Seventh Japan-Taiwan International Workshop on Hydrological and Geochemical Research for Earthquake Prediction

		Program of the Workshop (Oct.7, 2008)
	Time	
	10:00	KATO,H (Director of GSJ) , Greeting
1	10:10	NAKAMURA M.(FSRU),Observation of Ocean Bottom Crustal Deformation in Ryukyu trench
2	10:35	HU,Jyr-Ching (NTU), Monitoring of active faults in Taiwan by geodetic measurements
3	11:00	ASAI Y.(TRIES), Borehole Array observation system operated by Tono Research Institute fo Earthquake Science, ADEP and Some Interesting Results
4	11:25	MA, Kuo-Fong.(NCU) Possible Fluid Driven Open Crack Events Observed in Taiwan Chelungpu-fault Borehole Seismometers
	12:05	Photographing at the front of the main entrance of Geological Survey of Japan, AIST
	12:20	Lunch Meeting, Matsumoto,
5	14:00	TANAKA H.(SSUT),Fault lubrication by mechano-chemical dissolution of minerals
6	14:25	SHIGEMATSU, N.(GSJ).,Heterogeneous localisation of plastic flow in the deepest part of a seismogenic fault: insight from the Hatagawa Fault Zone, NE Japan
7	14:50	TSUNOMORI F.(LECUT), A Mechanism of Radon Concentration Decline Prior to 1978 Izu-Oshima-Kinkai Earthquake
8	15:15	TASAKA, S.(IMCG) Underground Water Observation in Wari-ishi Hot Spring, Gifu Prefecture
	15:40	Break
9	16:10	KANO Y.(DPRI),Permeability Around the Nojima Fault Detected Using Barometric response of Pore Pressure
10	16:35	LAI W.-C.(DPRC), Dynamic effects on coseismic groundwater level changes : Cases study of 2003~2006 ML≧6 earthquakes in Taiwan
11	17:00	KOIZUMI N.(GSJ), Groundwater changes related to the 2004 Mid-Niigata Prefecture Earthquake and Niigataken Chuetsu-oki Earthquake in 2007
	17:25	Discussion
	18:00	Banquit
	DPRC	Disaster Prevention Research Center, National Cheng Kung University
	DPRI	Disaster Prevention Research Institute,Kyoto University
	FSR	Faculty of Science,Ryukyu University
	GSJ	Geological Survey of Japan, AIST
	NCU	National Central University,Taiwan
	LECUT	Laboratory for Earthquake Chemistry, University of Tokyo
	DGNT	Department of Geosciences, National Taiwan University
	IMCG	Information and Multimedia Cenger, Gifu University
	TRIES	Tono Research Institute of Earthquake Science
	SSUT	Schoolof Science, the University of Tokyo

Observation of Ocean Bottom Crustal Deformation in Ryukyu trench

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Ryukyu trench is a major convergent plate boundary where the Philippine Sea plate is subducting at a rate of about 8 cm/yr. No large earthquake (inter-plate earthquake) has been reported along the Ryukyu subduction zone for the last 300 years. However, the presence of the coupling in the Ryukyu trench has been unclear. Detection of deformation by coupling using land-based GPS network (about 100 km far from the trench) would be difficult if the coupling area is distributed near the trench.

To mitigate earthquake and tsunami disaster the clarification of the subduction process along the Ryukyu trench is important to understand for the Ryukyu Islands. We have started observation of sea floor crustal deformation to investigate the inter-plate seismic coupling in the central Ryukyu trench.

We had set the seafloor reference point at about 35 km landward from the axis of the Ryukyu trench by R/V Tonan-Maru (Okinawa Prefectural Fisheries and Ocean Research Center). 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 (side length of 2 km). We carried out three campaign observations for the period from January to July 2008. Each epoch consists of three observation days. The RMS of travel time residuals for each campaign analysis is about 70 micro-seconds.

Difference of positions between January-February and July epochs indicates an easterly movement of about 19 cm. This is inconsistent with the movement estimated from plate coupling (about 2.5 cm northwestward for a half-year) or decoupling (0cm for a half-year) models.

Earthquake swarm had started from 31 May 2008 (maximum Mw=4.7) near the trench about 20km trench-ward from the reference point. These events were normal faulting type and occurred in the subducted Philippine Sea plate. The observed easterly movement may indicate a slow-slip (slip of about 2m) event in the Philippine Sea plate.

Monitoring of Active Faults in Taiwan by Geodetic Measurements

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4. Central Geological Survey, MOEA, Taipei, Taiwan

On the progress of science and technology for instrument renewal toward the research of the earthquake activity in recent 10 years, the study of the earthquake potential and seismotectonics is more accurate and more efficient. These new geodetic methods provide different time spans of observation and the ability of detection of minor crustal deformation. This study uses the 44 continuous-recording GPS stations and campaign-mode GPS network together with 23 precise leveling lines established by Central Geological Survey to monitor the activity of major faults in Taiwan. The main goals of this project are (1) analysis of time series of continuous GPS and borehole strainmeters for the anomaly of signals from crustal deformation; (2) the crustal strain accumulation from GPS velocity field; (3) characterization of activities of seven major active faults and earthquake based on the baseline change of continuous GPS stations; (4) assessment of earthquake potential based on the subsurface fault geometry, fault parameters, slip rate along the fault patches from numerical modeling; (5) characterization of repeating earthquake sequences and comparison with the measurement of continuous GPS and borehole strainmeters; (6) assessment of earthquake potential and precursor based on the possible signals of crustal strain. Thus, the performance and aim of this project combine the precise leveling, GPS and borehole strainmeters in order to monitor the activity of major faults. Furthermore, we will combine the geological data, numerical modeling and the analysis of fault activity to provide the valuable information of near-field fault activity, seismogenic structures and process, mechanics of seismotectonics and possible precursors of big earthquakes.

Borehole Array observation system operated by Tono Research Institute of Earthquake Science, ADEP and Some Interesting Results

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Deep boreholes (deeper than about 500m) enable the high S/N ratio observations for detecting very small signals without artificial noises and meteorological disturbances. But the cost of digging deep borehole is too expensive. Therefore, in order to bring cost down per a sensor, we have developed multi-component borehole instruments (Figure 1) for deeper boreholes than about 1 km (e.g. Figure 2) with smaller diameters than 98 mm.

The newest instrument is composed of 6 strainmeters (4 horizontal and 2 vertical), 2 tiltmeters, 3 seismometers, 3 magnetometers, 1 thermometer, and A/D conversion unit for each sensor; arbitrary combination and addition of more sensors are possible. We use the 16 bit SAR (successive approximate register) A/D converter. The original sampling interval for each sensor is 9.6 kHz. The dynamic ranges for seismometers and others are improved 21 bits and 24 bits from 16 bits by averaging the 17 and 129 sampling data, respectively. Frequency responses of the observation system are not spoiled by this procedure, because averaging numbers are determined in consideration of final sampling rates. Final sampling rates are 400 Hz for seismometers, 40 Hz for strainmeters and tiltmeters, and 20 Hz for magnetometers and thermometer, respectively. Data obtained from each record are transmitted to a surface by using only one coaxial cable. Before installation of the multi-component borehole instrument, we install a wireless intelligent type strainmeter at the bottom of the borehole, and perform in-situ stress measurement by using the overcoring method. And then we install the multi-component borehole instrument at the bottom of the deep boreholes with expansion grout.

The multi-component borehole instruments were installed at the bottom of the seven deep borehole sites in Tono region, central Japan. These observation sites form the borehole array observation system with approximately 10 km in length and in WNW-ESE direction (Figure 3). The deepest borehole (JRJ) is 1030m and the second (BYB) is 1020m. Up to the present, this array system has observed the good tidal signals, strain-steps associated with large earthquakes, and remarkable strain changes associated with the activity of non-volcanic deep low-frequency tremors in the Tokai district, central Japan. We will present the details of our borehole array observation system and above-mentioned results obtained from the borehole observations.

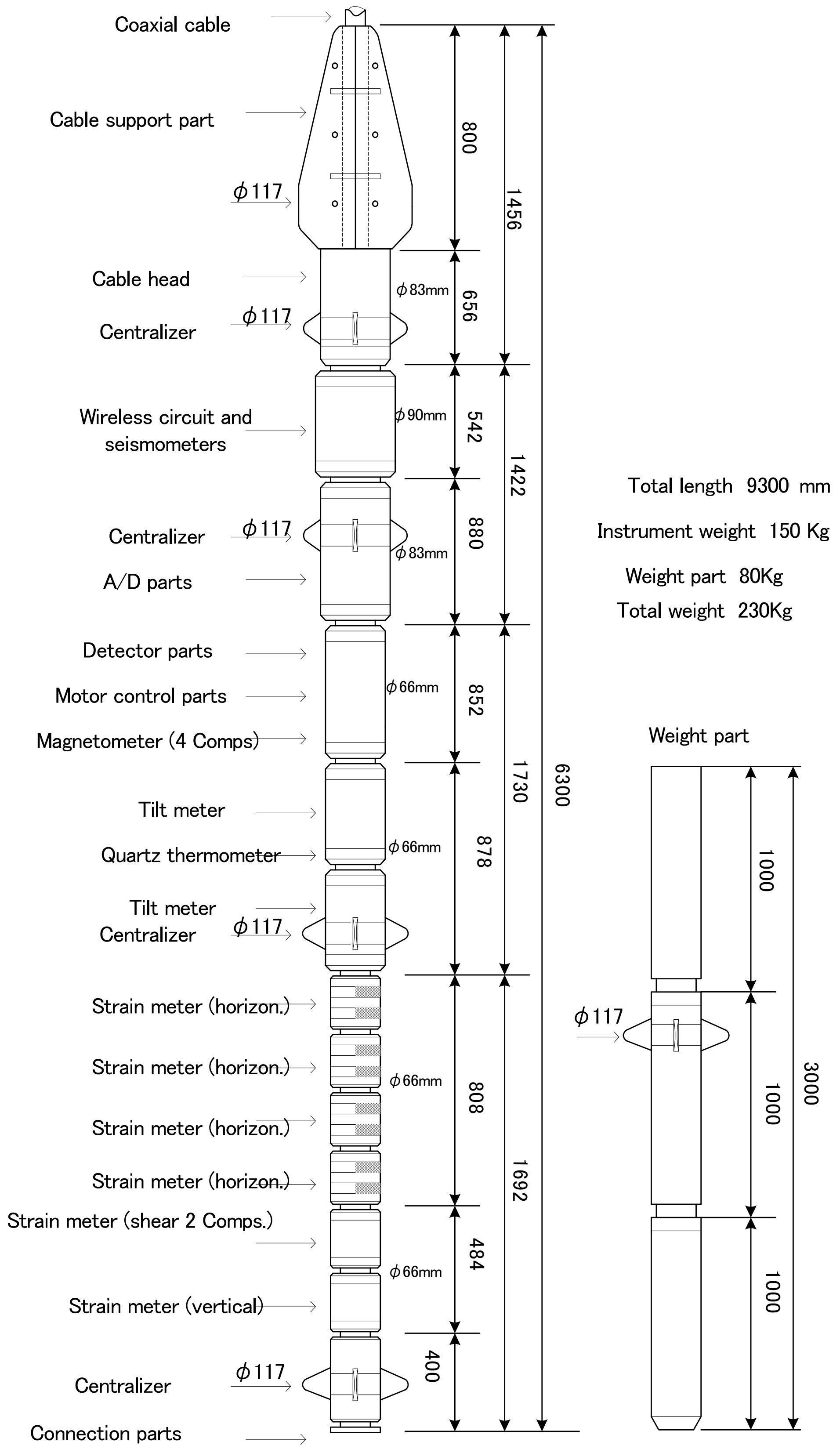

Figure 1. A small diameter Multi-component instrument for crustal activity employed for JRJ.

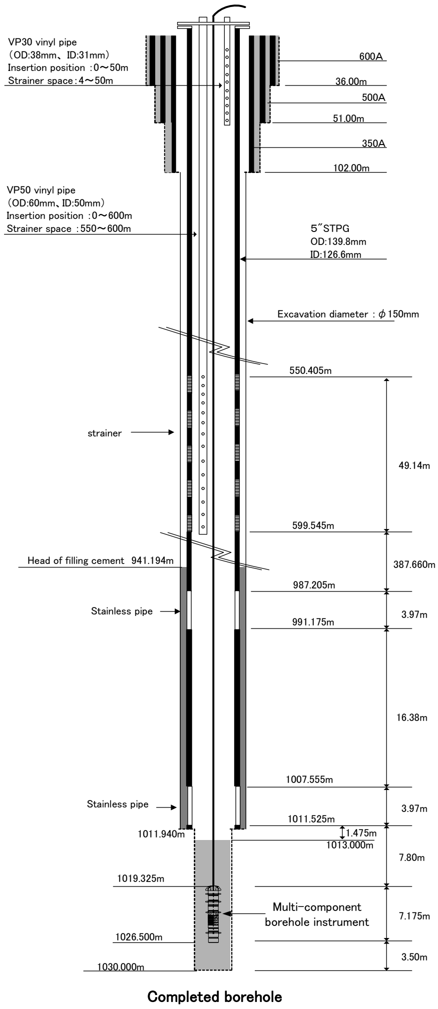

Figure 2. Structure of borehole for Jorinji station (JRJ; 1030m depth).

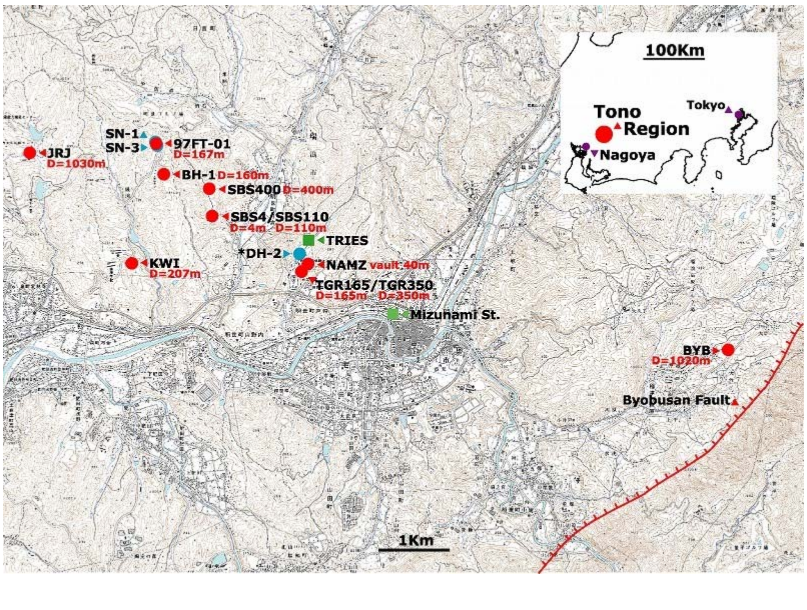

Figure 3. Borehole array observation system operated by TRIES. Red numerals indicate depth of borehole.

POSSIBLE FLUID DRIVEN OPEN CRACK EVENTS OBSERVED IN TAIWAN CHELUNGPU-FAULT BOREHOLE SEISMOMETERS

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Taiwan Chelungpu-fault drilling project drilled two holes, 39m apart of hole-A and hole-B, and one branch crossing the Chelungpu fault to retrieve the fresh slip zone associated with the 1999 Chi-Chi earthquake. The TCDP hole-A is 2 km deep, and a 12-cm primary slip zone (PSZ) at the depth of 1111km was identified. After the successful drilling of the TCDP, the TCDP borehole was used as an in-situ fault zone dynamic observatory. A state-of-the-art 7 level seismometer, which placed from the depth of about 950m to 1300m crossing the large slip fault zone associated with the 1999 Chi-Chi earthquake was installed in the borehole. The seismometers were installed over the depth range of hanging wall and footwall with the depth interval of about 50-60m. We focus our studies on the possible fault zone related micro-events.

In addition to the observation of micro earthquakes, we observed events showing the distinct P-wave without S-wave. These distinct P-wave only events had been observed continuously through time. For the five months of observational period, more than 30 events were detected. These events can be classified into different group according to their similarities in P-wave. Group A shows the distinct upward motion, while the Group B shows the distinct downward motion. The events in the same group are almost identical in P-waves, but with slightly difference in pulse width. It suggests the events in the same group have similar mechanisms, but with different source dimension and stress drop. The characteristics of the events from waveform observations suggest these events are repeatable from different locations. These events in Group A and B have the apparent velocity mostly ranged from 4.9 km/sec to 5.8 km/sec for the incident angle of 40-50 degree. The preliminary analysis from particle motions indicate the events might be in the depth range of about 1300m to 1500m, and within 150-500m horizontal to the TCDP BHS site. The seismic waveform simulation from 2D finite-difference for a double-couple event in the dipping fault zone structure shows distinct S-wave in synthetics for events from these incident angles. While a modeling for a Compensated Linear Vector Decomposition (CLVD) with a dipole in NS direction gives the synthetics with distinct P-wave without S-wave. It suggests that these events might be resulted from open cracks in the fault zone. A cross fault experiment of fluid injection test (FIT) was carried out in late 2006 and early 2007 with a high pressure fluid (~4MPa) injected in hole-B with chemical and gas observations and monitoring in hole-A. Whether these open cracks events are associated with the FIT or the existing features from fault zone remain a question. However, our observations show that these open crack events are lasting not only during the FIT experimental period but continuously through the observational period. Although the distinct features in chemical and gas observation were detected through the cross-hole experiment in FIT, no triggered events associated with FIT had been observed. The behavior of the open crack events might play a role to present the status of the stress on the locked splayed fault during the inter-seismic period.

Dynamic mechanochemistory of seismic slip - lubrication by super saturated fluids

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The Chelungpu fault, which was activated during 1999 Chi-Chi Earthquake, had been drilled to penetrate and recover the earthquake slip zone materials at deeper level (1100 m depth) in the crust, from year 2004 to 2005. Three holes are drilled (Hole A, B and C) and recovered the drilled core materials. Identification of slip layers of Chi-Chi Earthquake, thermal property measurements across the slip zones, estimates of frictional heat energy during earthquake, and quantifications of true fracture energy have been conducted using Hole A and C core (Tanaka et al 2006, GRL, Ma, Tanaka et al., 2006, Nature, Tanaka et al 2007, GRL). We present here the results of nano-scale observations for slip zone materials by using HR-TEM and TXM technique and fundamental process of generating nano-grains is discussed.

Hole C core contained slip concentration zone, which is 12 cm in thickness, in which four independent layers composed of fine crushed materials were identified. The zone is directly juxtaposed with lower undamaged host mudstone by planner surface. Each of four layers shows about 3 cm in thickness, which contains crushed grains with maximum diameter of 0.1 mm. Further, each layer contains ultra-fine grained layer at the bottom, about 1 cm in thickness, which contains no visible grains. XRD analysis clarified that the materials in this layer are mostly composed of quartz. Grain size distribution is measured under OM, SEM, and HR-TEM, from 100 nm to 100 um in grain diameter. The distribution follows the fractal model (N(D) = 0.0045D-2.3; N, numbers of grains, D, grain diameter). Under SEM (SEI) observation, many of fractured grains are enveloped by viscous thin film, which extends from one side of fractured grains. This texture is similar with that observed by Otsuki for his samples after slip deformation experiments.

Minimum size of grains observed under HR-TEM is 3 nm. The grain size distribution for grains larger than 100 nm in diameter follows the fractal law and grain shape is highly irregular. Grains smaller than100 nm show some specific characteristics, that is, smaller the grains, more the spherical shapes and more equi-granular. Thus, the grains smaller than 100 nm are no longer described by fractal distribution model. We refer tentatively these grains as nano spherules. By SAD and EDX analysis under HR-TEM, the nano spherules are mainly composed of crystallized quartz associated with minor amounts of carbonates (siderite) and amorphous materials. The result corresponds well with that of XRD analysis. These observations lead following three conclusions, (1) nano spherules are not generated just by fracturing, based on their shapes and grain size distributions. (2) Considering the results of SEM observations, nano spherules would compose viscous materials enveloping larger fractured grains. (3) Mica clay minerals and feldspars, which are common in host mudstone rocks, are disappeared in ultra-fine grained layer. This implies that chemical process of dissolution - elements dissipation - SiO_2 precipitation occurred associated with mechanical fracturing. Therefore nano spherules would be generated through mechano-chemical process during co-seismic slip. Dynamic shear strength drop are recently observed by rapid slip experiments (DiToro et al., 2004, Nature). Some experiments reported that the products contain gelled materials. Large differences of ultra-fine products between previous reports and our observations are existence of nano spherules and their crystallinity. If the nano-spherules are generated during seismic slip, dynamic weakening would be expected because mode of friction turns into rolling friction, which is 10 to 20% of shear friction, by huge amounts of equigranular and spherical grains. This may be alternative explanations for dynamic weakening. Quantitative process of dynamic fracturing - dissolution and precipitation of nano grains will be discussed in our presentation.

Heterogeneous localisation of plastic flow in the deepest part of a seismogenic faults: insight from the Hatagawa Fault Zone, NE Japan

Norio SHIGEMATSU (GSJ, AIST),

The hypocentres of inland earthquakes are generally located in the shallow part of the Earth's crust, and mainshocks usually occur in the deepest part of the seismogenic zone (e.g., Sibson, 1982, 1984; Nakamura and Ando, 1996). The temperature of the base of the seismogenic zone lies between 300 and 400 ° C (Ito, 1999), which corresponds to the brittle-plastic transition in the Earth's crust (Sibson, 1982, 1984). These observations suggest the important role of plastic behaviour along the deep-level extensions of seismogenic faults in the generation of large inland earthquakes (Shimamoto, 1989; Scholz, 1990).

This study examines plastic flow in fault rocks exposed along the Hatagawa Fault Zone (HFZ) of NE Japan. The fault zone, developed in 110 Ma granitoids (Ohtani et al., 2004), ceased activity by 98.1±2.5 Ma (Tomita et al., 2002). Three different fault rocks (mylonites with microstructures A and B, and cataclasite) are exposed along the fault. Microstructure A formed at the brittle-plastic transition. The temperature conditions for microstructure B were higher than those for Microstructure A; those for the cataclasite were lowest. Microstructure A is exposed in limited regions (maximum length extent of approximately 6 km) along the HFZ. Many zones of localised deformation (also containing crush zones) developed within the outcrop extent of microstructure A.

The distribution of microstructure A is considered to represent the latest-stage localised zones of plastic flow, associated with strain weakening accompanied by dynamic recrystallization of feldspar (e.g. Shigematsu, 1999). This limited outcrop extent suggests the restriction of plastic displacement to certain intervals at depth ranges with P-T conditions of the brittle-plastic transition. Many localised deformation zones with crush zones are observed in rocks with microstructure A, suggesting that numerous fractures nucleated due to ductile fracture of highly deformed fine-grained feldspar in the outcrop extent of microstructure A (Shigematsu et al. 200; Rybacki et al., 2008). Interaction between fractures that nucleated by ductile fracture and stress concentrations associated with the restricted development of plastic displacement possibly promoted the nucleation of large earthquakes.

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A Mechanism of Radon Concentration Decline
Prior to 1978 Izu-Oshima-Kinkai Earthquake

Tsunomori F. (University of Tokyo), Kuo M.C.T (National Cheng Kung University)

An earthquake of magnitude 7.0 occurred between Izu Peninsula and Izu-Oshima Island in central Japan on January 14, 1978. Precursory changes in a radon concentration in groundwater were observed at the SKE radon-monitoring station located 25 km from the epicenter approximately 3 months prior to the Izu-Oshima-Kinkai Earthquake (Wakita et al., 1980; Wakita, 1981). Because of the similarity between the radon anomaly pattern and volumetric strain changes measured at Irozaki (Figure 1), this radon concentration anomaly is now believed to have predicted the 1978 earthquake (Wakita et al., 1988). In this report, we will discuss about a radon decline mechanism prior to the earthquake.

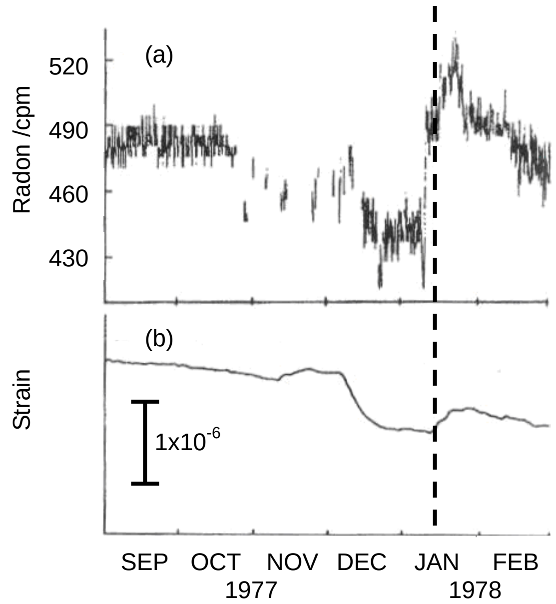

Figure 1. (a)Groundwater radon concentration change and (b)volumetric change prior to 1978 Izu-Oshima-Kinkai Earthquake. (Wakita, 1988)

According to Andrews (1977), the radon concentration in a porous geologic media is expressed as $C_{Rn} \propto E/\phi$, where E and ϕ are respectively the radon emanation power and the porosity of rocks in such medium. This equation should be improved as $C_{Rn} \propto SE/\phi$, where S is surface area of rocks because radon-222 is supplied through surface of rocks. The emanation power E is regarded as constant because E depends only the concentration of radium-226 ($T_{1/2}$ ~ 1600y). To decrease in radon concentration therefore either S has to decrease or ϕ has to increase.

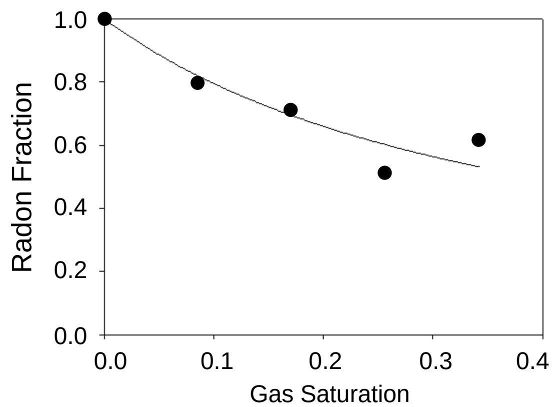

Figure 2. Variation of radon fraction remaining in groundwater with gas saturation at 15 °C using formation brine from the SKE.

Assuming the strain change at an aquifer of SKE station was as same as Irozaki shown in Figure 1(b) (Wakita et al, 1988), dilatancy (porosity increase) was created by approximately 2×10^{-7} strain change on the aquifer from mid-November to mid-December 1977. In this period, if new fractures were generated at dilatancy process the effect of porosity increase on the radon concentration would be canceled. It is therefore presumed that the radon decline prior to the 1978 earthquake is caused by dilatancy at the aquifer without new fracture creation.

In order to evaluate the porosity change, radon-partitioning experiments were carried out to determine the variation of the radon concentration remaining in groundwater with the gas saturation at formation temperature (15 °C) using formation brine from the SKE well (Figure 2). The estimated fracture porosity at the SKE aquifer was approximately 2×10^{-5}.

In conclusion, (1) the radon decline prior to the 1978 earthquake may be caused by dilatancy at the aquifer without new fracture creation, (2) The estimated fracture porosity at the SKE aquifer prior to the earthquake was approximately 2×10^{-5}.

Underground Water Observation in Wari-ishi Hot Spring, Gifu Prefecture

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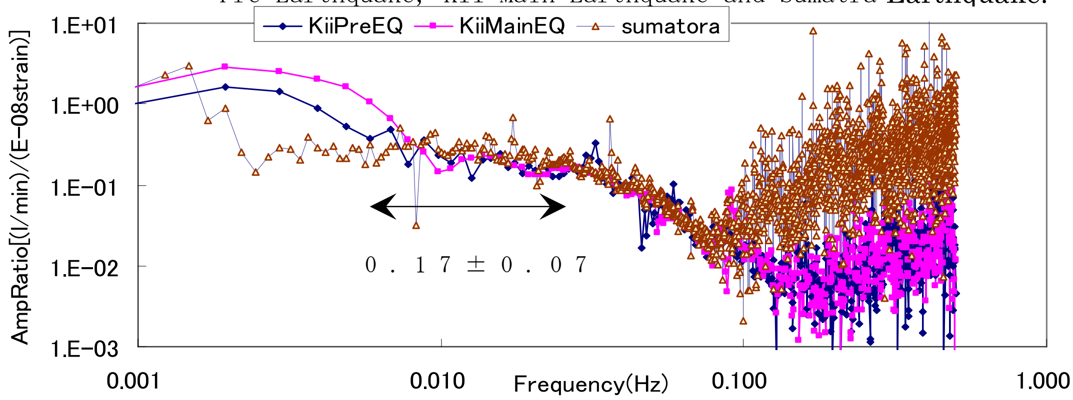
The continuation observation of water flow rate was carried out at the Gifu Hida Kamioka, Wariishi hot spring, in Center of Japan. The amount of water flow from 850m below ground was measured in the 10 minute interval from 1998 to 2004, and at intervals of 1 second from 2004, by using the electromagnetic flux meter with the accuracy of 0.25%.

The observation result of water change is related to the crust distortion accompanying the earth tide or the occurrence of an earthquake through change of the pore pressure of a stagnant water layer.

The purpose of this research is to clarify relation of water change, and seismic waves and crust distortion, and to clarify the relation of the occurrence of groundwater and an earthquake from a viewpoint of earthquake prediction.

Analysis of water flow was performed in the following four viewpoints, 1)hypocentral distance of the earthquake and magnitude, 2)earth tide, 3)seismic waves, 4)crust strain at the time of the occurrence of earthquakes.

Fig. Comparison with FFT Amplitude Ratio of Water and strain in three big Earthquake, KII Pre-Earthquake, KII Main-Earthquake and Sumatra Earthquake.



Permeability Around the Nojima Fault
Estimated Using Barometric Response of Pore Pressure

#Yasuyuki Kano (DPRI, Kyoto University), Yuichi Kitagawa (AIST)
Atsushi Mukai (Nara Sangyo University), and
Takashi Yanagidani (DPRI, Kyoto University)

Using an 800-m-deep borehole, which is one of the three boreholes drilled by the project, "Fault zone probe", we have continued pore pressure monitoring. On August 2006, we installed a new pressure gauge and fixed the seal of the wellhead. We analyzed the data between August 2006 and March 2007 to estimate the poroelastic constants that characterize the rockmass around the borehole. The pressure inside the borehole fluctuates around 197 kPa. Barometric and tidal responses are clearly observed. From the barometric response, we can determine loading efficiency. We obtained a loading efficiency of 0.45 by fitting the barometric and pore pressure records which are low-pass-filtered at a period of 1.25 day for each month. Combining tidal response, and the loading efficiency, we can determine the shear modulus. The ratio of observed pore pressure to calculated tidal areal strain is 22 GPa, which yields an estimate for the shear modulus to be 24 GPa.

Hydraulic diffusivity can be estimated from the attenuation of the ratio of pore pressure change to barometric pressure change at lower frequency bands. The cutoff does not appear in the period range shorter than 11.5 days. Assuming the water table to be a surface of one-dimensional fluid flow, the upper bound of hydraulic diffusivity is estimated to be 1.5 m^2/s. We further examined barometric response (Figure 1) of pore pressure data recorded from August 2000 to April 2006. The cutoff appear above the period of 11.5 day (Figure 2), which shows that there are no significant change of hydraulic diffusivity, and thus permeability from 2001 to 2007. This result is consistent with the permeability estimation using the pore repssure response to repeated injection tests (Kitagawa et al, 2006, Tectonophys. and Mulai et al., 2006, Tectonophys.).

Dynamic effects on coseismic groundwater level changes：Cases study of 2003-2006 $M_L \geqq 6$ earthquakes in Taiwan

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Abstract

During the period from 2001 to 2005, the Disaster Prevention Research Center (DPRC) of National Cheng-Kung University established a groundwater observation network composed of 16 stations for research of earthquake-related groundwater changes under the support of the National Science Council, Water Resources Agency, Taiwan and Geological Survey of Japan. The 18 earthquakes whose magnitudes are 6 or greater occurred in and around Taiwan during the period from 2003 to 2006. We checked the groundwater level data before and after these earthquakes.

Some of the coseismic groundwater level changes can be explained as the poroelastic responses to the earthquake-induced volumetric strain changes inferred from the fault dislocation models. But the other changes can not be explained by the volumetric strain changes either qualitatively or quantitatively. At first we regarded the coseismic static volumetric strain change and the peak ground acceleration (PGA) as the main factors to cause the coseismic groundwater level changes. The results show that the dynamic strains induced by ground shaking could be another possible factor for the coseismic groundwater level changes. It seems to appear especially in shallow aquifers with high hydraulic conductivity in lose-cemented and permeable sedimentary deposits. The similar effects can also be recognized in the coseismic groundwater level changes related to the 1999 ChiChi earthquake.

Groundwater changes related to the 2004 Mid-Niigata Prefecture Earthquake and Niigataken Chuetsu-oki Earthquake in 2007

Naoji Koizumi1), Satoshi Itaba1), Tsuyoshi Toyoshima2), Masashi Kaneko3) and Kazuyoshi Sekiya3)

1) Geological Survey of Japan, AIST, 2) Graduate School of Science and Technology Earth Science, Niigata University, 3) Niigata Prefectural Office

Geological Survey of Japan, AIST has been monitoring groundwater in and around the Kinki and Tokai districts for earthquake prediction research since 1970's. Niigata Prefectural Office has also been observing groundwater for monitoring land subsidence in Niigata Prefecture. The 2004 Mid-Niigata Prefecture Earthquake (MJMA6.8) and Niigataken Chuetsu-oki Earthquake in 2007 (MJMA6.8) occurred in Niigata Prefecture, Japan on October 23, 2004 and July 16, 2007, respectively. The two earthquakes have a similar magnitude, epicenter and mechanism (Fig.1). At many of the observation wells, we detected changes in groundwater level or pressure related to the two earthquakes (Fig.1) but no clear precursory changes. At all of our observation wells in Niigata Prefecture, trend changes were observed after coseismic step-like changes for both of the earthquakes. At some of the stations in and around the Kinki and Tokai districts, coseismic trend changes and/or step-like changes were observed. The pattern of the changes were almost similar for the two earthquakes. Those changes were considered to be caused not by the static volumetric strain changes but by the ground shaking.

Fig.1 Coseismic groundwater level or pressure changes in response to the 2004 Mid-Niigata Prefecture Earthquake (left) and to the Niigataken Chuetsu-oki Earthquake in 2007 (right). Contours denote the coseismic static volumetric strain changes calculated from the dislocation model of the Geographical Survey Institute (left:2005; right: 2008). △: Increase, ▽: Decrease, ○: No change, ＊: Oscillation, ★: Epicenters of the 2004 Mid-Niigata Prefecture Earthquake and the Niigataken Chuetsu-oki Earthquake in 2007. Dotted rectangular is the fault models of them