

Interplate coupling in the Ryukyu Trench: possibility of large interplate earthquakes and mega-tsunamis

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Abstract

Although the seismic coupling is assumed to be only 5 % along the Ryukyu Trench, the mega-tsunamis occurred repeatedly in the Ryukyu Trench. The source of 1771 April 24 Yaeyama tsunami was the latest interplate earthquake which occurred at the south of Ishigaki Island, south Ryukyu Trench. The recurrence interval of the mega-tsunami in the Ryukyu Trench was about 500 years from ages of the coral fossils which brought from reef to land. However, the displacements associated with the back-slip cannot be detected in the GPS station in the Ryukyu arc if the coupled zone is limited near the Trench. To detect the inter-plate coupling near the central Ryukyu trench, the GPS/acoustic seafloor observation had been started. This measurement system contains two main tasks: precise acoustic ranging between a ship station (observation vessel) and seafloor transponders, and kinematic GPS positioning of observation vessels. The seafloor reference point was set at about 33 km landward from the axis of the Ryukyu trench (southeast of Okinawa Island). A set of three acoustic transponders has been installed on the seafloor, at a depth of about 2900m. The coordinates of the seafloor benchmark were calculated using the least-squares technique; this technique minimizes the square sum of acoustic travel-time residuals. The result shows that the benchmark moved to northwest direction for two years at a rate of 4 cm/yr relative to the Amurian plate. Since the benchmark would move south direction at a rate of 2 cm/yr if the interplate coupling rate is weak, this movement shows that the coupled zone is distributed near the Trench. The estimated width of the interplate coupling area is about 50 km from the Ryukyu trench. The results also show that the length of the coupled area is over 50 km. Since the calculated displacements are not sensitive to the change in the length of the coupled area, the accurate length is uncertain. The observation suggests that the coupled zone exists near the Ryukyu Trench. This can cause magnitude 8 class earthquake if length of the coupled zone is over 100 km. The coupled zone near the Ryukyu Trench would be the source of historical mega-tsunami which occurred repeatedly at an interval of 500 years, and it would cause large interplate earthquakes and mega-tsunami in future.

1. INTRODUCTION

The Ryukyu Trench is a convergent plate boundary. The Philippine Sea plate is subducting at a rate of 82 mm/yr in the central Ryukyu Trench (Seno, 1993). The seismic coupling, which is defined by the ratio of the seismic slip rate estimated from the cumulative seismic moment of large interplate earthquakes to the relative plate velocity, is 5 % in the Ryukyu Trench (Peterson and Seno, 1993).

The Ryukyu Trench had been absence of large historical earthquakes: few earthquakes whose magnitudes are over 6.0 had recorded since 1600 (Utsu, 1979). An exceptional event was the 1771 Yaeyama earthquake. The magnitude of the earthquake was estimated as 7.4 from the distribution of seismic intensity (Usami, 2002) (Fig. 1). The maximum runup height of the tsunami reached 30 m in an island of the south Ryukyu arc [Nakata and Kawana, 1995]. The inundation area of the tsunami reached 1~3 km inland at Tarama island, where is circular island whose diameter is 4.5 km and has plateau-like topography (average heights was about 10 m) (Fig. 2). The magnitude estimated from the distribution of the tsunami runup heights was 8.5 (Abe, 1999). The magnitude estimated from the tsunami runup heights was extremely larger than the magnitude from the seismic intensity distribution. Recently, for the cause of the earthquake, the interplate earthquake near the southern Ryukyu Trench was proposed from the numerical simulation of the tsunami (Nakamura, 2009a) (Fig. 1). The traces of the mega-tsunamis before 1771 were shown from the boulders of the coral which were moved from the reef to land by mega-tsunamis.

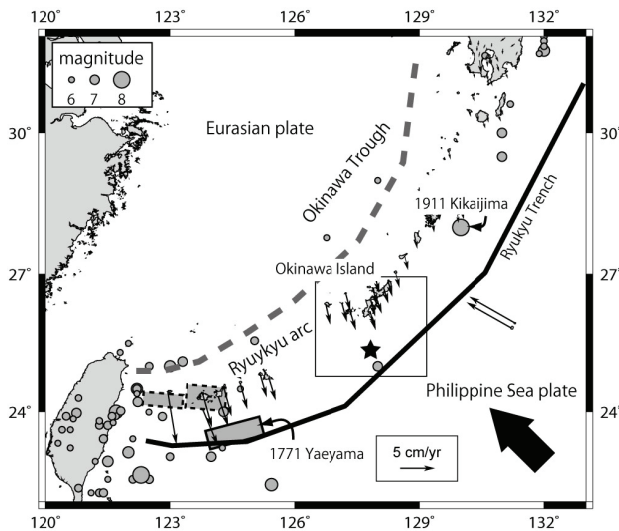


Fig. 1: Plate tectonic setting of Ryukyu Trench region. Arrows show the GPS stations in the central and south Ryukyu arc. Circles show the epicenters of historical earthquakes whose magnitudes were over 6.0 (Utsu, 1979). The star shows the position of the benchmark in this study. Rectangles with dotted lines show the faults of slow slip events (Heki and Kataoka, 2008; Nakamura, 2009a). Rectangle show the fault of the 1771 Yaeyama tsunami (Nakamura, 2009b).

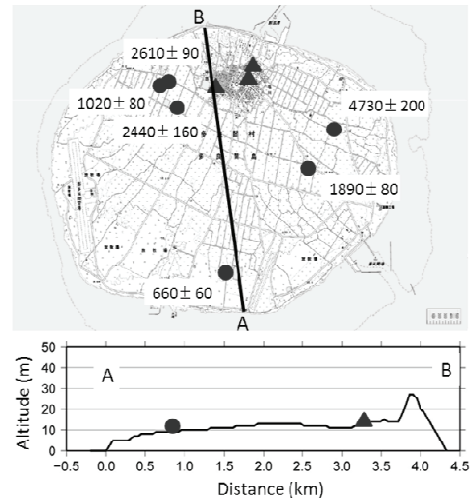


Fig. 2: (top) Inundation area of the 1771 Yaeyama tsunami in the Tarama Island. Triangles show the inundated houses. Circles show the tsunami boulders. Numbers show the age of the coral fossil on the boulders. (bottom) vertical cross section of Tarama Island.

Although the seismic coupling is weak from 100 years large earthquake activity along the Ryukyu Trench, historical records suggest that large interplate earthquakes generated mega-tsunami, which attacked the islands of the south Ryukyu arc. This implicates the strain accumulation in the Ryukyu

plate boundary zone. However, the detection of coupled zone has some difficulties. Since the GPS stations of the Islands arc region are aligned along the trench, the horizontal deformation along the trench can be detectable. However, since the baseline length perpendicular to the trench is short, the horizontal deformation perpendicular to the Trench is difficult. From the 2D numerical simulation, the estimated horizontal velocity is less than 7 mm/yr far from the 100 km from the Trench axis when the convergence rate of the plates are 100 mm/yr, the coupled zone start from trench axis, and its width is 50 km.

Since the daily positions have some ambiguities, it is difficult to detect deformation by the coupled zone using GPS measurement whose locations are restricted to the island arc. The deformation of the overriding continental plate by the coupled zone near the Trench can be detected using the seafloor geodetic technique.

2. METHODS

The observation system for seafloor crustal movement measurement comprises of two main components: 1) the precise acoustic ranging between a ship station (observation vessel) and the sea-bottom transponders, and 2) kinematic GPS (Global Positioning System) positioning of the observation vessels (e.g., Fujimoto et al., 1995; Spiess et al., 1998) (Fig. 3). One sea-bottom benchmark is composed of three sea-bottom transponders. The azimuth, roll, and pitch of the ship were monitored by using the optical gyro compass and computed the relative position of transducer against the GPS antenna.

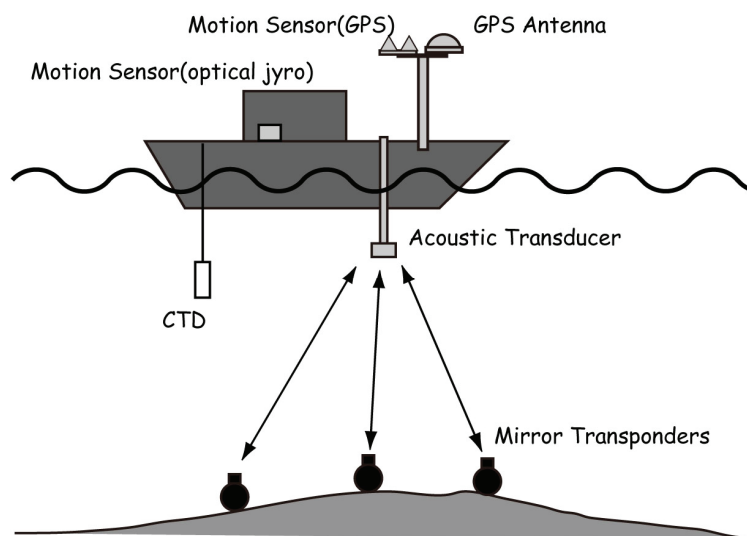


Fig. 3: Schematic illustration of the GPS-acoustic geodetic system.

The sea-bottom benchmark is installed at Ryukyu Trench (Fig. 1). The water depth at the site is about 2900 m, and the horizontal separation distance of the sea-bottom transponders is about 2000 m. The

common acoustic ranging signal, with a carrier wave frequency of 12.987 kHz and a signal length of 14.322 ms, is transmitted every 10–12 s from the transducer at the ship station to all the sea-bottom transponders. The sea-bottom transponder returns the same signal to the ship station. The waveforms of the retuned signals are recorded and digitized at a sampling rate of 500 kHz by a 16-bit A/D converter. The travel times of the acoustic signals are measured precisely by means of the cross-correlation computation, and accuracy of the travel times are checked manually. The round-trip traveltimes were translated into the distance between the transducer and the transponders.

The positions of the ship transducer at the timing of signal transmission and receiving are determined through the post-processing kinematic GPS positioning technique employing the IGS (International GNSS Service) precise ephemeris. The GPS signals are recorded every 0.2 s using dual-band GPS receivers at both the ship and onshore GPS reference stations (Fig. 4). All the GPS receivers are equipped with the 10 MHz external frequency reference unit to correct the internal clocks. The coordinate of sea-bottom benchmark, defined as the center of the triangular configuration composed of three sea-bottom transponders, is calculated using the least-square technique, which minimizes the square sum of travel-time residuals (Ikuta et al., 2008). During the observations, the temporal variation in sound speed was one of the major causes in the decrease of seafloor positioning accuracy. To address such concern, CTD (Conductivity, temperature, and Depth) measurements are performed several times during each observation. The temporal variation in sound speed is corrected in the calculation procedure of locating the sea-bottom benchmark (Ikuta et al., 2008) on the basis of the CTD measurement data.

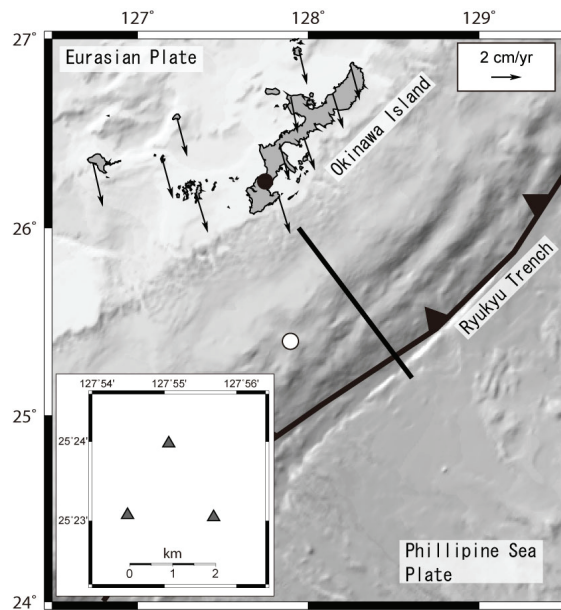


Fig. 4: Location of the benchmark unit (star) at central Ryukyu Trench and onshore reference stations for kinematic GPS positioning (solid circle). Solid arrow shows the horizontal velocity at the GEONET GPS network. The enlarged map on the bottom left shows the location of the seafloor transponders.

The seafloor deformation monitoring started in January 2008 and we repeatedly observed five times until November 2009. The onshore GPS reference station is installed at 80 km relative to the sea-bottom benchmark. The observation vessel was “*Tonan-maru*” of Okinawa Prefectural Fisheries and Ocean Research Center, Japan. The usual duration of acoustic ranging at one observation was about 36 hours.

We could follow arbitrary trajectories while sending and receiving signals at the observations of January 2008 and February 2008. The *Tonan-maru* could not follow arbitrary trajectories during measurements at the observations of July 2008, May 2009, and November 2009 because it could not send or receive signals while running owing to loud screw noise. We let the *Tonan-maru* drift with the wind and current for several hours while sending and receiving acoustic signals. Each drift resulted in an observation line and was repeated until the trajectories covered a suitable area. The rms was 70micro-second.

3. INTERPLATE COUPLING AREA

We estimated the horizontal velocities of the benchmark by linear interpolation. The obtained horizontal velocity is 30 ± 19 mm/yr to westward and 35 ± 23 mm/yr to northward (Fig. 5). The benchmark moved to 309° direction at the rate of 46 mm/yr relative to the Amurian plate (Fig. 6). We estimate the position of the coupled area in the central Ryukyu Trench. First we calculated the motion of the central Ryukyu arc. The crustal movement of the Ryukyu arc is described as the combination of the block motion and the deformation by the interplate coupling. For the estimation of the motion of overriding plate, we employed the daily position results of GPS network in the Okinawa Island and surrounding Islands by the GSI during the 8-years period between the January 1, 2002 and December 31, 2009. Horizontal velocities were calculated from the time-series analysis for the GPS stations with removing the annual and biannual components. The coseismic displacements were not observed in this region during this period. The velocities of the GPS stations are converted to the coordinate of the Amurian plate. The observed horizontal velocities of the GPS stations in the central Ryukyu arc were 23–30 mm/yr to $160\text{--}170^\circ$ direction relative to the Amurian plate. The predicted motion of the central Ryukyu arc on the Amurian plate was 2.7 mm/yr to 290° direction relative to the Amurian plate using GSRM 1.2 model (Kreemer et al., 2003). The difference in the motion between the Amurian plate and the central Ryukyu arc is originated to the rifting of the Okinawa Trough.

Then we estimated the motion of the central Ryukyu arc using the block model. We adopted a rigid block rotation model for the motion of the central Ryukyu arc. In the Ryukyu arc, direction of the extension stress is along the arc (NE–SW direction in the central Ryukyu arc) (Kubo and Fukuyama, 2003). The block rotation and deformation model of the central Ryukyu arc has been estimated previously from GPS measurements (Nakamura, 2004). The estimated strain rate is of 18×10^{-9} strain/yr, which is dominant with extension strain parallel to the Ryukyu Trench. This corresponds to the velocity difference of 1.8 mm/yr per length of 100 km along the Island arc. Since the velocity difference by the extension strain is so small compared with the velocity error of the benchmark, we treated the motion of the central Ryukyu arc as a rigid body. The estimated Euler pole and rotation rate relative to the Amurian plate are 28.129°N , 135.027°E , and 3.53×10^{-8} radian/yr, respectively.

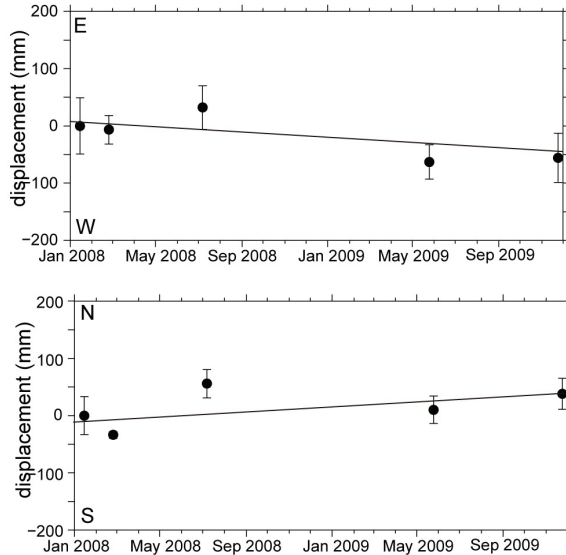


Fig. 5: Results of repeated measurements at the benchmark. In Figure 4a, the temporal variation in the horizontal coordinates of the benchmark unit relative to the Amurian plate is plotted for the following five observations. The lines show the liner-interpolated results for five observations.

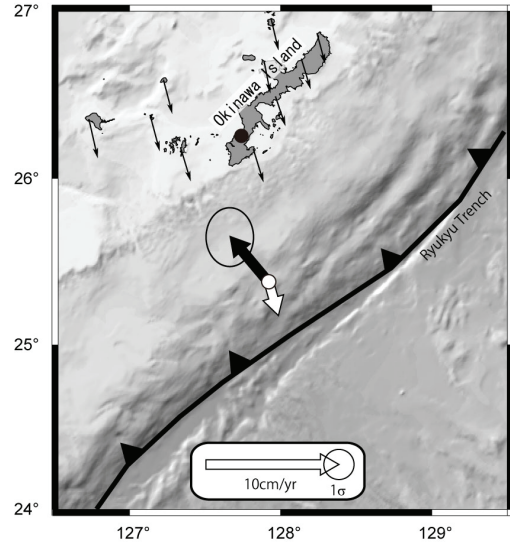


Fig. 6: Location of the benchmark unit (open circle) at central Ryukyu Trench and onshore reference stations for kinematic GPS positioning (solid circle). Open arrow shows the observed horizontal velocity at the benchmark. Solid arrow shows the estimated horizontal velocity at the benchmark from the central Ryukyu block model. The horizontal velocities are fixed to the Amurian plate.

Then we calculated the horizontal velocity at the benchmark near the Ryukyu Trench using the position of Euler pole and rotation rate of the central Ryukyu arc. The estimated horizontal velocities at the benchmark near the Ryukyu Trench were 29 mm/yr to 160° direction relative to the Amurian plate (Fig. 6). This suggests that the benchmark moves to south direction if the plate interface is not locked. However, the observed motion of the benchmark is northwest direction. This suggests that the plate interface is partially locked and the Ryukyu arc near the Ryukyu Trench is deformed by the back-slip.

Then we estimated the length and width of the coupled area. For the model of subducting plate, we adopted the result of refraction survey (Kodaira et al., 1996). The survey line passes about 40 km northeastward from the benchmark (Fig. 5). We set the dip of the subducting plate to 6° from the result of the refraction survey. The convergence of the Philippine Sea plate relative to the Amurian plate is 83 mm/yr to 300° direction (Kreemer et al., 2003) (Fig. 6). Since the central Ryukyu arc at the benchmark is moving to 160° direction at the rate of 29 mm/yr as mentioned above, the convergence of the Philippine Sea plate relative to the central Ryukyu arc is to 310° direction at the rate of 106 mm/yr.

To model the displacement by the interplate coupling, we adopted the back-slip modeling approach (Savage, 1983). The Interseismic back-slip by the coupled zone is the difference between continuous

steady state rigid-block motion along the plate interface and continuous aseismic slip along the plate interface downdip of the coupled zone. For the calculation of the displacements by faulting we employed the formula by Okada (1992).

We set the length of the coupled zone to 100 km, changed the width of the coupled zone to 30 km, 50 km, 70 km, and 90 km, and calculated the horizontal displacements by the back-slip (Fig. 7). We set the position of the half length of the coupled area to be the position of the benchmark. The top of the coupled zone is set to the Trench axis. The depth of down-dip edge of the coupled zone for the width of 30 km, 50 km, 70 km, and 90 km is 10 km, 12 km, 14 km, and 16 km from the sea surface, respectively. When the width of the coupling area is 30 km, the horizontal velocity is 9 mm/yr to 300° direction at the benchmark. This is smaller than the observed. For the widths of 50 km, 70 km, and 90 km, the calculated displacements are 35 mm/yr, 49 mm/yr, and 54 mm/yr, respectively. The directions of these cases are 330°. These are consistent with the observed value (46 ± 21 mm/yr). On the other hand, the calculated horizontal velocities (7–21 mm/yr) at the south Okinawa Island and in the vicinity of the Okinawa Island, which are slightly smaller than the observed ones (23–30 mm/yr) when the width of the coupled area is 90 km. These suggest that the horizontal velocities by the backslip could be detected by the GPS network when the width of the coupled area is over 90 km. Then we assumed that the width of the coupled area is between 50 km and 70 km. The depth of lower limit of the coupled zone ranges 12–14 km from the sea surface (Fig. 8).

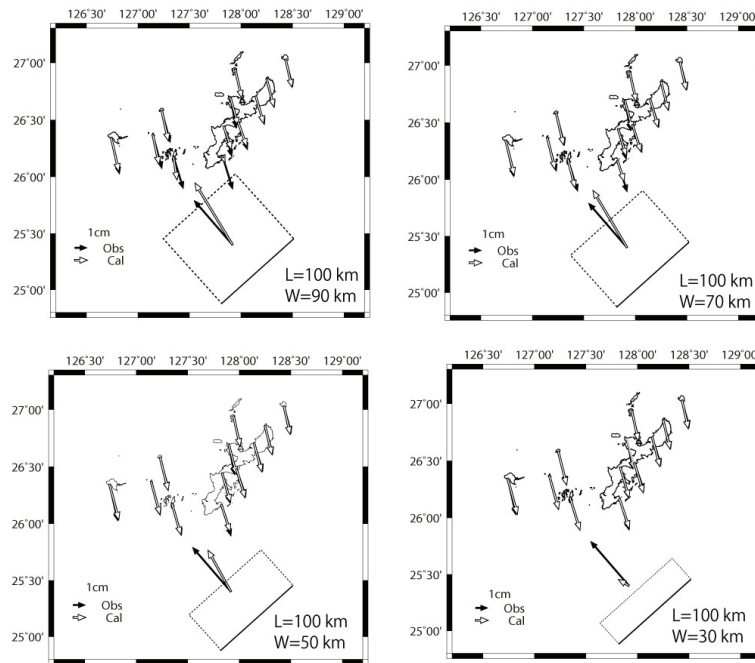


Fig. 7: Red and black arrows denote the observed and calculated horizontal velocity at GEONET GPS stations and the benchmark relative to the Amurian plate. Rectangles show the fault of the coupled zone. Solid lines show the top of the fault. Fault width is set to (a) 70 km, (b) 50 km, and (c) 30 km, respectively.

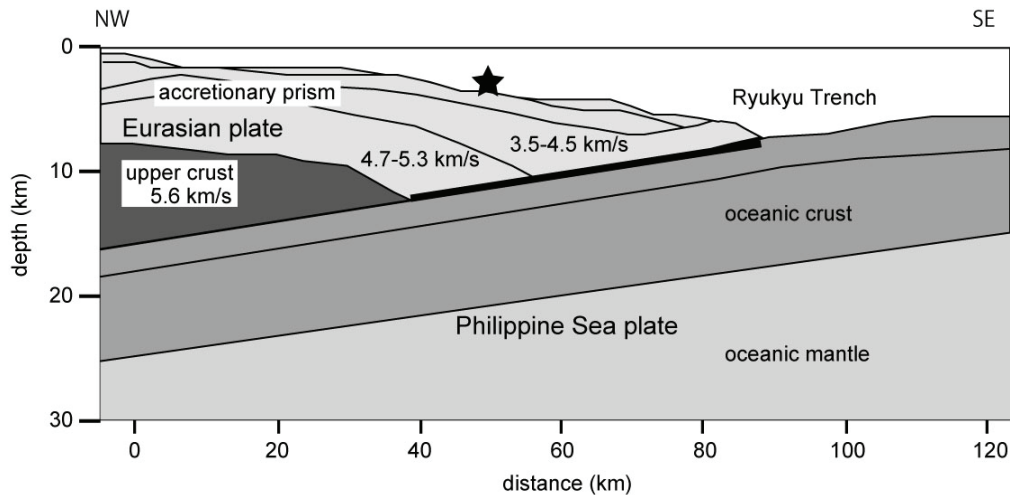


Fig. 8: Vertical cross section of the refraction survey at central Ryukyu Trench in the profile shown in Figure 4 (Kodaira et al., 1996). Numbers in the figure are P wave velocity. Thick line shows the estimated fault plane of the coupled zone with fault width of 50 km. The star shows the benchmark.

4. DISCUSSION

The updip and downdip rupture limits of great subduction thrust earthquakes were controlled by thermal structure (Tichelaar and Ruff, 1993]. From the data on the past great earthquake seismic limit for Cascadia, SW Japan, south Alaska and Chile, updip limit of seismic zone corresponds to the position where the thrust temperature reaches about 100 °C, that is, depths of about 4 km from sea surface. This temperature agrees with the phase transition from smectite to illite which occurs between ~100 °C and 150 °C (Pytte and Reynolds, 1989).

However this model is not consistent with the temperature model estimated in the central Ryukyu Trench. In the central Ryukyu Trench, the age of the subducting Philippine Sea plate is 50 Ma (Deschamps and Lallemand, 2002). Convergence rate of the Phillipine Sea plate to the Ryukyu arc is 106 mm/yr. Using the 1-D temperature model of the subduction area where plate age and convergence rate are similar, the temperature reaches to 100 °C at the depth of 10–12 km from sea surface for the plate age about 50 Ma (Oleskevich et al., 1999). Since observed coupling area is shallower than 12–14 km in depth in the central Ryukyu Trench, the phase transition of the clay minerals is excluded for the cause of the coupled zone.

The alternative model is that the coupled zone is distributed near the shallow part of the subduction zone when the pore pressure in the overriding continental lithosphere is low. The distribution of coupled zone is controlled by the pore pressure in the Hikurangi subduction zone, New Zealand (Fagereng and Ellis, 2009). When the pore pressure is in the state of hydrostatic, the brittle-viscous transition occurs significantly shallower than the near-lithostatic case. The interplate coupled zone continues from the Trench to depth of 10 km in the east of North Island of the New Zealand. The slow slip events occur at the depth of 10–15 km in the east of the North Island.

In this case, the continental lithosphere above the coupled zone is compressional stress regime, whereas the continental lithosphere above the stable sliding zone is extensional stress regime. The Ryukyu arc is in the extensional stage, which is shown as the rifting of the Okinawa Trough and trench-parallel extensional stress in the Ryukyu arc.

The distribution of the coupled zone in the Ryukyu Trench suggests that the inter-plate large earthquakes and tsunami would occur repeatedly in the Ryukyu Trench. The ages of the coral fossils on the tsunami boulders concentrate to several periods: about 200, 500, 1000, 2000, and 2500 years ago (Goto et al., 2010). This shows that the tsunami occurred repeatedly in the Ryukyu Trench.

5. CONCLUSION

We employed a GPS-acoustic measurement to monitor the seafloor deformation by the interplate coupled zone near the central Ryukyu Trench. The system consisted of kinematic GPS technique in the aerial region and acoustic ranging in the underwater region. The benchmark moved 30 mm/yr to west direction and 35 mm/yr to north direction relative to the Amurian plate. The calculated horizontal velocity at the GPS stations are consistent with observed ones when the width of the coupled zone is over 50 km.

The observed coupling area is shallower than 12 km in depth in the central Ryukyu Trench. The coupled zone at the shallow part of the plate interface is the unstable sliding of clay mineral on the higher pore pressure condition.

The traces of mega-tsunamis recorded in the historical records (old literatures and tsunami sediments) in the Yaeyama region suggest the mega-tsunami had been attacked in this area about 5 times for 3000 years. The interplate coupled zone near the Ryukyu Trench would be the cause of repeating mega-tsunami in this subduction zone.

6. REFERENCES

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