1) Interplate coupling along the central Ryukyu Trench inferred from GPS/acoustic seafloor geodetic observation

Mamoru Nakamura

University of the Ryukyus

The Ryukyu trench is a major convergent plate boundary where the Philippine Sea plate is subducting at a rate of about 8 cm/yr. Large earthquakes have not been reported along the Ryukyu subduction for the last 300 years. Because the rate of release of seismic moment in the Ryukyu Trench over the last 80 years is 5% in consideration of the plate convergence rate, interseismic coupling in the trench is assumed to be weak.The GPS measurements by Japan Geographical Survey Institute also show the southward motion of Ryukyu arc, which is due to extensional rifting of Okinawa Trough. Backslip by the interplate coupling between the subducting Philippine Sea plate and the overriding Eurasian plate cannot have been detected in the GPS network along the Ryukyu Islands.

We have started the GPS/acoustic seafloor observation to detect the inter-plate coupling in the central Ryukyu trench. For this measurement, we used a system capable of performing 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 transponders are placed to form a triangular. Five campaign observations were carried out for the period from January 2008 to November 2009. Each epoch consists of three observation days. 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 RMS of travel time residuals for each campaign analysis is about 70 micro-seconds.

The result shows that the benchmark moved to northwest direction for two years at a rate of 6 cm/yr against the Okinawa Island. Then we calculated the width of interplate coupling area using observed movement of the benchmark. The estimated width of interplate coupling area is 30–50 km from the Ryukyu trench. This result suggests that the interplate coupling occur up-dip of the seismogenic zone in the Ryukyu subduction zone.

2) Foreshock Characteristics in Taiwan: Potential Earthquake Warning

Cheng-Horng Lin

Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan

Whenever a felt earthquake occurs, people may ask whether a larger earthquake will come nearby soon or not. If the result comes out with a positive, then the previous felt earthquake might be considered as a valuable foreshock for the short-term earthquake prediction. How to identify foreshocks before a major earthquake is one of the important works in short-term earthquake warning. Abundant earthquakes in the Taiwan area might provide a good opportunity for investigating general foreshock characteristic as well as the potential earthquake warning. Here 10 earthquake sequences with significantly felt foreshocks (ML 4.0) are identified from an examination of 161 earthquakes (ML   5.0) in the Taiwan area in a period of 15 years. In addition to addressing larger magnitudes (ML 4.0), the criteria for selecting foreshocks have considered that (1) the earthquakes occurred within a distance of 15 km and 5 days to the main shock and (2) focal mechanisms of the main shock and foreshocks were generally consistent. The results show felt foreshocks often occurred at the strongly heterogeneous crust, particularly along the convergent zone between the Eurasian and Philippine Sea plates. Besides, the absence of clustered earthquakes after some large foreshocks may be considered as a criterion to distinguish felt foreshocks from the main shock for improving our ability of earthquake warnings in the Taiwan area.

3) Creeping distribution on the Longitudinal valley fault at Yuli area estimated by precise leveling survey, Southeast Taiwan 2

Masayuki Murase[1], Nobuhisa Matta[2], Kazuhiro Ozawa[2], Jui-Jen Lin[3], Matsumura Yoshihiro[2], Hsien-Hsing Hsieh[4], Hui-Yuan Fang[3], Wei-Fang Sun[3], Wen-shan Chen[5], Cheng-Horng Lin[3], Naoji Koizumi[6]

1. Nihon University
2. Nagoya University
3. Academia Sinica, Taiwan
4.National Central University, Taiwan
5.National Taiwan University, Taiwan
6. AIST, Geological Survey of Japan, Active Fault and Earthquake Research Center

Longitudinal valley faults in eastern Taiwan are commonly considered collision boundary between the Eurasian plate and Philippine sea plate. Yuili fault, one of the active segments of the longitudinal valley faults, is reverse fault with east dip.

We established about 30km leveling route from Yuli to Changbin to detect the vertical deformation in detail (Murase et al. 2009). The installation interval of benchmarks near the fault area is about 100 m. Others were installed every about 300m. Compared to the 2km installation interval of the Geological Survey Institute, Japan for making the map, installation interval of our survey is dense. The precise leveling surveys were conducted in August 2008, August 2009 and August 2010.

The overview of the deformation detected in the period from 2008 to 2009 is as follows. It was detected about 2.7 cm uplift, referred to the west end of our route, at about 2km region across the fault. Uplift was gradually-reduced with the distance from the fault, and was 1.5 cm at the east coast. In the observation period, there is no significant earthquake in Yuli fault. It suggests the detected deformation as a cause for the creep motion of the Yuli fault. The deformation detected in the period from 2009 to 2010 denotes the same tendency and rate of that from 2008 to 2009. It suggests that the creeping occur at the same location of the fault with constant rate.

From this result, the preliminary creep distribution was estimated in the Yuli fault. We adopted a two-dimensional reverse fault model to estimate the creep distribution. Chen et al. (2010) discussed shallow part of the fault geometry using the seismic reflection survey in Yuli fault.
Since the route of the seismic reflection survey was located near our leveling route, we adopted the shallow part of the fault geometry that was detected by using the seismic reflection survey.
The deeper part of the fault geometry was optimized using the genetic algorithm in order to conform to the leveling data. The goodness of the fit of the examined models is determined on the basis of Akaike's information criteria (AIC).

In August 2010, we installed more three routes in Yuli and conducted them. Since it was first time to conduct the leveling survey in these new routes, we will be able to detect deformations next year. In this symposium, we will present an overview and our purpose of our observation in the new routes.

4) Seafloor geodetic observation in Taiwan

M. Ando[1], S.-B., Yu[1], R. Ikuta[2], C.-H. Lin[1], H.-Y. Chen[1], and Y. Tu[1]

1: Institute of Earth Sciences, Academia Sinica, Taiwan
2: Department of Geosciences, Shizuoka University, Japan
Key words: seafloor geodesy, KGPS, transponder, crustal deformation, tectonics, Taiwan

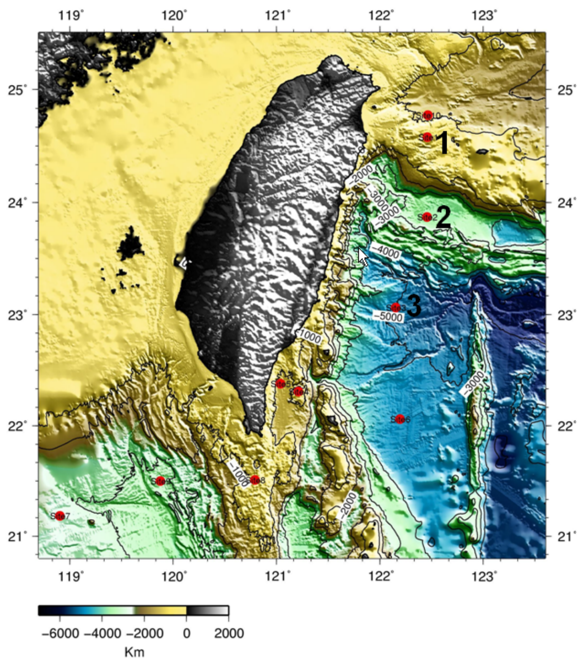

Fig. 1 Map showing Sites 1,2 and 3, and other planned seafloor geodetic observation sites.

The island of Taiwan is located at the junction between two subduction systems. East of Taiwan, the Philippine Sea plate (PH) subducts northward beneath the Eurasian plate (EU) along the Ryukyu subduction system. While south of Taiwan, the plate including South China Sea subducts eastward beneath the Philippine Sea plate along the Manila trench. The convergent rate between the Philippine Sea plate and the southeast Eurasian continental margin is about 82 mm/yr in the azimuth of 310 deg as determined by the GPS observations.

Despite the analysis of currently available GPS observation data and the plate motion models, we still have a very unclear picture of the coupling along the subduction zone fronting the Ryukyu trench and Manila trench. Since Taiwan and the Okinawa islands are located more than 50-100 km from the trench axis, the crustal deformation from plate coupling would have significantly diminished inlands. Thus, the present question regarding the coupling conditions of the Ryukyu and Manila subduction zones cannot be resolved based on currently available data. It is necessary to obtain crustal deformation data closer to the trench axis where the coupling effect is large enough to distinguish between the two cases – decoupled or coupled subduction.

This study proposes the use of the seafloor crustal deformation observation to solve this issue effectively. The geodetic survey was performed at three sites (Fig.1). Observation periods are summarized in Table 1 wherein the vessel used at each survey is also shown:

Site 1: This site is located east of Ilan and lies on a shallow ridge extending from the islands of the Ryukyu arc. The average depth is about 1,300m. Three transponders of Codes 3, 4 and 5 were deployed during the first survey. Unfortunately, Code 5 did not respond quite well after it was launched to the ocean bottom. For this reason, the transponder Code 9 was deployed during the second survey. In addition Code 4 was replaced by Code 12 in 2010 because of the exhaust of its battery.

Site 2: This site is located east of Hualien and lies on the flat basin at depths about 3,800m in the upper plate of the Ryukyu trench. Transponders Codes 6 and 7 were deployed at the first survey while the transponder Code 8 malfunctioned before deployment. The transponder Code 8 was repaired and subsequently deployed during the second survey. During the first observation, a buoy was used that has three GPS antennae and an acoustic transducer. Their signals were transmitted through cables linked to receiving units installed on the vessel.

Site 3: This site is located east of Chenggong and in the flat basin at depths about 4,800m in the Philippine Sea plate. Transponders Codes 10, 11 and 13 were deployed at the first survey. The buoy was also used for the first survey.

The acoustic ranging and KGPS data were analyzed with the software of OCDASAN (Ikuta et al., 2008) to estimate the location of the seafloor units. Unfortunately, the location error is still as large as 10 to 30 cm, which is significantly higher than those obtained by Ikuta et al. (2008). We have been investigating reasons behind the large error values. It is likely that three major error sources must be considered: 1) picking errors of acoustic signal arrivals, 2) KGPS location error and 3) relative positioning errors between sensors (the GPS antennae and the acoustic transducer) on the observation vessels.

One of the results with a relative higher accuracy was obtained from the observations between May and July 2009 at Site 1 as shown in Fig.2. However, this relative motion is within the range of errors and not tectonically significant. Further studies must be focused on this problem in the next stage.

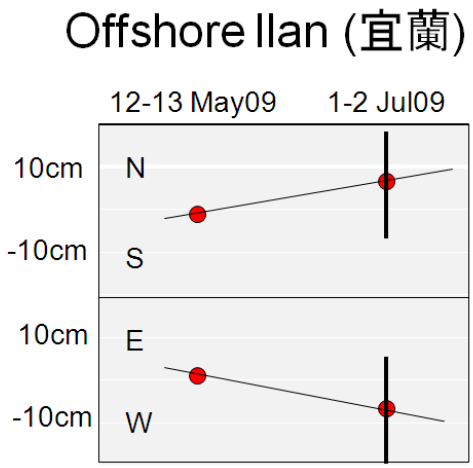

Fig. 2 Relative horizontal displacement at Site 1 east of Ilan observed in July 2009 with respect to the observation on May 2009. The error bars (vertical thick lines) show a deformation rate of the triangular array of three transponders.

Table 1 List of observation sites and dates of surveys

Site	Location	Depth	1st Survey	2nd Survey	3rd Survey
Site 1	Off Ilan	1,300m	2-3Oct2008 (Fishing boat A)	12-13May2009 (Fishing Boat A)	19-20JUN201 (OR2, Buoy)
Site 2	Off Hualien	3,500m	18-24 Oct2008 (OR1, Buoy)	11-12Mar2009 (Whale Watching Boat A)	9-10SEP2009 (Whale Watching Boat B)
Site 3	Off Chenkong	4,800m	3-8 Sep2009 (OR3, Buoy)	10-13Nov2009 (OR3)	

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5) New Continuous Radon Monitoring in Nakaizu Observatory

Fumiaki Tsunomori[1] and Shigeki Tasaka[2]

1.Graduate School of Science, University of Tokyo

2.Information and Multimedia Center, Gifu University

The radon monitoring system in Nakaizu Observatory was improved for a continuous absolute value measurement. In order to demonstrate a mechanism of the preseismic phenomena of the radon concentration in groundwater, two important technical progresses are required. The first is to develop a robust radon monitor for a groundwater observation. Though a semiconductor-type radon counter provides a highly sensitive measurement, but radon concentrations measured are strongly affected by the humidity of sample gases. For a groundwater radon monitoring, a scintillation method is appropriate because this method ensures a stable radon concentration for the sample humidity and temperature. The second is to conduct a precise gas extraction. According to Henry's law dominating the gas behavior in water, dissolving radon was extracted by mixing a radon free air with a groundwater sampled. Most important parameters are flow rates of the groundwater and the radon free air, and temperature of the radon free air must be conformed to that of the groundwater. We will discuss the stability of the handcrafted radon counter and the extraction efficiency of radon gas from groundwater.

6) Chemical monitoring of the Atotsugawa Fault zone by using new designed QMS

Hidemi Tanaka[1],Masaki Murakami[2],Fumiaki Tsunomori[1],Koji Shimada[3]
and Masaaki Sugimoto[1]

1.Department of Earth & Planetary Science, Graduate school of Science, University of Tokyo
2.Department of Geology and Mineralogy, Graduate school of Science, Kyoto University
3.JAEA, Fast Breeder Reactor Research and Development Center, Monju

Recent development of crustal monitoring system, using accurate seismometers array enables us to recognize slow slip events along the plate boundary deep beneath the crust (Obara, 2002). Fluids dehydrated from hydrous minerals, such as chlorites and mica clay minerals have been believed to behave as one of the most important lubricants for driving these events (Katsumata and Kamaya 2008).

In contrast, mechanical and/or chemical signals from seismogenic zone of the inland earthquakes are hardly detectable because of lower speed of accumulation of stress, crustal complexity and distance from surface of the crust to the seismogenic depth.

The fluid climbing up from deep crust through large fault zone would have a potential to be excellent sensors for monitoring the crustal conditions at inland earthquake area.

Many researchers have executed fluid monitoring to detect chemical signals of earthquake precursors. Most of the results were, however, in doubt and not deterministic, because of lack of reasonable interpretation.

After penetrating Atotsugawa active fault zone by drilling, we have been developing gas-monitoring system using QMS, and recently system becomes gradually stable. In this presentation, we introduce outline of our gas monitoring system, GROWDAS.

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7) Analysis of strain anomalies by strainmeters in Taiwan

Jyr-Ching Hu[1], Chih-Yen Chen[1,2], and Chi-Ching Liu[3]

1. Department of Geosciences, National Taiwan University, Taiepi, Taiwan
2. Central Geological Survey, MOEA, Taiwan
3. Institute of Earth Sciences, National Taiwan University

Taiwan is located along the boundary between the Philippine Sea plate and the Eurasian plate, one of the most active plate boundaries in the world. The oblique collision between these two plates drives the mountain building and high seismic activity in this area. Over 20 of borehole strainmeters, both Gladwin tensor strainmeters and Sacks-Evertson dilational borehole strainmeter (one and three components), were installed over the island. Slow earthquakes over one or two days of duration were observed several times during 2004 for a network near the plate boundary, and most of them are identified to be triggered by the typhoons. For the largest event on December 3rd, 2004, 3 episodes of slip in this event are identified, and model accordingly, looking for solutions with sources on the fault indicated by the seismicity. All changes are very slow so we use static solutions for deformation due to a buried shear dislocation and generate a time series by successive calculations for a model with slow propagation of the rupture. This very simple model gives a remarkably good fit to the data. Importantly, we can find a reasonable and simple model for a slow earthquake that satisfies the data. Permanent GPS observations over the same area are used to perform the strain time series, and compared with the strainmeter observations. Strainmeter data showed slower strain accumulation than the GPS strain during 2004 while several slow events occurred, and keep similar accumulating rate during 2005-2007. For a strainmeter network (3 stations) near a reservoir in southern-west Taiwan, the orientations of major strain axis of all 3 sites keep stable during 2004 and 2006.5-2007.5, but experienced a rotation of 90 degree during 2005-2006.5. These occurred on all 3 stations, and probably a process of the exchange of major and minor strain axis. The Mw 7.9Wenchuan earthquake of 12 May 2008 was the most devastating earthquake in China in the past 30 years in terms of human losses and property damage. The main shock ruptured with about 9 m of slip along the Longmen Shan fault zone located the boundary of Tibetan plateau and Sichuan basin. About 5-6 m maximum vertical offset was identified in the field survey after the earthquake. Nine borehole strainmeters installed at western Foothills in Taiwan orogenic belt captured significant step-like variation of area strain. The area strain increasing was observed from 0.01 to 0.2 microstrain at five boreholes located in Chiayi area southwestern Taiwan and Hisnchu area northwest Taiwan. The area strain decreasing was also observed from 0.05 to 4 mricostrain at three boreholes located at Hisnchu and Taipei area of northwest Taiwan. We attribute these step-like transient variations of area strain to the dynamic triggering of the Wenchuan earthquake.

8) Hydraulic diffusivity around the Kamioka mine estimated from barometric response of pore pressure

Yasuyuki Kano, and Takashi Yanagidani

Disaster Prevention Research Institute, Kyoto University, Japan

The frequency response of monitoring of pore pressure inside rock mass is significantly improved by closing the well. Pore pressure of the rock mass is successfully measured at higher frequencies (0.1 Hz ~ 2 Hz) using closed borehole well in contrast to using open wells that may have a high-cut response by wellbore storage effect. We closed the wellhead of the four artesian borehole wells that was drilled at the Kamioka mine, central Japan, and carried out the pressure measurement. We obtained that the pore pressure response both to barometric pressure change and to earth tides, which is in agreement with theoretical model derived from the linear poroelasticity. The amplitude of tidal response of the wells is consistent with those of response to seismic waves. We determined local shear modulus and loading efficiency, which correlates to the Skempton coefficient, from the observed data. The result suggested that the local shear modulus corresponding to borehole well tapped near crushed zone of the Mozumi-Sukenobu fault is smaller than that corresponding to borehole well tapped into host rock. We also estimated hydraulic diffusivity from the low-cut frequency of the barometric response of pore pressure. For the wells drilled near the Mozumi-Sukenobu fault, the in situ value of hydraulic diffusivity is 0.1 m^2/s, which is consistent with that determined by core measurement. At the site near the Atotsugawa fault, hydraulic diffusivity is estimated to be 0.1 m^2/s in one well. Pore pressure in the other well responds to barometric pressure in period range above 1 day, which implies that the aquifer is unconfined.

9) Frequency characteristics of the response of water pressure in closed well to volumetric strain in high frequency domain

Yuichi Kitagawa

AIST, Geological Survey of Japan, Active Fault and Earthquake Research Center

The expression for the response of water pressure in closed well to crustal strain is newly developed. It is shown that the response of water pressure in closed well is not the same as the undrained response of poroelastic rock and has characteristics different from the response of water level of open well. The oscillations of water pressures and crustal strains due to the seismic wave of the 2010 Chile earthquake were observed. The oscillations of water pressures were basically negative-proportional to the oscillations of volumetric strains and the signals of water pressures existed in the frequency range from 0.002 to 0.1 Hz. In comparison with the volumetric strains, it is found that the responses of water pressures in closed wells are frequency-dependent. The new expression explains the frequency characteristics of the responses. The response is useful for the estimation of rock property. In addition, it is expected that the expression is applied to the study of phenomena caused by the pore water pressure in deep stratum which is difficult to observe directly.

10) The study of the mechanisms of earthquake-induced groundwater variation in Taiwan, 2003~2009

Wen-Chi Lai1,2, Chjeng-Lun Shieh1,3, Kuo-Chin Hsu2,Norio Matsumoto 4, Naoji Koizumi 4

1. Disaster Prevention Research Center, National Cheng Kung University, Taiwan
2. Department of Resources Engineering, National Cheng Kung University, Taiwan
3. Department of Hydraulic and Ocean Engineering, National Cheng Kung University, Taiwan
4. Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology

The earthquake-induced groundwater level changes were recorded in many historical records. Such changes have been monitored and investigated in the last thirty years. However, most of the previous studies, which are based on single event in different observations or multiple-independent events by many different data sources, involved uncertainties arising from different mechanisms and site effects. The quantitative analysis of earthquake-induced groundwater level changes remains a challenge.

Most of the evaluations of the coseismic static volumetric strain changes are based on the assumption of homogeneous and elastic material which is expanded in a half-infinite space. However, many of the coseismic and/or postseismic groundwater level changes caused by relatively distant earthquakes, show that the static volumetric strain changes can not well explain the earthquake-related changes. In this study, the data of 16 high resolution groundwater monitoring wells for 2004－2009 were utilized. A total of 196 events had been examined to explore the mechanism of the earthquake-induced groundwater variation. Earthquake-related groundwater level changes were compared to observed seismic accelerations and to inferred coseismic static volumetric strain changes at the wells. The strain to cause the groundwater variation composes two parts: static strain and dynamic strain. The static volumetric strain is caused due to the presence of inhomogeneous structures of tectonic structures and well-aquifer system, which the dynamic strain is mainly caused by ground shaking. On the whole, ground shaking seems a dominant factor for the earthquake-related changes at the most of wells because the calculated static volumetric strain is far less than the observed strain that corresponds to the earthquake-induced groundwater variation.

11) Review of cooperative hydrological and geochemical research for earthquake prediction in Taiwan

Naoji Koizumi[1] ,Norio Matsumoto[1], Wen-Chi Lai[2] and Chjeng-Lun Shieh[2,3]

1.AIST, Geological Survey of Japan, Active Fault and Earthquake Research Center
2.Disaster Prevention Research Center, National Cheng-Kung University, Taiwan
3. Department of Hydraulic and Ocean Engineering, National Cheng Kung University, Taiwan

Geological Survey of Japan (GSJ), AIST and Disaster Prevention Research Center (DPRC), National Cheng-Kung University, Taiwan have been carrying out the cooperative research of "Hydrological and geochemical research for earthquake prediction in Taiwan " since 2002. The first stage of the cooperative research was the period of 2002-2005 and we made an observation network of 16 wells in Taiwan to investigate earthquake-related groundwater changes. We also analyzed groundwater level changes caused by the 1999 Chi-chi earthquake and clarified the mechanism of them (Koizumi et al., 2004; Lai et al.,2004). The second stage was the period of 2006-2009. We analyzed long-term groundwater changes or recoveries after the 1999 Chi-chi earthquake(Koizumi et al., 2007). We also evaluated the earthquake-related groundwater changes observed by the new groundwater observation network (Lai et al., 2010). In Taiwan seismicity is more active and crustal deformation is more rapid than in Japan. Therefore research and observation of groundwater changes related to earthquake and crustal deformation in Taiwan will enable us to make rapid progress in hydrological and geochemical research for earthquake prediction. This cooperative research will also give important information for evaluation of long-term groundwater changes in tectonically active areas like Japan and Taiwan.

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