawa-Hinagu fault zone, respectively. Based on http://www.j-shis.bosai.go.jp/shm

**Early warning system:**
In Japan, two early warning systems for earthquakes and tsunamis that occur in the trench areas have recently been constructed (See IUGS E-Bulletin #118: http://iugs.org/uploads/IUGS%20Bulletin%20118.pdf). However, because of the present early warning system earthquakes in general (including the Tokyo area), people know about impending shaking some seconds to minutes before the first strong shake arrives. The difference between the velocity of P-waves and S-waves (approximately a few second per km; because the average velocity of the two waves are 6.5 and 3.5 km/second in the upper crust, respectively), means that at a distance of 100 km from the hypocenter, the difference of the arrival times between the two waves might be approximately 30 seconds. Usually, for any earthquake, we would have some tens of seconds after the arrival of the P-wave before the strong shake of S-wave. However, when far from an earthquake hypocenter, the P-wave shake is weak, although there may be some minutes to be prepared. During the Kumamoto earthquake, Tokyo-area people (Y. Ogawa included) listened to their mobile phones ringing the emergency signal as well as emergency TV broadcasting. One problem is that if two simultaneous small earthquakes occur, a warning would be issued. Further improvement to address issues like this are required.

One additional issue is that in this case two large shakes occurred within almost 50 hours of one another. In both case the JMA scale attained 7 (MMI scale 10 and 12). Such repeated strong shakes were not previously anticipated and constitutes a new occurrence. As such, the nature of such multiple quakes is not completely understood.

**Tectonic interpretation: Present status**

Tectonically, these seismic events occurred along the southwesterly extension of the active Medium Tectonic Line of Shikoku. But in Kyushu, the active fault zones are complicated. The E-W trending Beppu-Shimagbara graben, includes two large active volcanos, Aso and Unzen. GPS shows N-S stretching as well as NE-SW trending dextral shear strain, which is different from Shikoku or regions farther to the east (Figs. 1, 2, 3, and 26).

The stress field around the middle of Kyushu is generally known to be N-S stretching (vertical sigma 1, E-W sigma 2; a rare case in Japan - another is the active fault area in Fukushima), but this area is also sheared by E-W sigma 1 in general. The focal mechanisms of the main and aftershocks have both strike-slip and normal ruptures. SW Japan area is stressed by NW-ward oblique subduction of the Philippine Sea plate (4-5 cm/y) (Seno et al., 1993) and by E-W compression caused by the westward collision of Shikoku Island with Kyushu (original idea of Prof. Yoji Kobayashi, personal communication 1990s). As shown previously, a negative gravity anomaly extends from off Kyushu to the Bungo Straits (between Kyushu and Shikoku) running from south to north, consistent with the idea of collision-subduction between the two, and consistent with the E-W compression and shortening in middle Kyushu (Figs. 19, 20 and 22)
Summary and future topics:

As reported above, this 2016 Kumamoto inland earthquake series was unique as it involved many different types of faults in the mid to shallow crust (5-20 km, mostly around 15 km). Mostly there was a dislocation of NE-SW trending dextral faults by E-W compression, but some normal faults and even thrust type earthquakes occurred on 4th of May. Several of the fault segments or zones are in a large sense within the E-W trending Beppu-Shimabara graben, but those segments may have reacted independently, as connected or induced. Researchers plan to have an urgent, special session in Japan Geoscience Union Annual Meeting (JpGU) in the end of May, 2016 (www.jpgu.org/index-e). They will discuss various viewpoints. We list some of the future topics for research as below.

1] How and why were there a series of two large earthquakes, and were there two different main shocks that overlapped simultaneously to make the earthquake of April 16th so damaging?? Were these earthquakes connected, induced or chained, and did they rupture segments of a single large fault zone?? OR were multiple faults involved?? Were these events reactivation of previously known active faults?? Or were new fault systems involved?? How was the relationships of the so-called the “old failures” and the real earthquake faults??
2] Why has the seismicity extended to SW and E, and how? Just by stimulation induced by the earlier earthquakes?? Was water or gas involved?? Why or how did strike-slip faulting occur at the same time as normal faulting, or even as thrust faulting? And why have there been so many aftershocks.

3] Has the seismicity affected the magma chamber of the Aso Volcano?? One geophysicist in NIED claimed that the magma chamber was deformed, stretching to the W. If the upper crust was deformed, is it because the seismically active faults extended into the magma chamber?? In this case if stretched, magma pressure may not be increased but decreased, resulting the decrease of eruption potential. We have to watch the magma activity.

4] The seismically more active zone in west Shikoku is close to the Ikata nuclear power station. This station is on the Medium Tectonic Line, which is ACTIVE in Shikoku and Kii. Some researchers do not believe that the current series of quakes could continue to migrate to the E, but some do. In this case too, we have to watch. Also the Hinagu fault zone extends SW-ward, reaching close to another nuclear power station, only acting at present, called the Sendai station. Another series of earthquakes occurred in November, 2015. We need to watch both stations.

5] Earthquake prediction is a crucial problem to our present researchers, but we have to overcome, or at least we need to prepare adequate thinking amongst the public.

Concluding remarks: Although we knew of the active faults in Kyushu (and they have seen considerably activity over the past several hundred years, as is known from historical and archaeological (paleoseismical) research, but we (the governments or decision makers as well as citizens) tended to believe the general rumor that in Kyushu no strong earthquake shaking would come soon. For most of the 15 recent disastrous earthquakes in Japan in the 21 years since the 1995 Kobe earthquake occurred, there has been only limited preparation, and much disaster has occurred. Even so-called non-active faults have moved. This indicates that active fault research is not always perfect. The definition of an active fault is still vague, and ambiguous. People continue living on, and making houses and buildings on active faults. Hazard maps show earthquake probability, but if the probability is low, people tend to believe it is zero, but in such a mobile area, there are no zero probability areas. In addition, disastrous faulting is not always occurring along the higher probability areas. Officials should make and enforce laws against building close to active faults, like in California. In Japan only two prefectures or cities do such. Our science should play much stronger roles for society and for helping people to be prepared.

Myanmar earthquake:

The large (M 6.9) 2016 Mynmar Earthquake that occurred in NW Burma (Myanmar) on April 13th, 2016, 13:55:17 (GMT) was located 180 km NW from Mandalay at 23.133 N, 94.900 E, 134.8 km depth (based on
USGS site information as [http://earthquake.usgs.gov/earthquakes/eventpage/us20005hqz#general](http://earthquake.usgs.gov/earthquakes/eventpage/us20005hqz#general). This earthquake occurred along the Indian - Asia plate boundary, a subduction zone characterized by the subduction of Indian oceanic lithosphere beneath the Gangatic lowland that includes Myanmar. The earthquake occurred within the subducting slab and was not a rupture of the plate boundary.

**Ecuador earthquake:**

The magnitude 7.8 earthquake that struck along the west coast of Ecuador on April 16th injured more than 1500 people, killed at least 235 people, and destroyed more than 370 buildings. A further 151 buildings and 26 schools were significantly damaged during the earthquake. See [earthquake.usgs.gov/earthquakes/eventpage/us20005j32](http://earthquake.usgs.gov/earthquakes/eventpage/us20005j32), and k37 and so on.

The earthquake occurred at a depth of 21 km, was characterized by a thrust motion along a shallowly east-dipping fault, and is considered by have been a shallow but otherwise typical subduction-zone type earthquake that ruptured the plate boundary separating subducting oceanic lithosphere of the Nazca oceanic plate, from the overlying South American plate. The earthquake ruptured a ‘seismic gap’ in the Nazca – South American plate boundary that was bound to the south by site of the 1966 M8.1 earthquake that was located offshore of central Peru, and, to the north, by the 1906 M8.8 earthquake the occurred near Ecuador’s northern border with Columbia.

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((Related HP))

https://gbank.gsj.jp/activefault/index_gmap.html

http://www.jishin.go.jp/main/index-e.html

YY Below to be deleted:

(The 5th May, 2016; 10:00 JMT; 7.7g May 11, 2016; 19:40; 7.7h May 13, 2016; 02:30 JMT and SemiFinal May 23, 2016; 14:47 JMT by Y.O.: Final Version v88b May 24, 2016 after STJ rorrrection and revision)

(The End)