THE OFF-OKINAWA ISLAND EARTHQUAKE OF FEBRUARY 27, 2010

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CONTENT

1 INTRODUCTION

An earthquake with a magnitude of 6.9 on Japan Meteorological Agency Scale occurred near Okinawa Island of Japan. The focal depth of the quake, which occurred at 5:31 a.m. local time (2031 GMT Friday), was about 40 km under the sea 107 km east off Naha, capital of Okinawa.

Two people, both female and aged 74 and 66, were reportedly slightly injured in the earthquake according to the Prefectural government. Although the JMA agency issued a warning of up to 2-meter high tsunami waves for coastal regions of the main Okinawa island soon after the quake, it was soon downgraded at about 6: 30 a.m., and later lifted at around 7 AM. Small waves of up to around 10 centimeters reached Nanjo city on the island and Minamidaito just before 6 AM.

The damage reported after the quake were ruptured water pipes, fallen or cracked water tanks, fall of roof tiles and the collapse of some parts of walls of Katsuren Castle. In addition some slope failures also occurred.

2 GEOGRAPHY

Ryukyu Islands, which are also known as Nansei Islands, are situated on Ryukyu arc between Kyushu Island and Taiwan (Figure 1). The Ryukyu Archipelago is 1046 km long and it consists of 55 islands and islets with a total land area of 3090 square kilometers. The main islands are Amami-Oshima, Okinawa, Miyako, Ishigaki, Iriomote and Yonaguni from north to south. The archipelago was returned to Japanese sovereignty in 1972 after occupation by U.S. forces following World War II. The total population of the Ryukyu Islands is about 1,720,000.

Okinawa Main Island (Okinawa Honto) is by far the largest and most populous island in Okinawa Prefecture (Figure 2). The capital of Okinawa Prefecture is Naha on Okinawa main Island and it functions as the regional transportation hub. Okinawa is also home to many U.S. military bases

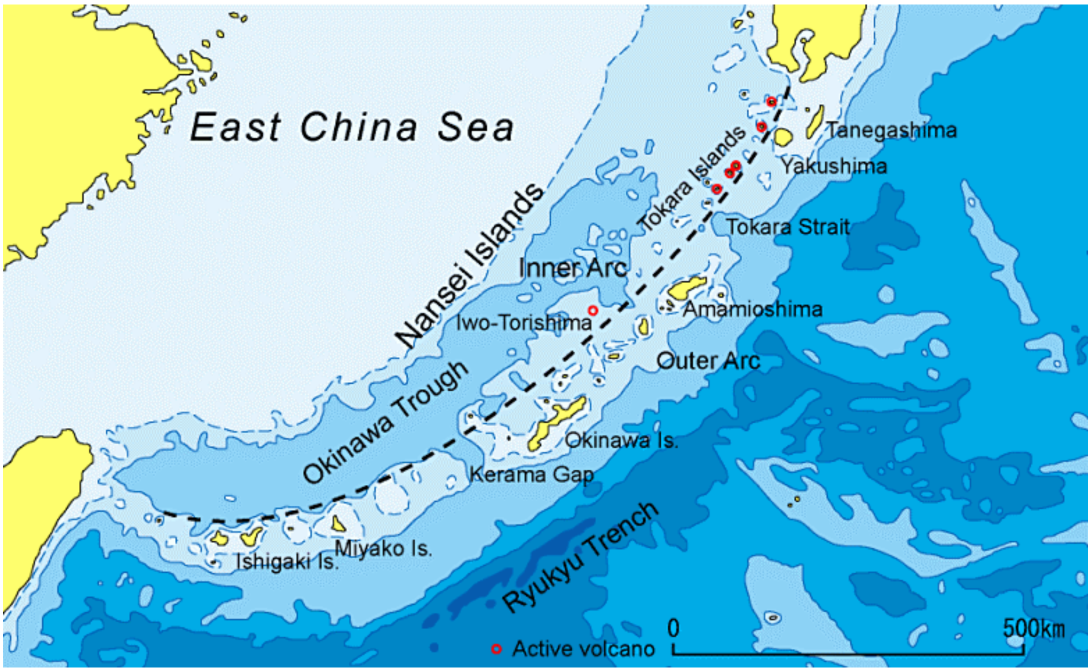


Figure 1: Location of Ryukyu Islands

Figure 2: A map of Okinawa Main Island

3 GEOLOGY AND TECTONICS

Ryukyu arc is considered to be a convergent plate margin where the Philippine Sea plate is subducting beneath the Eurasian plate (Figure 3). The arc is a rifting fragment of continental crust and it is roughly oriented NE-SW and the convergence rate between the Philippine sea plate and the Eurasia plate varies from 5 to 7 cm / year. Tectonic evolution since the Neogene is divided into three stages. Stage 1 (late Miocene) is pre-rift sedimentation. Stage 2 (Early Pleistocene) is the initial back-arc rifting. Stage 3 (Holocene) is the back-arc rifting still in progress.

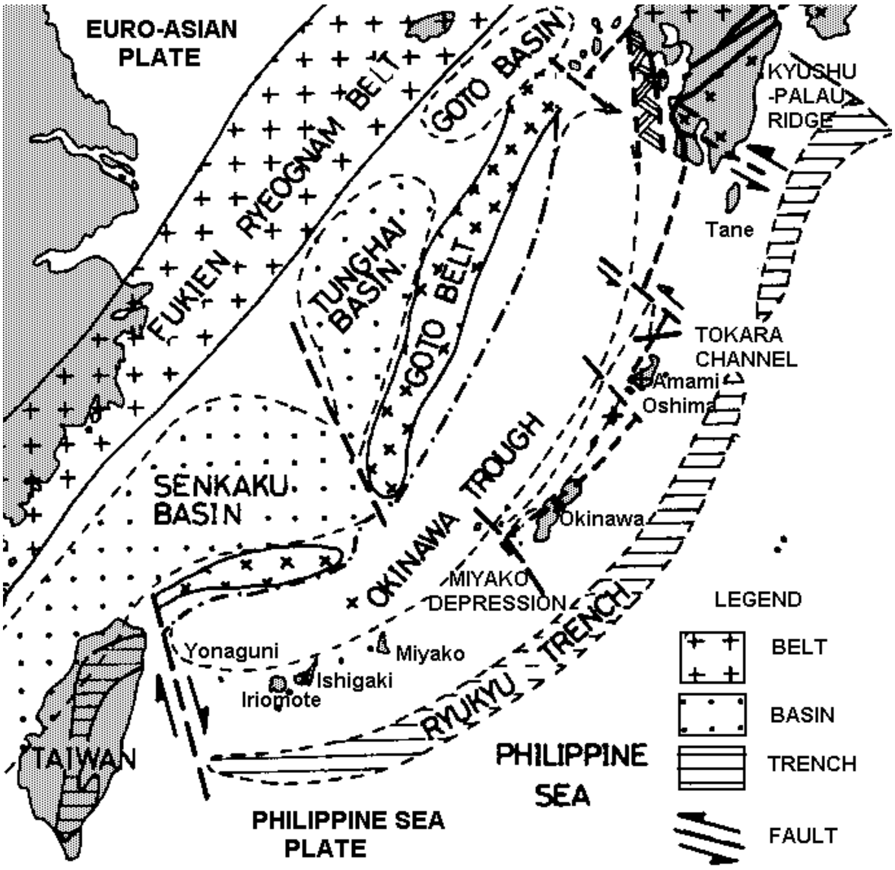


Figure 3: Tectonic features of Ryukyu Islands and their close vicinity (modified after Kizaki)

The formation of Ryukyu arc started in Miocene by rifting a detached block from Euro-Asian plate. This motion is said to be almost southward. While the Philippine Sea plate subducts beneath the rifting Ryukyu arc, the arc is bent between Taiwan and Kyushu-Palau ridge by rotation and rifting and it is fragmented into several blocks as seen in Figure 3. The geological investigations indicated that while the southern half of the arc rotates clock-wise, its northern part rotates anti-clock-wise. As a result of rifting, rotations and bending of the arc, normal faults, dextral and sinistral faults with or without downward or upward components developed since Miocene. The normal faults are only found at the upper-most part of the crust. The faults can be broadly classified according to their strike as NW-SE and NE-SW faults.

The age of the basement is pre-Cenozoic and the basement rocks consist of chert and schists. Cenozoic sandstone, shale and limestone overlay the basement rocks. These rock units are followed by Pliocene Shimajiri formation and all formations are covered with Quaternary Ryukyu limestone and Holocene deposits. Figure 4 shows the geology of Okinawa Island.

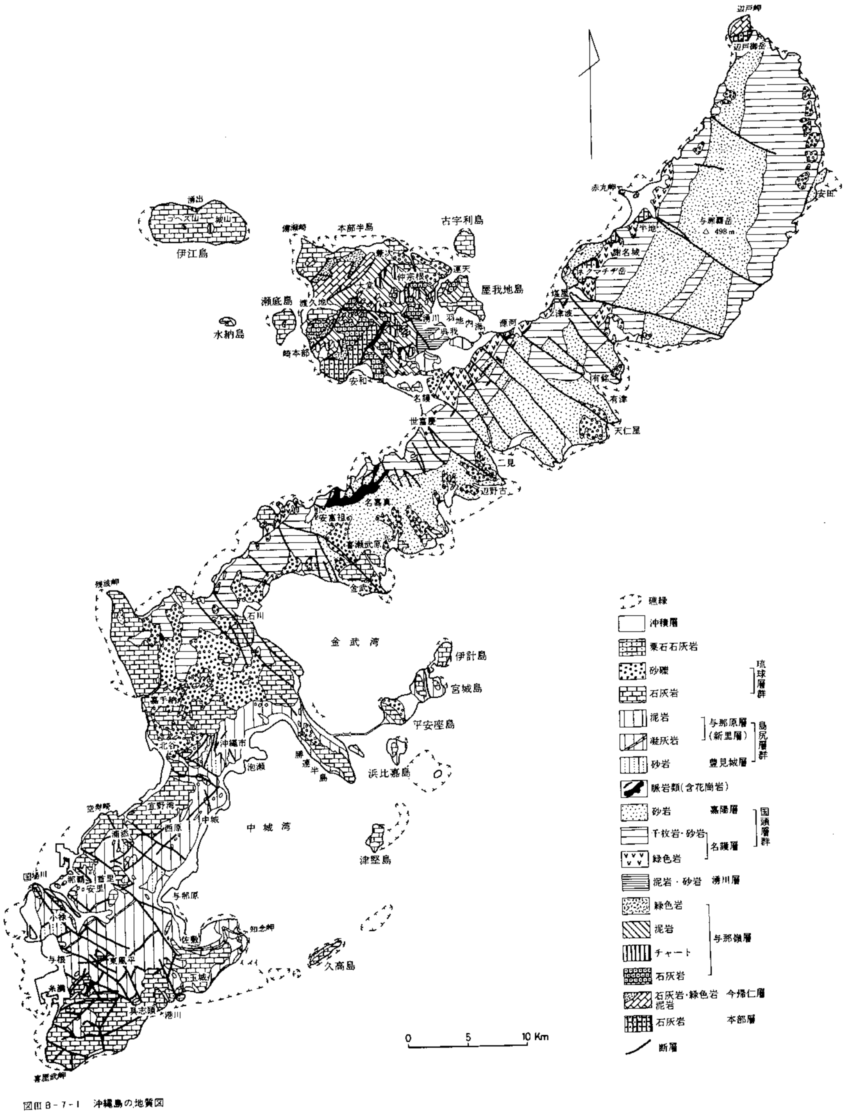


Figure 4: Geology of Okinawa island (modified from Kisaki)

The Ryukyu Islands earthquake of February 26, 2010, occurred near the boundary that accommodates most of the relative motion between the Philippine Sea and Eurasia tectonic plates (Figure 5). In the region of the earthquake, the Philippine Sea plate moves WNW with respect to the interior of the Eurasia plate, with a relative velocity of approximately 60 mm/yr. The Philippine Sea plate subducts beneath the Eurasia plate at the Ryukyu Trench and is seismically active to depths of about 250 km (Figure 6). The initial estimates of the earthquake's epicenter, focal-depth, and focal-mechanism imply that the shock occurred as an intraplate event either within the subducting Philippine Sea Plate, or within the overlying Eurasia plate, rather than on the thrust-fault plate interface that separates the two, but preliminarily data do not clearly discriminate between these two possibilities.

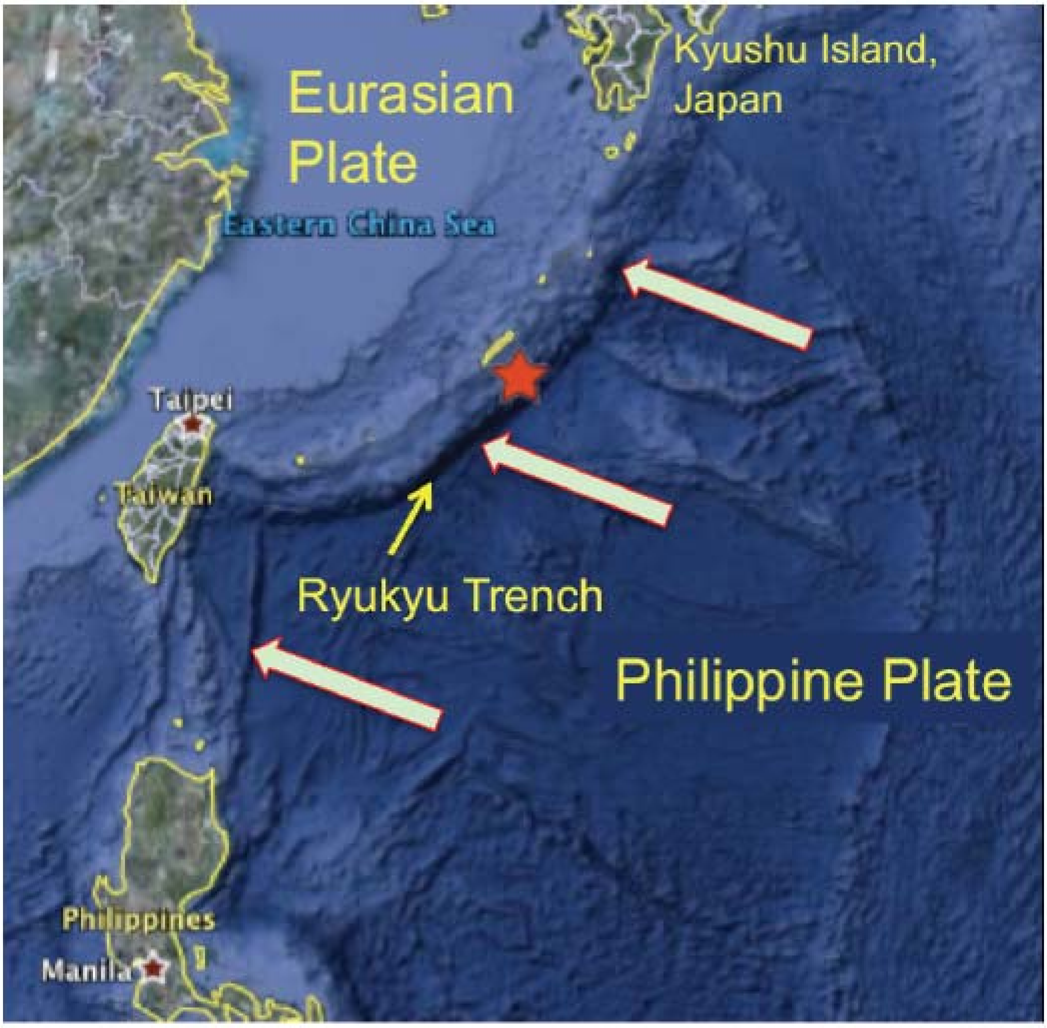


Figure 5: Plate movements in the vicinity of the earthquake epicenter (IRIS, 2010)

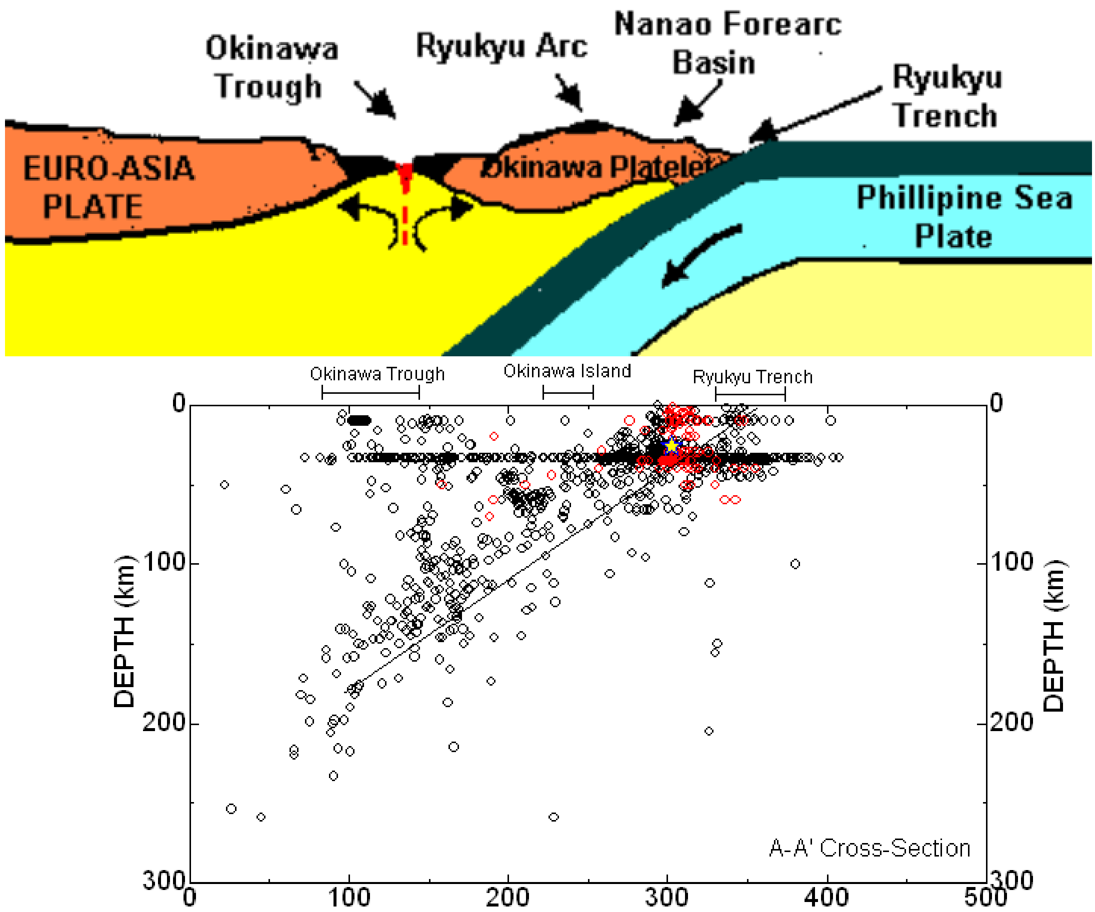


Figure 6: A cross-section of the earth-crust in the vicinity of Okinawa Island and associated seismicity together with aftershock activity

4 CRUSTAL STRAINING AND STRESSES

The authors have been using the deformations measured from GPS network of GEONET of Japan (Figure 7) to obtain current crustal straining and stress changes. Although the GPS stations are sparsely located, it is possible to obtain information on the current situation of crustal straining and stress changes of Ryukyu Islands. The authors have been using the method proposed by Aydan. This method utilizes the principles of Finite Element Method (FEM) to obtain incremental strain and stress changes. Figure 8 shows the stress changes obtained from deformations between 1997 and 2008. As noted from the figure stress changes are not uniform along the Ryukyu Islands.

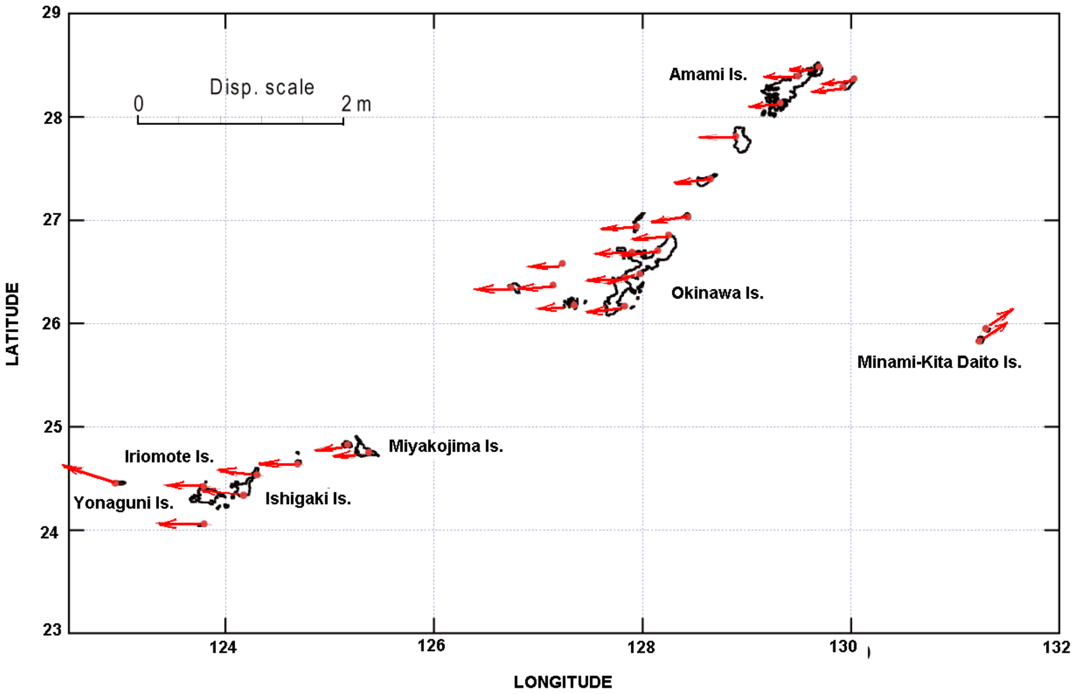


Figure 7. Crustal deformation of Ryukyu Islands between 1997 and 2008

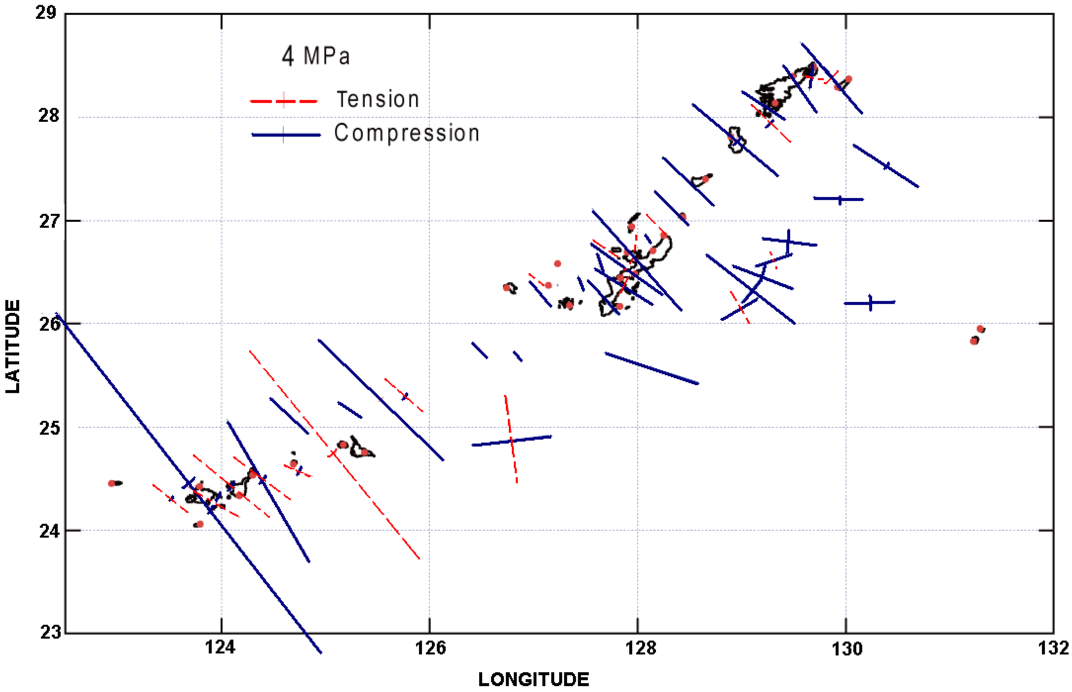


Figure 8. Stress changes of Ryukyu Islands between 1997 and 2008.

The authors in several islands performed measurements on the striations of the faults. The other measurements on fault striations were gathered from additional sources. Many focal plane solutions are obtained worldwide and in Japan by several institutes such as USGS and Harvard University from USA and NIED and ERI of Tokyo University from Japan. These solutions can be easily accessed through INTERNET nowadays. The epicenters of earthquakes obtained by HARVARD along the Ryukyu arc and the parameters of the earthquakes nearby Ryukyu Islands are selected by adopting the condition of $h \leq 30km; M_w \geq 6.0$.

The inferred maximum horizontal stress and its direction from, the fault striations and focal mechanism solutions of earthquakes are shown in Figure 9 together with the in-situ stress measurement from the AE technique. The maximum horizontal stress generally acts perpendicular to the arc axis although some of inferred maximum horizontal stress directions are parallel to the arc axis. This fact may arise from the choice of the causative fault plane. The compressive horizontal stresses are high in the vicinity of the Ryukyu trench while its magnitude decreases along Okinawa trough.

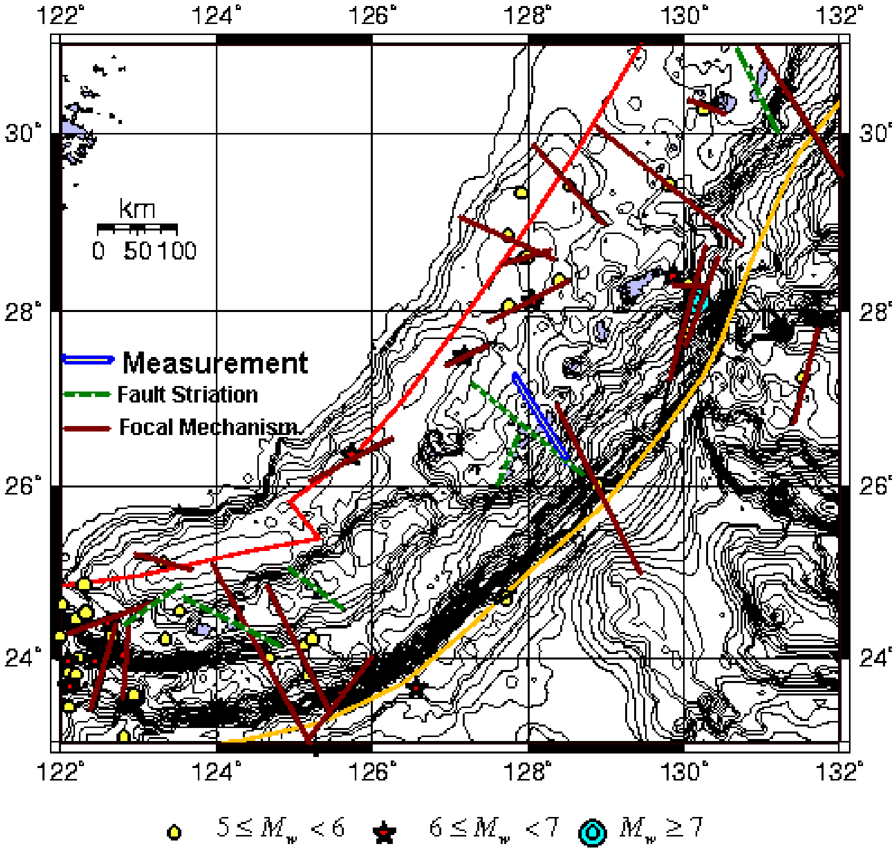
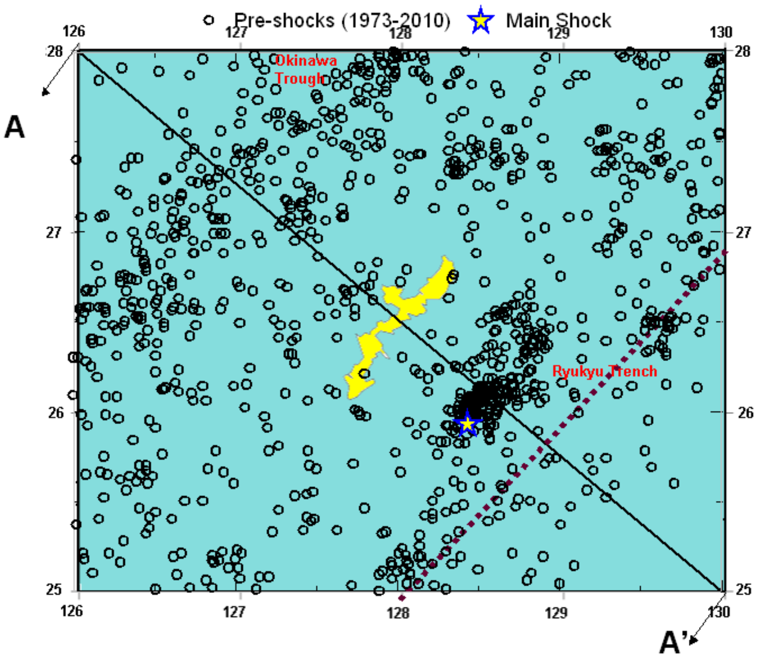


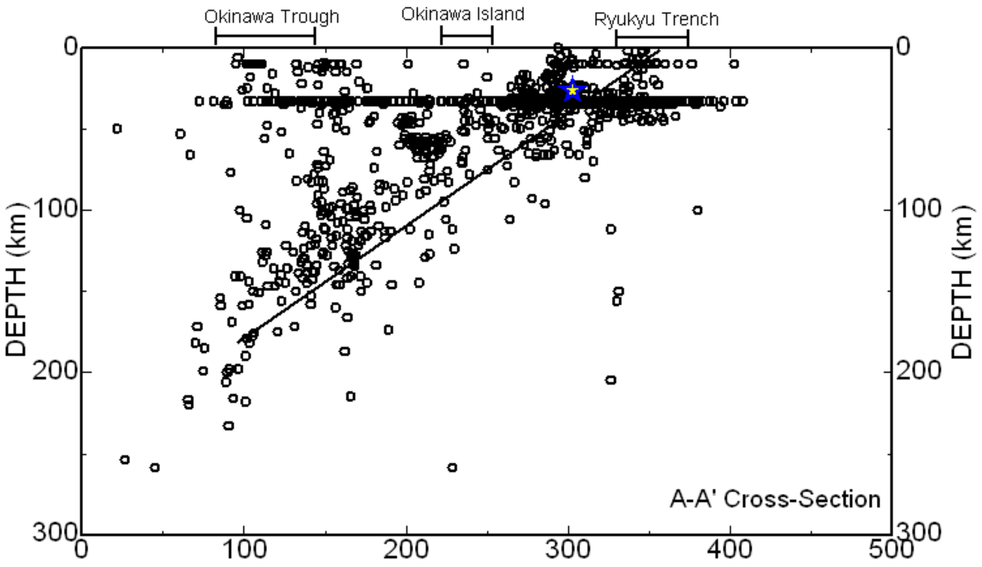
Figure 9: Maximum horizontal stress directions and their magnitude inferred from the fault striations and focal mechanism solutions of earthquakes together with the in-situ stress measurement.

5 SEISMICITY AND FOCAL MECHANISMS OF PAST EARTHQUAKES

Figure 10 shows the pre-seismicity of the earthquake-affected area together with the main shocks. It is interesting to note that the high seismicity is observed in the close vicinity of the hypocenter. The depth of the earthquakes extends up to 250 km below Okinawa Trough. The seismic activity mainly concentrated in the Okinawa trough, Ryukyu Trench and the upper zone of the subducting Philippine Sea Plate.



(a) Pre-seismicity



(b) Projected cross-sectional seismicity projected on a line A-A'

Figure 10: Pre-seismicity of the earthquake affected area.

The time variation of the pre-seismicity of the region between Latitudes 25-28E and Longitudes 126-130E since 1973 is shown in Figure 11 using the database of the USGS, which is publicly accessible. As noted form the figure, a cyclic seismic activity with a period of 10-11 years is noted. Nevertheless, the seismicity seems to be increasing by obeying the following function

$$\sum M = 3.251(t - 1973)\text{^}2 \quad (1)$$

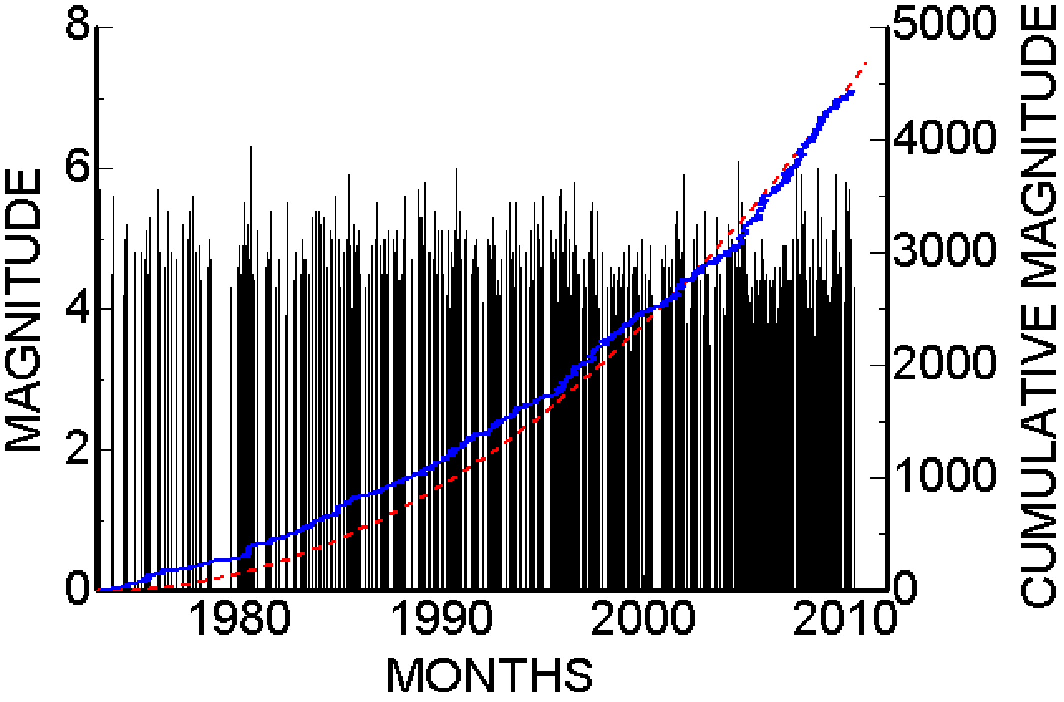


Figure 11: Time variation of the seismic activity in the earthquake-affected area

Figure 12 shows the focal mechanism solutions obtained by NIED. The shallow events in Okinawa Trough indicate mainly normal faulting with slight lateral-slip component due to probably the bending stress in Euro-Asian plate resulting from the subduction of the Philippine Sea Plate. Shallow earthquakes with normal faulting character also occur in the Euro-Asian plate in the close vicinity of Ryukyu trench. However deeper events have the character of the either thrust faulting or strike-slip faulting sense. The strike-slip events are generally concentrated along the known Kerama and Tokara gaps, which probably allow the kinematic rotation of each sub-blocks of the upper crust of the Okinawa Platelet.

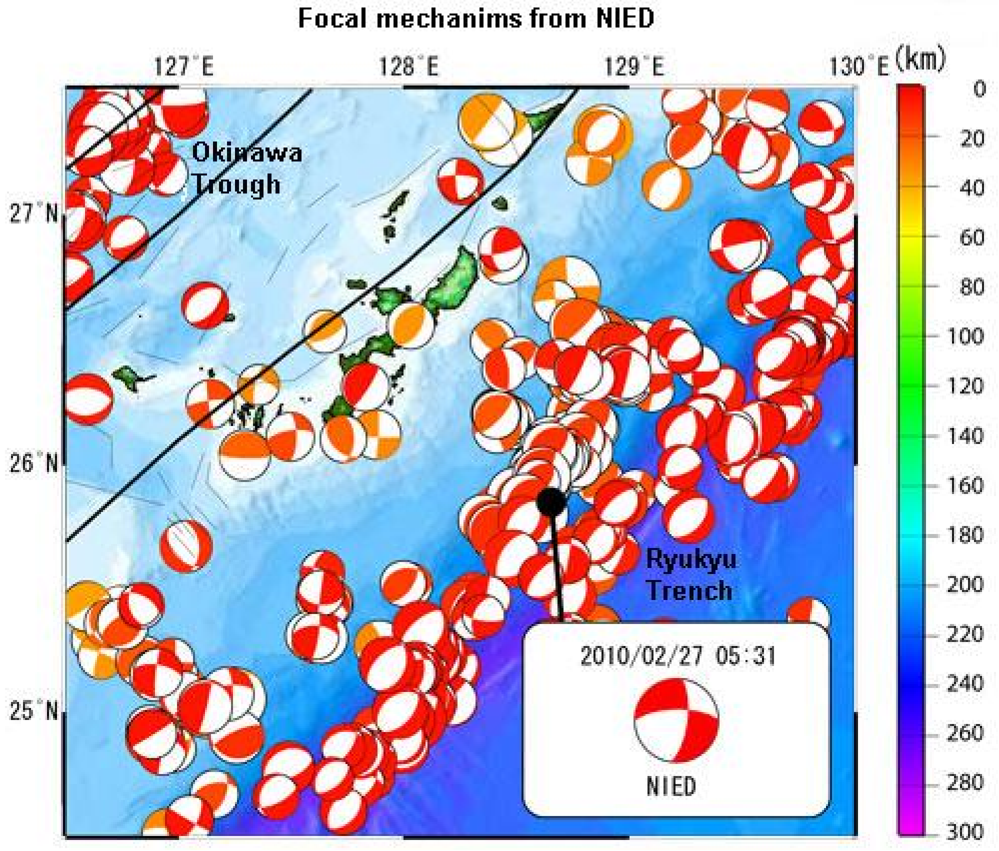


Figure 12: Focal mechanism solutions by NIED (from Ryukyu University)

6 SEISMIC CHARACTERISTICS OF MAIN SHOCK AND AFTERSHOCKS

Various seismological institutes estimated the characteristics of the main shock on Feb. 27, 2010 as given in Table 1 and as shown in Figure 13. The estimated parameters are very close to each and they implied that the earthquake occurred by strike-slip faulting. The Harvard solution estimated the duration of the earthquake as 15s. The authors utilized the relations proposed Aydan (2007) to estimate the size of the fault plane and duration of the earthquake for a moment magnitude of 7.0 and the results are also given in Table 1. As usual, focal mechanism solutions imply two possible fault planes. The fault plane striking almost E-W is expected to be the causative fault plane in view of aftershock activity following the main shock as seen in Figure 14. The aftershock activity is observed on an 80 km long and 40 km deep cross-sectional area.

Table 1: Seismic parameters of the main shock of 2009 Suruga Bay Earthquake

Institute	Mw	Strike (°)	Dip (°)	Rake (°)	Depth (km)	Length (km)	Width (km)	Duration (s)	Dmax (cm)
USGS	7.0	89	81	-10	22				
F-NET(NIED)	7.0	93	90	2	32				
ERI-TU	7.0	91	87	3	18				
JMA	7.0	89	77	6	31				
HARVARD	7.0	91	72	3	18			15.0	
Ö.A.	-	-	-	-	-	63	16	21.7	175

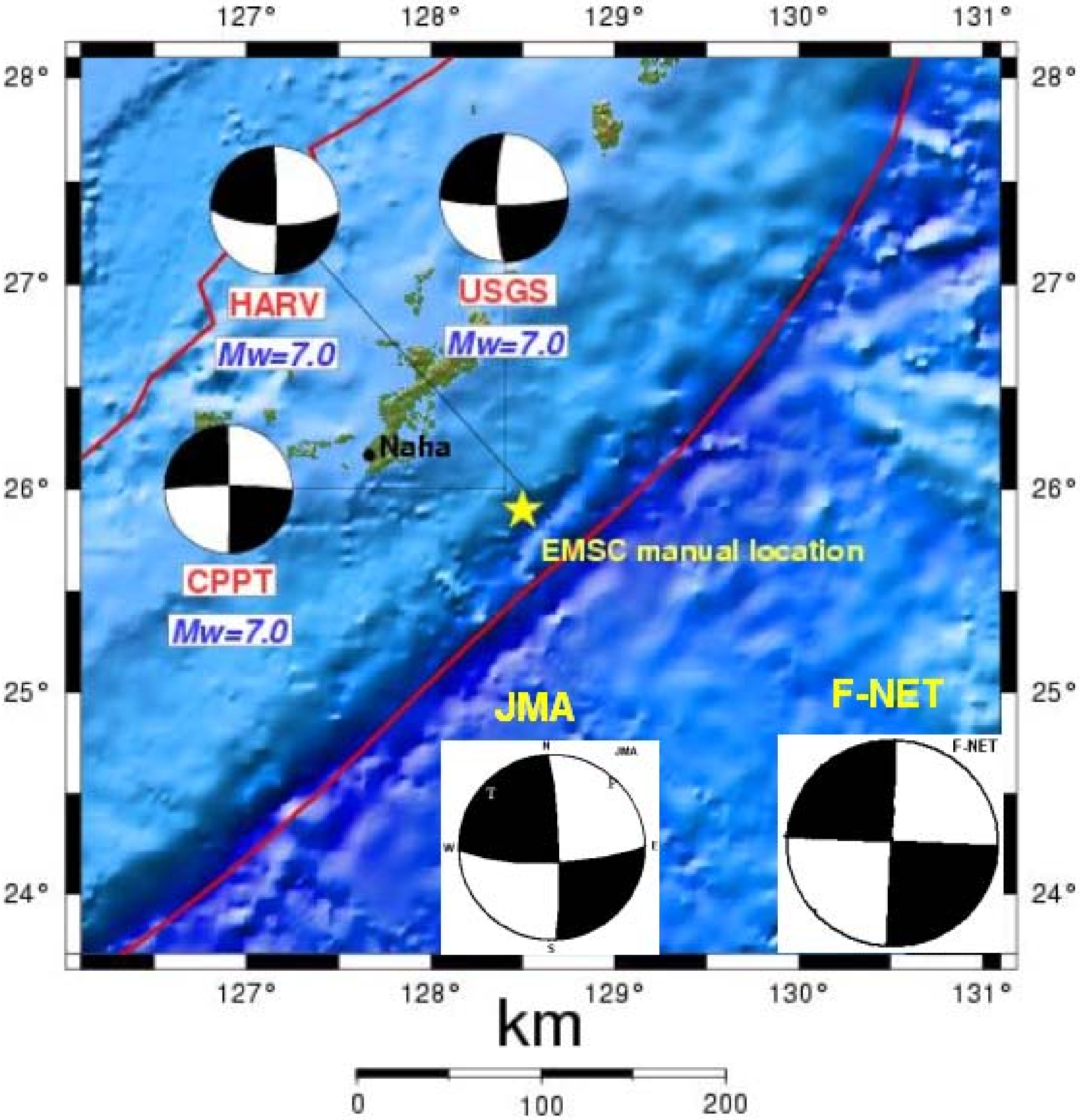
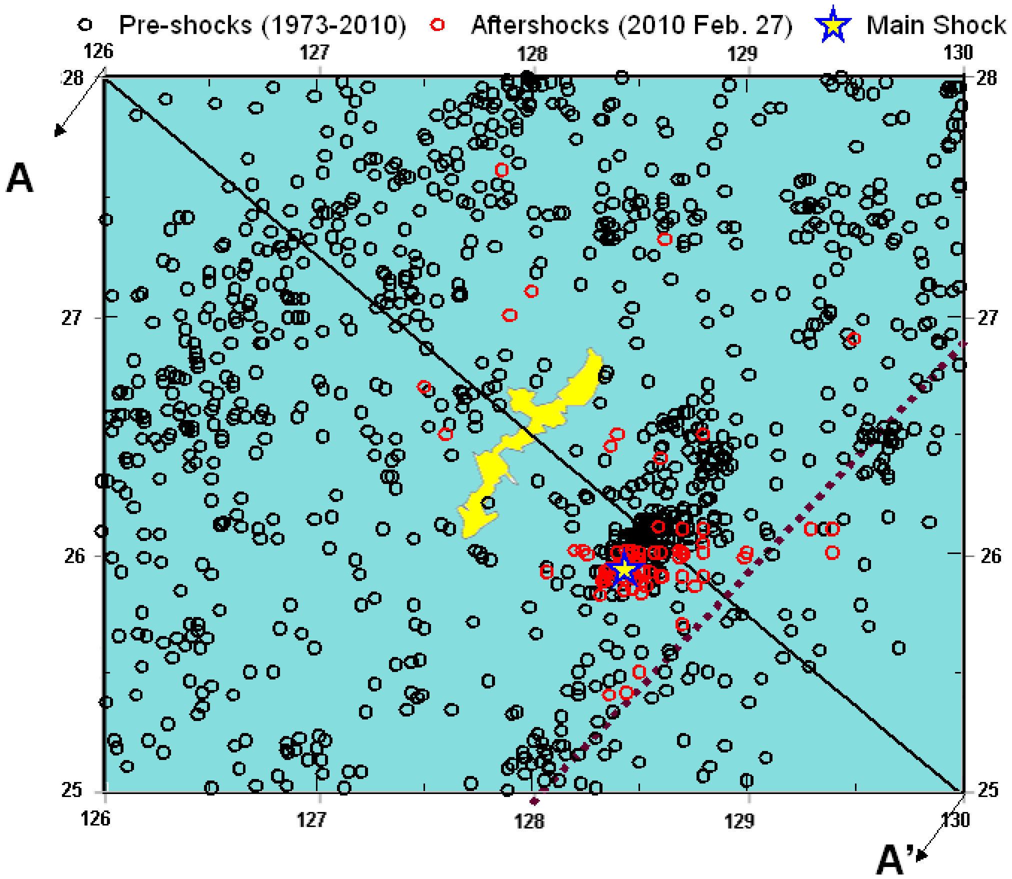
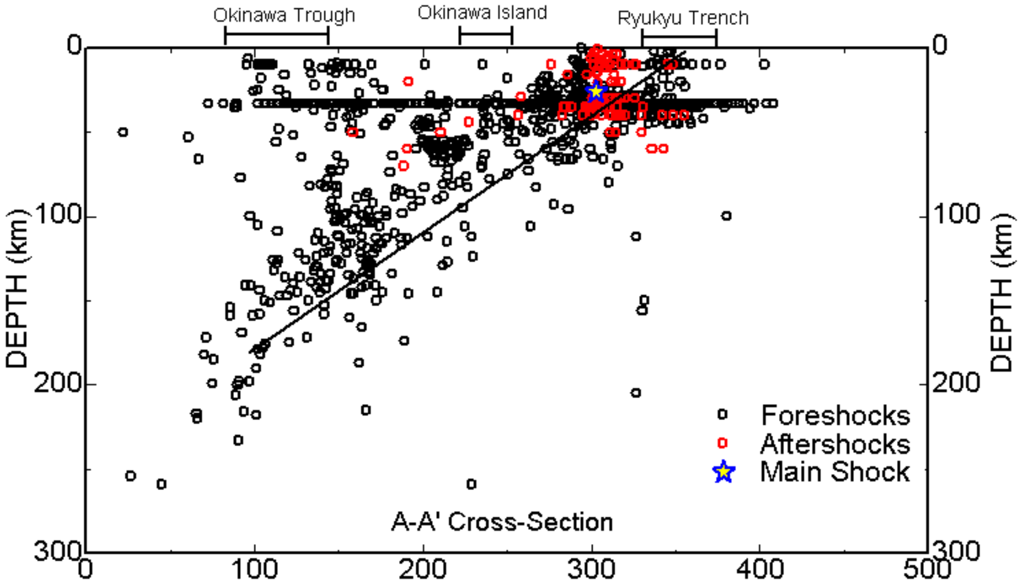


Figure 13: Focal mechanism solutions by various institutes (modified from EMSC, 2010)



(a) Foreshock and aftershock activity



(b) Projected foreshock and aftershock seismic activity along line A-A’

Figure 14: Foreshock and aftershock activity in the earthquake-affected area

7 STRONG MOTIONS

There are 5 K-NET strong motion stations owned by the National Research Institute for Earth Science and Disaster Prevention (NIED). The nearest strong motion to the epicenter is Chinen (Re=90 km) and the maximum ground acceleration was 123 gals. Figure 15 shows the ground accelerations in Okinawa and Kume Islands. The second highest ground acceleration were observed at Kunigami. The shear wave velocity of ground up to a depth of 5 m in all stations ranges between 150-250 m/s. The attenuation of maximum ground acceleration and velocity data are compared with some of empirical relations proposed by Aydan (2001, 2007) as shown in Figure 16. The empirical relations proposed by Aydan consider the directivity effect and type of faulting and the type of earthquakes. It was assumed that the earthquake was an intra-plate strike-slip earthquake. As noted from the figure good correlations are observed between estimations and measured values. Figure 17 shows the acceleration response spectra for strong motion records shown in Figure 15. The acceleration response spectra imply that Nago and Gushikawa records indicate some long-period effects. This may be related to the existence of relatively thick sedimentary deposits at these stations.

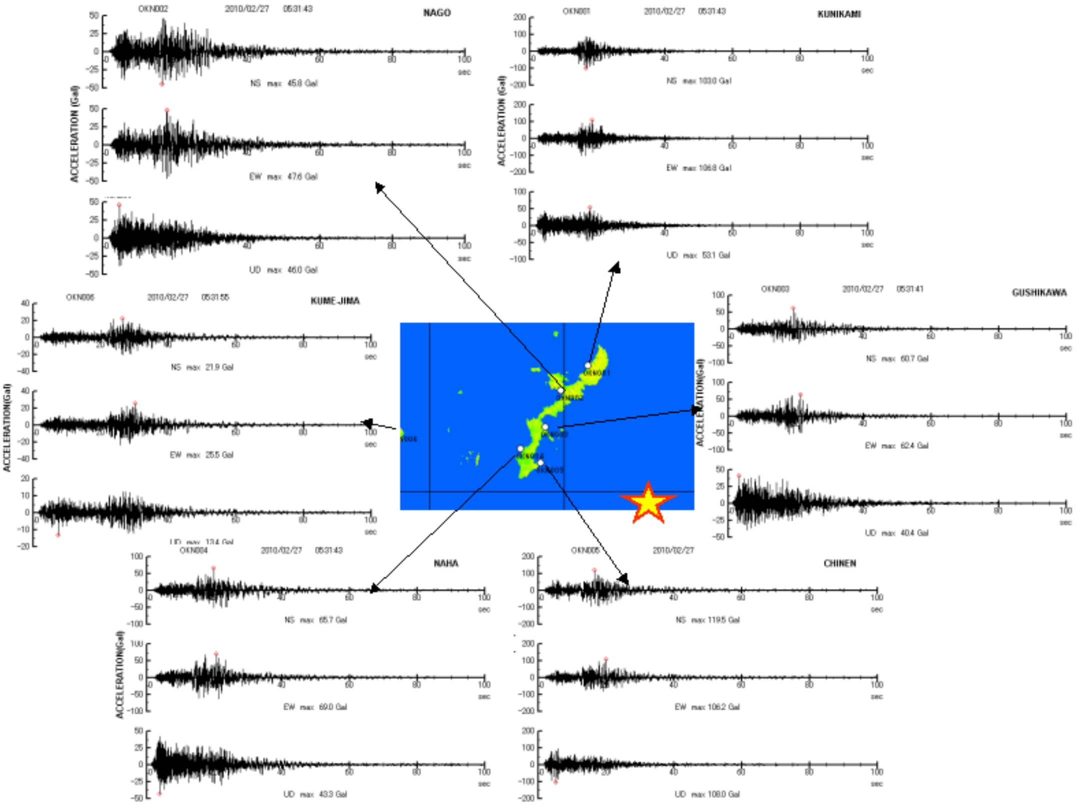
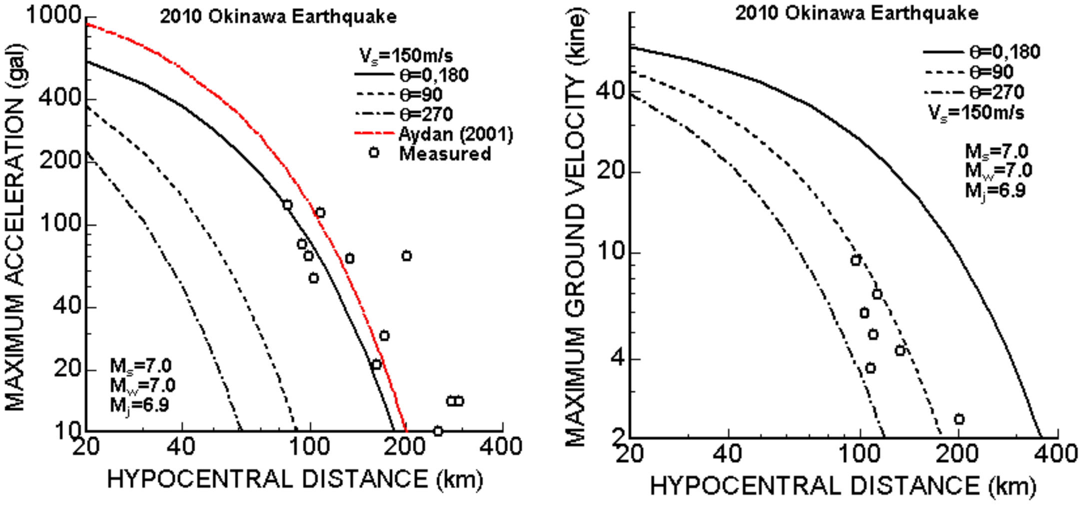


Figure 15: Acceleration records at strong motion stations in Okinawa and Kume Islands



(a) Maximum ground acceleration (b) Maximum ground velocity

Figure 16: Attenuation of maximum ground acceleration and velocity with distance

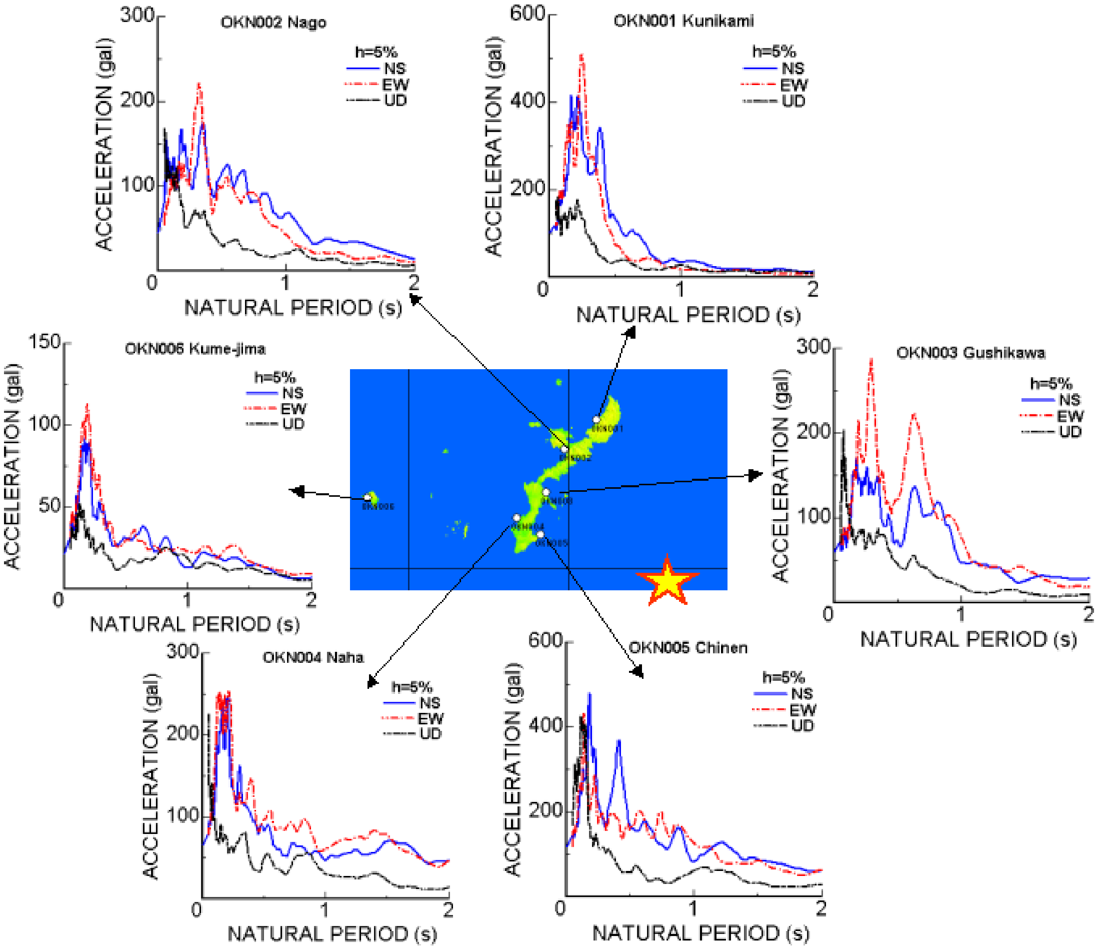


Figure 17: Acceleration response spectra of strong motions stations in Okinawa and Kume Islands

8 STRUCTURAL DAMAGE

As expected from the ground acceleration records and their response spectra, the damage should be none or light. The data compiled by the Fire Disaster Management agency (FDMA) are given in Tables 2-4. The damage concentrated mainly in areas with soft ground. Figure 18 shows some examples of damage compiled from mass media reports.

Table 2: Building damage

Location	Type of damage	Number of Building
Uruma City	Roof tile or walls	3
Urasoe City	Wall cracking	1
Nanjo City	Brick wall	2
Itoman City	Window glasses broken	1

Table 3: Water Tank Damage

Location	Type of damage	Number of Damage
Uruma City	Water tank broken	5
Urasoe City	Water tank broken	1
Nanjo City	Water tank broken	3
Itoman City	Water tank broken	4
Ginowan City	Water tank broken	10
Tomigusuku City	Water tank broken	18
Naha City	Water tank broken	3
Other locations	Water tank broken	9

Table 4: Water pipe damage

Location	Type of damage	Number of Damage
Uruma City	Pipe broken	1
Naha City	Pipe broken	2
Okinawa City	Pipe broken	10
Nishihara City	Pipe broken	15
Nanjo City	Pipe broken	10
Tomigusuku City	Pipe broken	5
Hahebaru town	Pipe broken	7
Other locations	Pipe broken	2

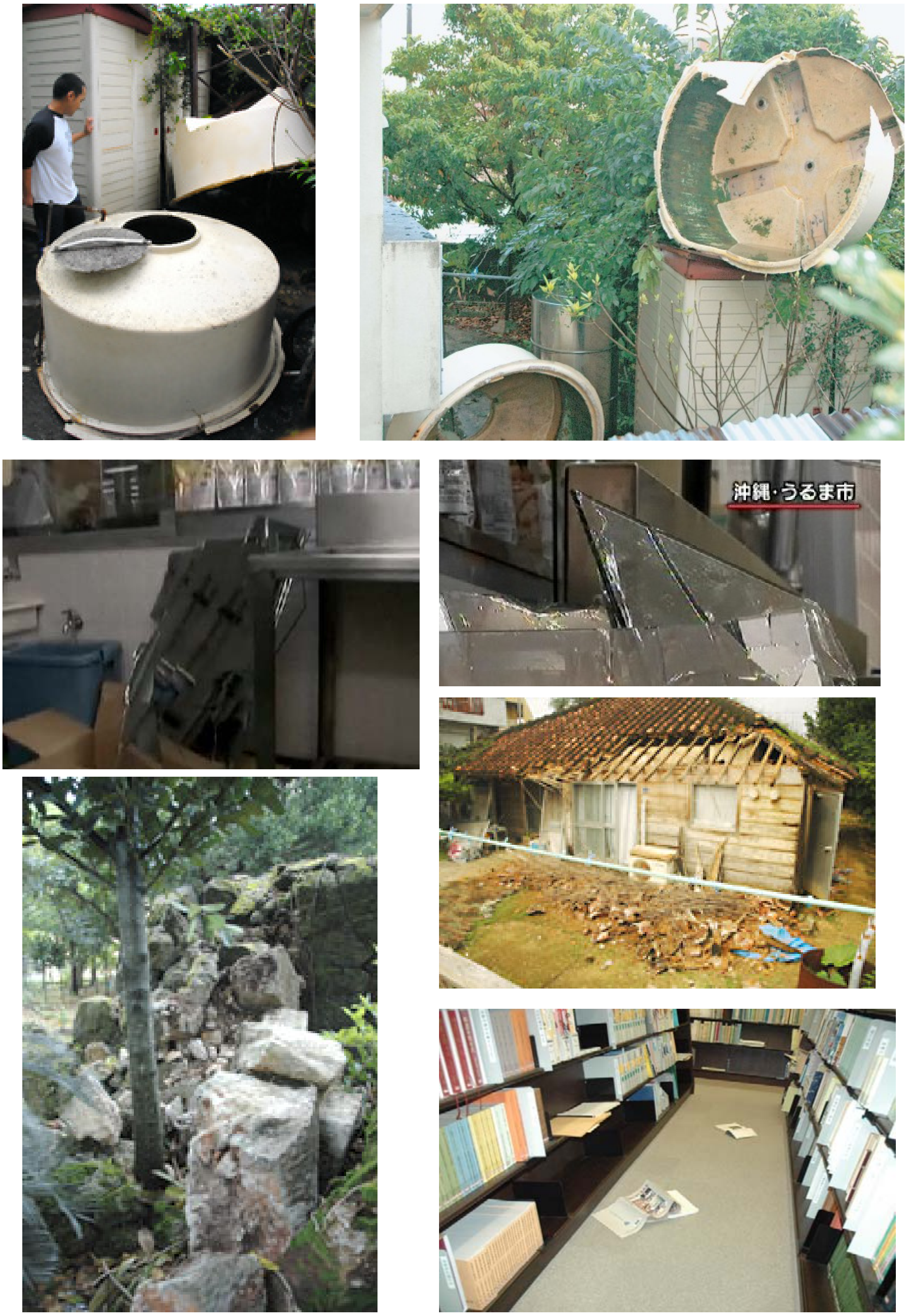


Figure 18: Some examples of damage compiled from mass media

The collapse of some of castle walls at Katsuren Castle, which is designated as a world heritage site, occurred. The castle is located over a hill in Uruma City and the nearest strong motion station of the K-NET strong motion network is Gushikawa. The NW corner of the castle wall with a height of 4m collapsed and there were numerous dislocations blocks and rotation of blocks in the castle as seen in Figure 19.

Figure 19: Collapse of the castle wall and dislocation or rotation of blocks and walls

The authors carried out a series of analyses using the acceleration records at Chinen and Gushikawa strong motion stations of the K-NET strong motion network. The typical size of the blocks ranges between 50 to 60 cm as seen in Figure 20. The authors used their method (Tokashiki et al. 2008) to back-analyze the collapse of the wall using the strong motion records at Gushikawa and Chinen. The wall is stable against toppling mode for strong motions at Gushikawa and Chinen. If the records taken at Gushikawa are used, the relative sliding can not be greater than 10cm, which implies that the wall should be stable although some slip might take place. However, if the records taken at Chinen are used the relative sliding can be greater than 60 cm for $\theta = 5^o$, which exceeds the half size of the block and this implies that the wall should collapse (Figure 21). The bulging of the wall and inclination of the foundation rock strongly supports that this condition would be prevailing at the location of the collapse. As the castle is situated on the top of the hill, it is likely that ground motions were amplified.

Figure 20: Close-up views of the collapsed wall and typical rock block

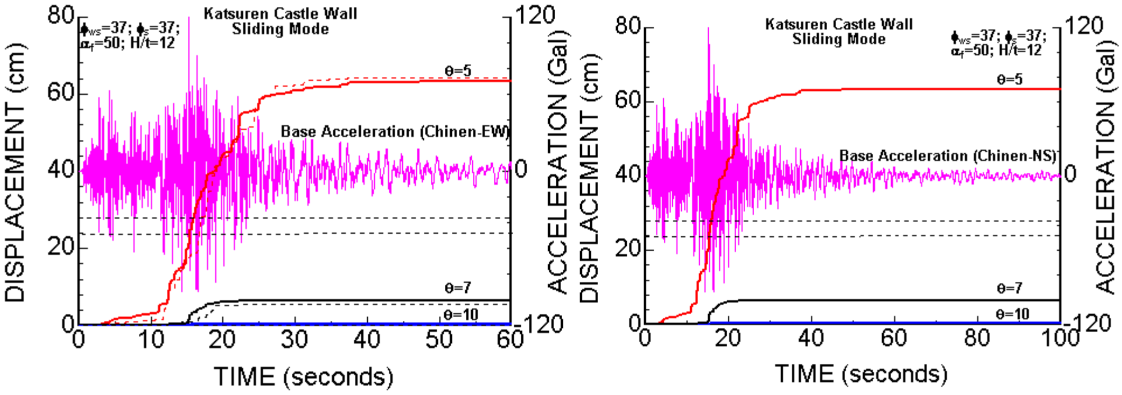


Figure 21: Sliding responses of the castle wall for Chinen record.

9 GEOTECHNICAL DAMAGE

Slope failures occurred in Nanjo City and Nakagusuku (Figure 22). The authors also found that embankment of roads to Nakagusuku Castle were also partially failed (Figure 23).

Figure 22: Slope failure in Nanjo City (from mass media)

Figure 23: Partial failure of road embankment near Nakagusuku

10 TSUNAMI

The character of the earthquake was strike-slip faulting with a small thrust component. As expected from the character of the earthquake, tsunami is very unlikely. The earthquake caused very small tsunami waves. The highest tsunami wave was observed in Nanjo City and Minami-Daito island after about 15 minutes. The tsunami wave height was about 10 cm in Nanjo City while it was much less in Minami-Daito Island. Figure 24 shows the tidal wave observations at several observation points.

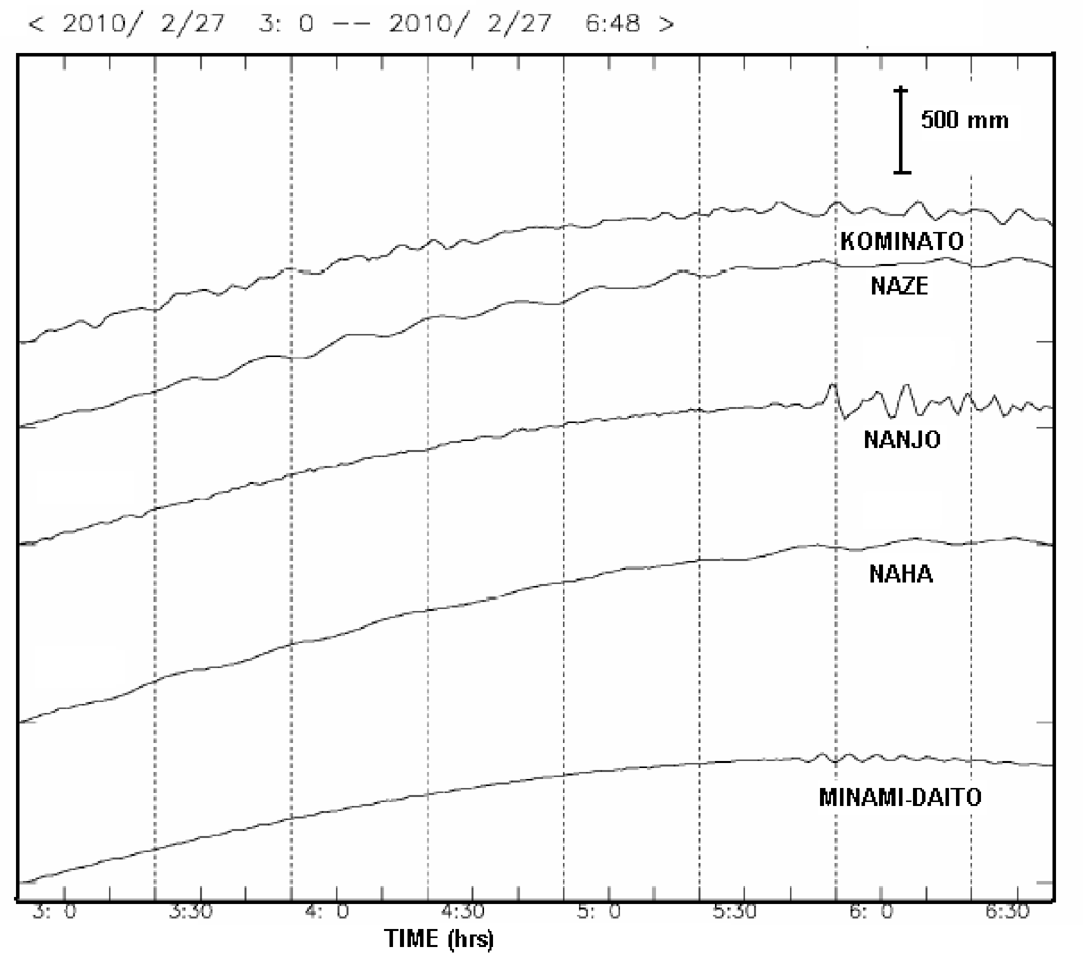


Figure 24: Tidal wave records at several ports in the earthquake-affected area

11 EARTHQUAKE EARLY WARNING SYSTEM

Japan Meteorological Agency introduced a new system of early warning system for earthquakes. Figure 25 shows the warning time around the epicenter issued for the 2010 Off-Okinawa Island earthquake. The system was successful for issuing warnings for the given specified conditions. Nevertheless, this system was of no use for people in the close vicinity of the earthquake epicenter, who were waken up by the intense ground shaking and falling objects. Although the system may be usefull for stopping the operation of large industrial plants, power plants and trains and roadway traffic in areas with a warning time period of more than 10s, it is practically useless for people, who were directly hit by the earthquake.

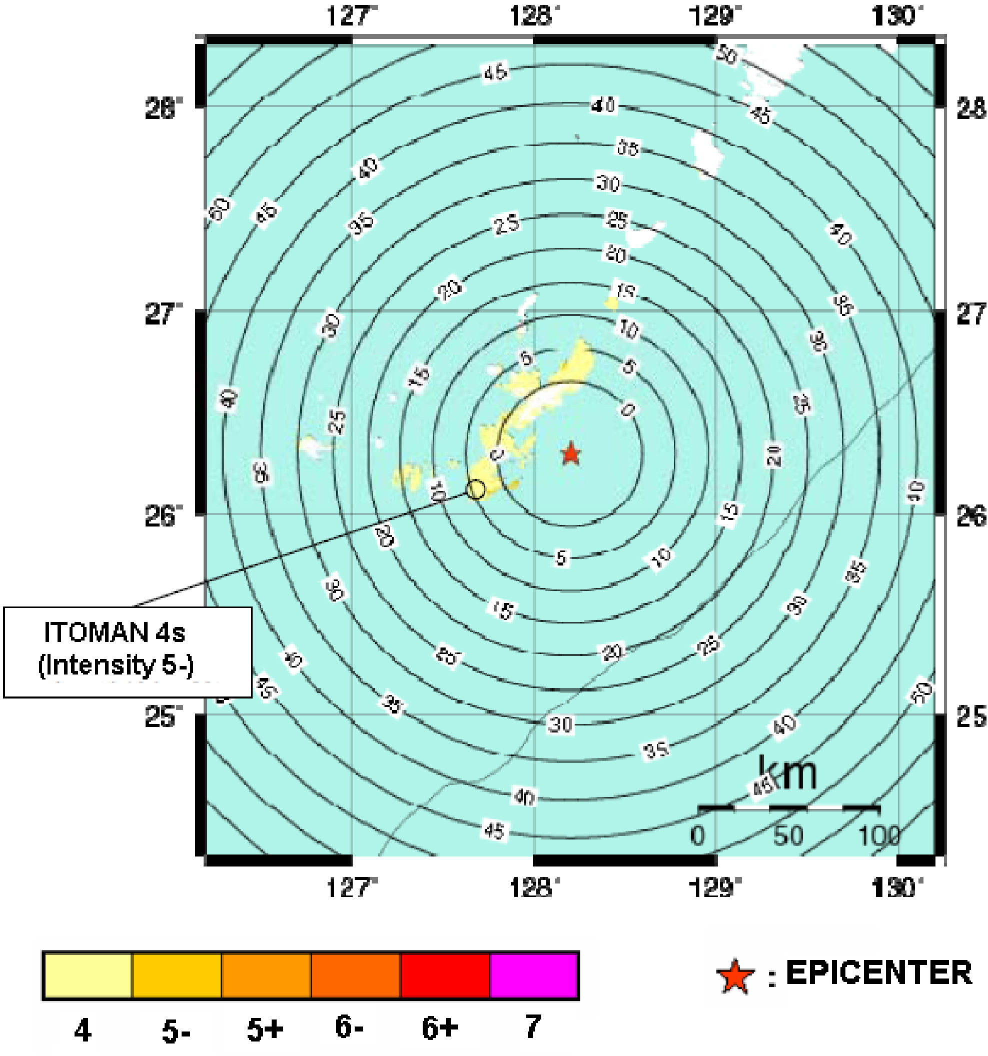


Figure 25: Warning time contours around the earthquake epicenter

12 CONCLUSIONS

Although the Ryukyu Archipelago is a seismically active part of the world, the general impression is that the Archipelago is not seismically active. The earthquake on 2010 Feb. 27 showed that the importance of the consideration of seismicity in Ryukyu Islands. As the earthquake was at least 90 km away from the populated areas, the ground motions were that high to cause major damage. However, castle walls are collapsed, toppling of water tanks, rupture of water pipes and embankment and slope failures occurred. There are many stone masonry historical remains in Ryukyu Islands and they are very vulnerable to earthquakes as seen in Katsuren Castle remains.. The seismic stability of these masonry structures should be re-evaluated.

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