Continuous Observation of Groundwater and Crustal Deformation for Forecasting Tonankai and Nankai Earthquake in Japan

Itaba, S., Koizumi, N., Matsumoto, N., & Ohtani, R. (2010) *The Frank Evison Volume II*, 251-260.

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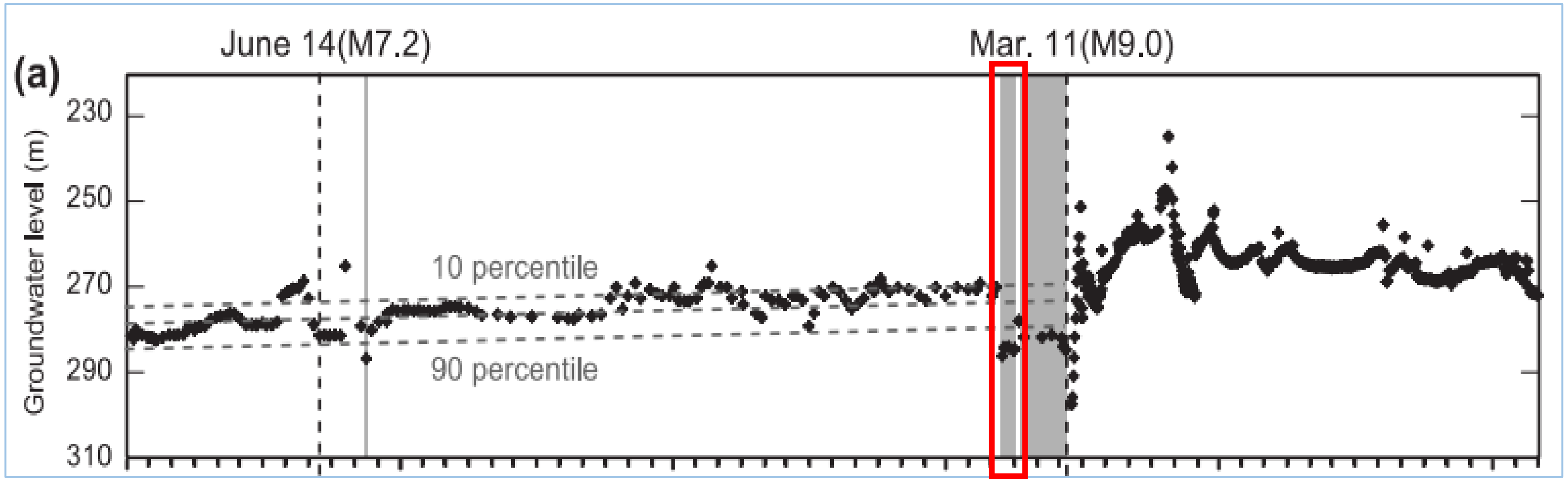
Introduction

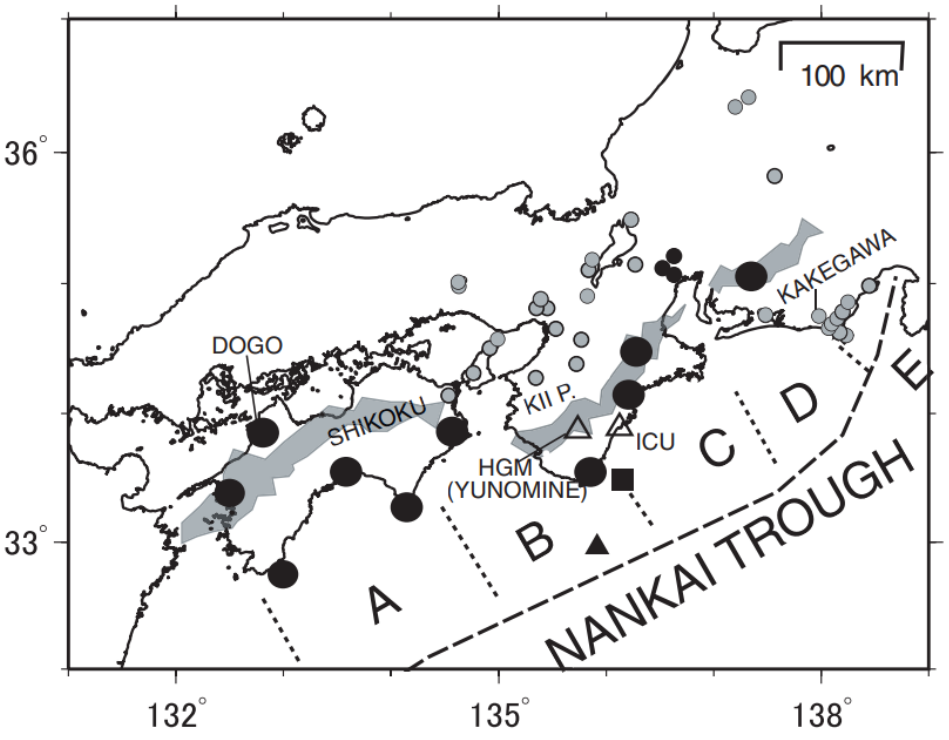
Pre-seismic Groundwater Level Changes

- The fluid in the crust is very sensitive to crust strain and solid deformation lead to the groundwater level changes in a well from the confined aquifer even if the deformation in the crust is small **(Shi et.al., 2008)**.

- Anomalous groundwater changes started three months before 2011 M 9.0 off the pacific coast of the Tohoku Earthquake, Japan **(Orihara et.al., 2014)**.



Nankai and Tonankai Earthquake



Nankai, Tonankai and Tokai earthquakes are large inter-plate earthquakes that have occurred repeatedly in the Nankai and Suruga Troughs at intervals of around 100–200 years since A.D. 684

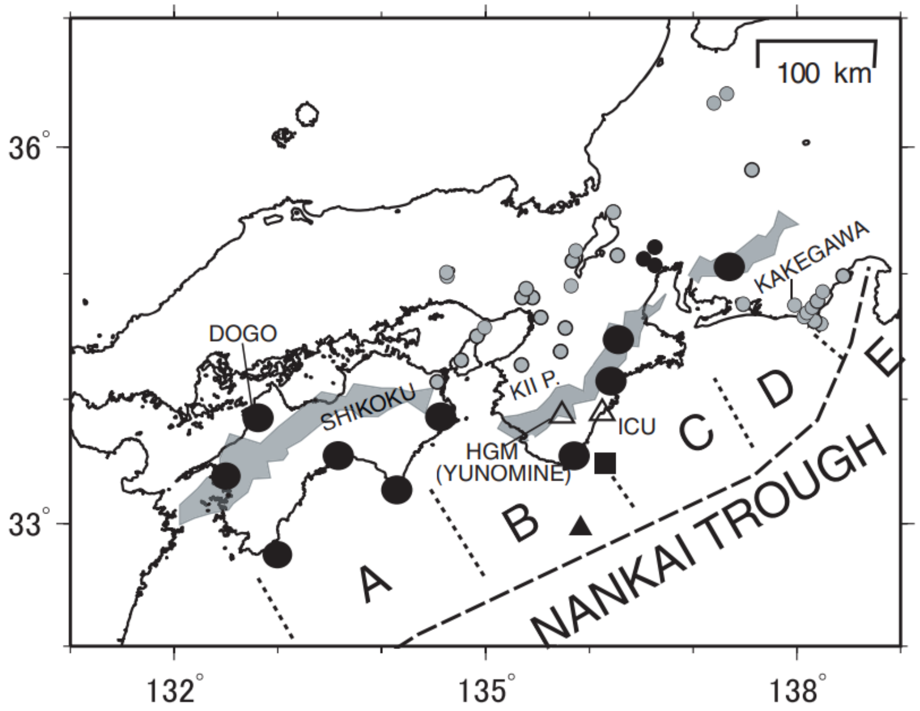
Nankai Trough	A & B	Nankai Earthquake
	C & D	Tonankai Earthquake
Suruga Trough	E	Tokai Earthquake

- Historical records spanning the past 1,300 years indicate that Nankai earthquakes have occurred eight or nine times since A.D. 684 (one of the most well-known large inter-plate earthquakes in the world).

- Tonankai earthquakes have occurred six times since 1096.

Pre-seismic groundwater level changes??

Observation Data



△ : New observations stations (HGM & ICU)

● : New observations stations

○ : Existing groundwater observation stations

▲ : 1946 Nankai Earthquake

■ : 1944 Tonankai Earthquake

- Groundwater monitoring in the Tokai area for earthquake prediction has been done since 1970s.
- The Geological Survey of Japan (AIST) has a network of about 40 groundwater observation stations in and around the Tokai and Kinki areas in Japan

Pre-slip model of the impending Tokai Earthquake in the Suruga Trough.
&
The assumption that groundwater level changes are proportional to volumetric strain changes

The observation network has the ability to detect pre-seismic groundwater level changes

In 2006, construct new observation network (12 stations)

Stimuli of the Head Variations of Groundwater

- The groundwater level could be affected by the environmental factor that can trigger a response or called as stimuli.
- The natural stimuli such as rainfall, sea tide, earth tide, barometric pressure and earthquake usually contribute more to the head variations of a groundwater system than does artificial stimuli such as pumping.
- The head variations of groundwater which include the stimuli well known as mixed signal which is leading to difficulty in extracting the head variations contributed by a single stimulus (**Tsai & Hsiao, 2020**).

The decomposition process is important since the groundwater level changes affected by a stimulus or less stimuli are mandatory to analyze the anomalies of the groundwater level changes related to the earthquake

The analysis of the pre-seismic groundwater level changes induced by the earthquake lead to the better understanding for the earthquake prediction.

Objective

Continuous observation:

- Understand the crustal deformation and groundwater level changes, and evaluate groundwater changes related to the 1944 Tonankai and 1946 Nankai earthquakes.
- Monitor groundwater level changes and crustal deformation related to the episodic slow slips precisely in order to research their mechanism.

Methodology

Observation System

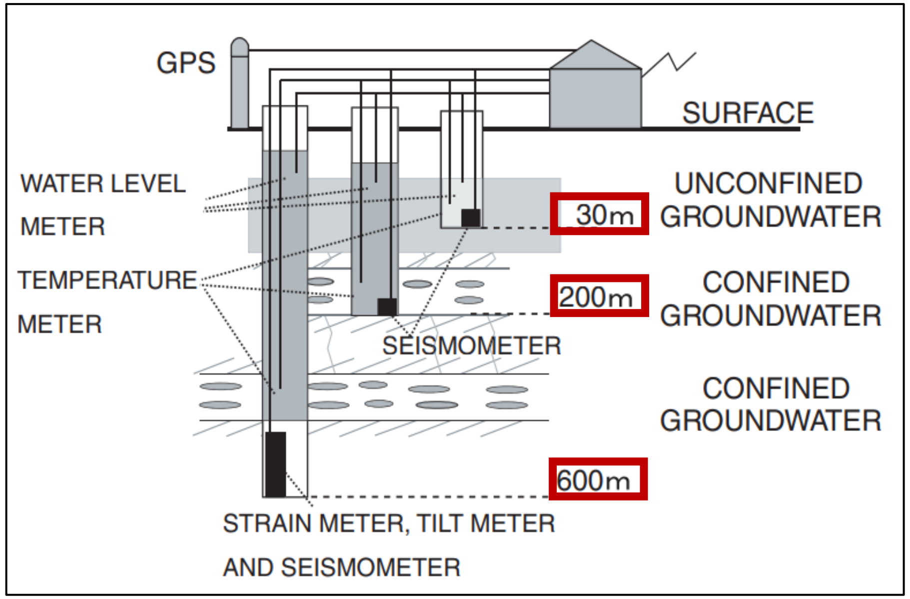
Main Idea: groundwater changes are considered to be responses to seismic crustal deformation.

The system capable to observe the groundwater level as well as crustal deformation

The groundwater level are observed at each well.

Crustal strain and tilt observed by means of a multicomponent borehole strain meter and borehole tiltmeter (bottom of 600-m-deep and 200-m-deep well).

- Monitor any changes in shallow unconfined groundwater levels and deep-confined groundwater pressure.
- observe groundwater movement among the three wells.



Sampling rate for each observation

Observation	Sampling rate (Hz)
Groundwater level	1
Groundwater temperature	1
Crustal strain	20
Crustal tilt	10
Seismometer	100–1,000

- The first two new station, HGM and ICU were located at the area where the groundwater level changes expected to occur.
- Observe not only with the pre-slips and main shocks for the Tonankai and Nankai earthquakes, but also with the **episodic slow-slip events** (SSEs) accompanied by non-volcanic tremors on the plate boundary.

Detail Information of Observation Stations at HGM and ICU

Depths of screens and strainmeters and tiltmeters at HGM and ICU

Station	Latitude (°)	Longitude (°)	Altitude (m)	Well	Screen depth (m)	Depth of the strain and tilt meters (m)
HGM	33.87	135.73	123	HGM1	320.4–331.3	368.2–375.0
				HGM2	180.9–191.8	–
				HGM3	24.3–29.8	–
ICU	33.90	136.14	27	ICU1	522.4–533.4	583.9–590.8
				ICU2	95.7–106.6	–
				ICU3	13.4–18.8	–

Screen casing pipe with slots through which groundwater flows in and out

BAYTAP-G for Groundwater Level Decomposition

- Tidal components and the effect of atmospheric loading on the strain and groundwater level as well as pressure are also removed by BAYTAP-G, a program for tidal analysis.

- **Jan et al. (2007)**, in their study use the BAYTAP-G program to filter out the response of the groundwater level to non-rainfall effects, such as barometric pressure and earth tide.

- **Ishiguro et al. (1983)** adopted the Bayesian technique after **Tamura et al. (1991)** devised a method to eliminate the tidal effect on groundwater level using the Bayesian Tidal Analysis Program in a Grouping Method (BAYTAP-G).

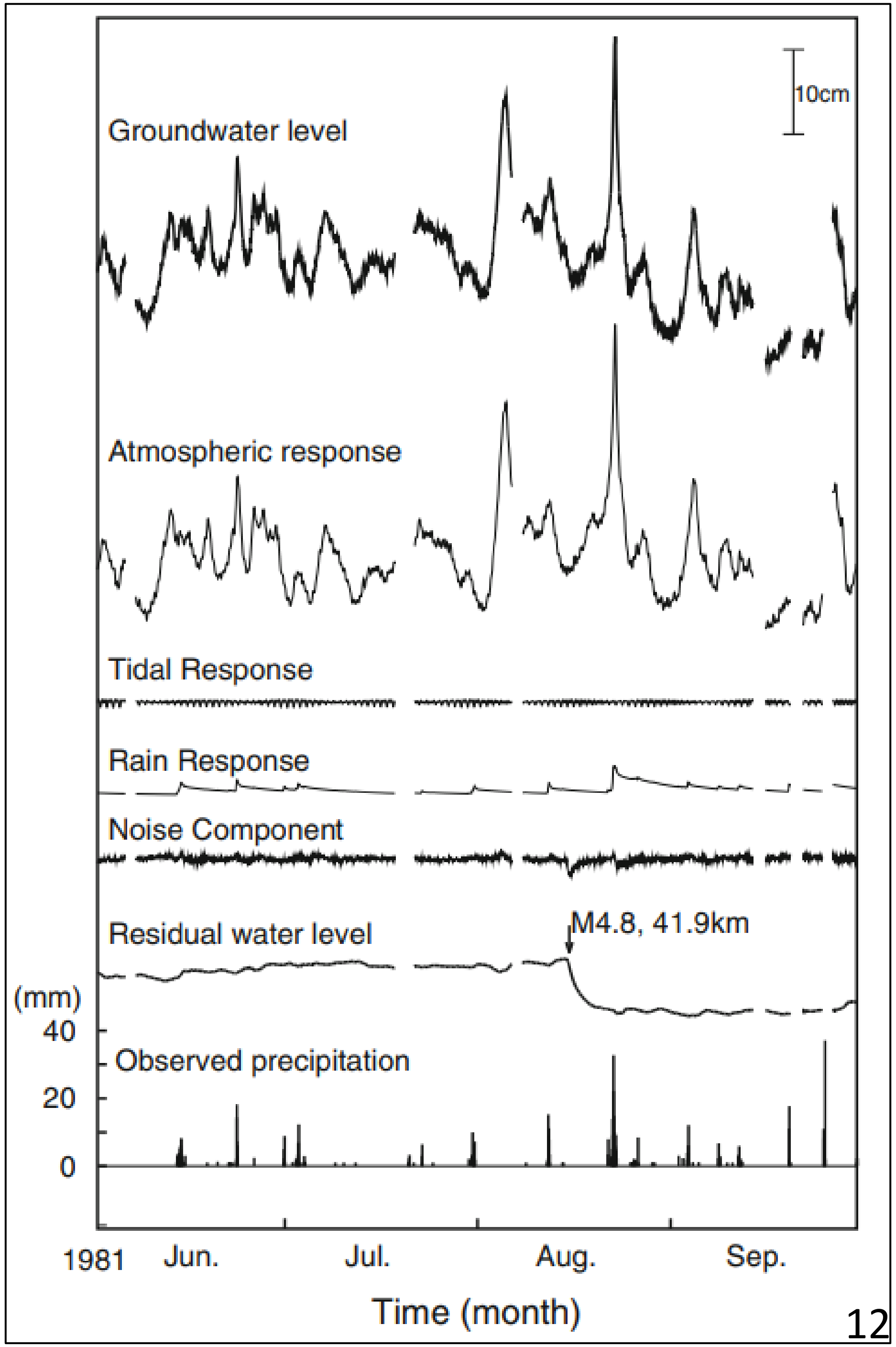
- Their findings demonstrated that the observed groundwater levels can be divided into several components, including a trend component, a noise component, a response to barometric pressure with lagged terms, a response to various groups of tidal constituents with a frequency-dependent phase shift, and so on.

BAYTAP-G

- Developed by M. Ishiguro, Y. Tamura, T. Sato and M. Ooe. This program uses a Bayesian modeling to analyze time series that contain both tidal and other variations: this includes tidal gravity, ocean tides, and strain and tilt data.

- Using BAYTAP-G, **Matsumoto et al. (2003)** detected 28 co-seismic changes and two possible pre-seismic and inter-seismic anomalies in the residual groundwater level with magnitudes of more than 8 mm, which are statistically significant fluctuations.

- Groundwater level in Haibara well is separated into the **atmospheric** and the **tidal responses**, the response to **precipitation**, the **noise component**, and the **filtered residual water level** from June to September, 1981.



Results and Discussion

Past Pre-seismic Crustal Deformation and Groundwater Level Changes

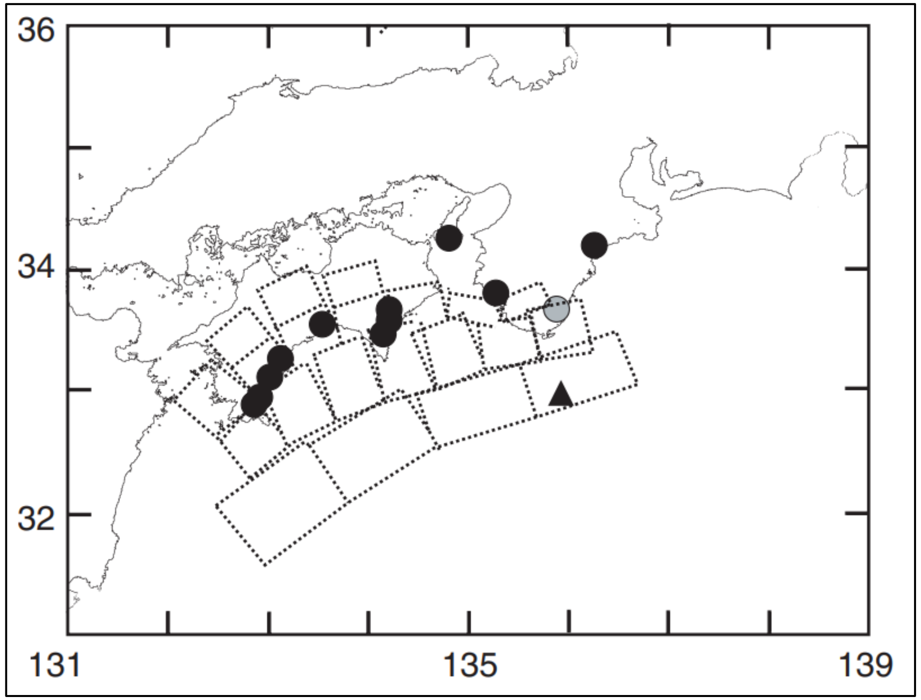
Tonankai Earthquake

The M 7.9 1944 Tonankai earthquake was preceded by pre-seismic crustal deformation and followed by co-seismic and post-seismic changes in groundwater levels.

- A pre-seismic crustal deformation occurs in Kakegawa in the Shizuoka Prefecture, which can be explained by the pre-slip or the pre-seismic aseismic slip on the plate boundary.

- The groundwater level at the Yunomine hot spring coseismically and postseismically dropped more than 1 m at the time of the 1944 Tonankai Earthquake.

Nankai Earthquake



●: Pre-seismic groundwater level drops

○: Decrease in hot-spring discharge

▲: 1946 Nankai Earthquake

- The M 8.0 1946 Nankai earthquake, followed 11 pre-seismic drops in groundwater levels and one decrease in discharge from a hot spring near the coastal regions of Shikoku and the Kii Peninsula
  - The 11 unconfined groundwater levels fell 1–10 days prior to the 1946 Nankai Earthquake.
  - A decrease in hot-spring discharge is 6h prior to the 1946 Nankai Earthquake.
- Similar drops in groundwater levels also occurred before the 1854 event.

Pre-seismic Groundwater Level Drops

Mechanisms

Reported groundwater level drops or discharge decrease can be explained by the reverse slip on the plate boundary in Nankai Trough.

Reverse slip occurs on the plate boundary in the Nankai Trough

Southern coasts of Shikoku and Kii Paninsula will be in extension

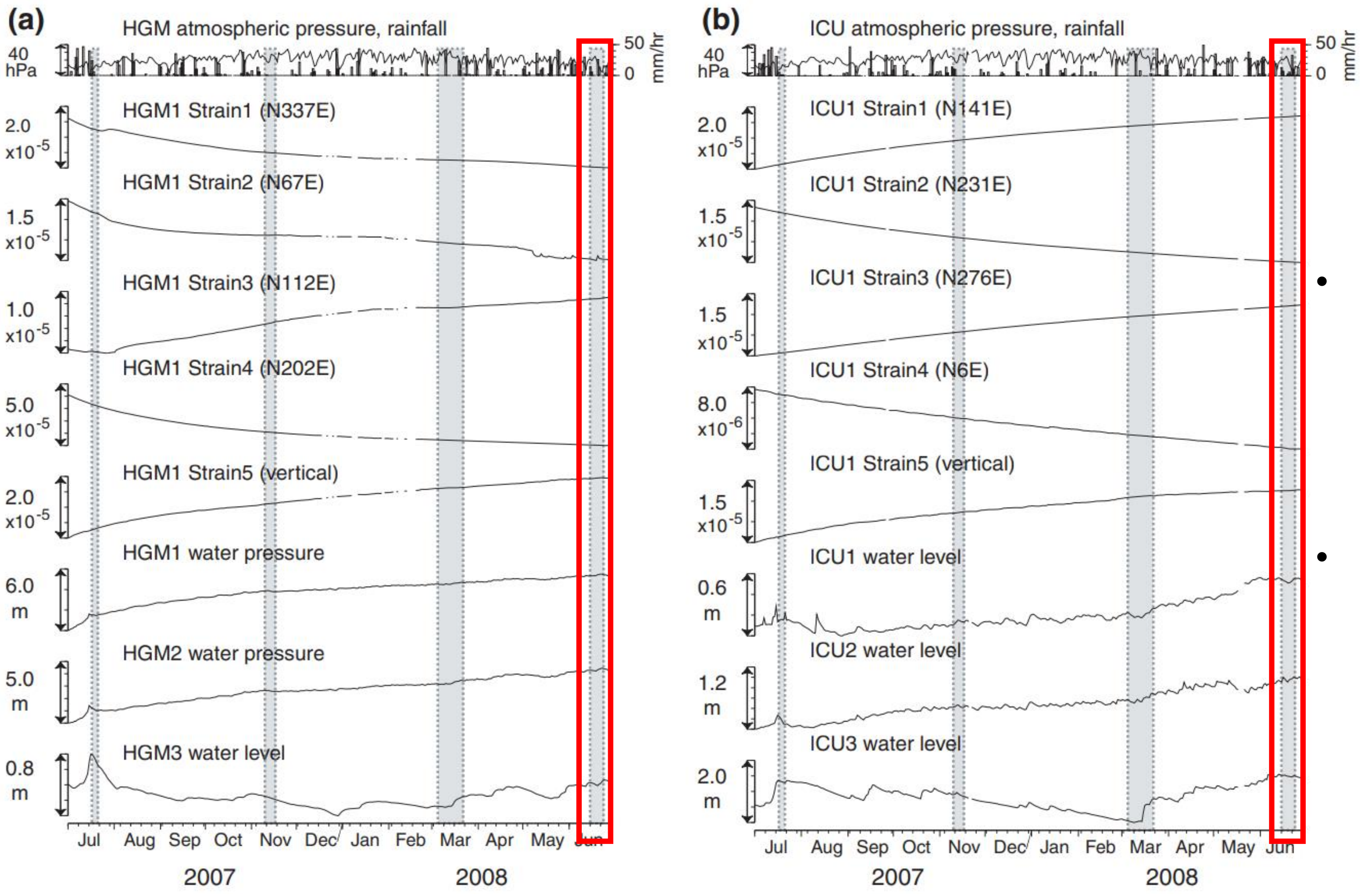
Unconfined groundwater levels can decrease relative to the surface and pressure of the confined groundwater.

Another plausible mechanisms is that if tensile cracks open in rock near the surface, then fluid will flow into them and water level will fall.

Recent Observation in Hongu-Mikoshi (HGM) and Ichiura (ICU) Stations (2007-2008)

Long-term Changes from May 2007 to June 2008

Well	Screen depth (m)
HGM1	320.4–331.3
HGM2	180.9–191.8
HGM3	24.3–29.8
ICU1	522.4–533.4
ICU2	95.7–106.6
ICU3	13.4–18.8

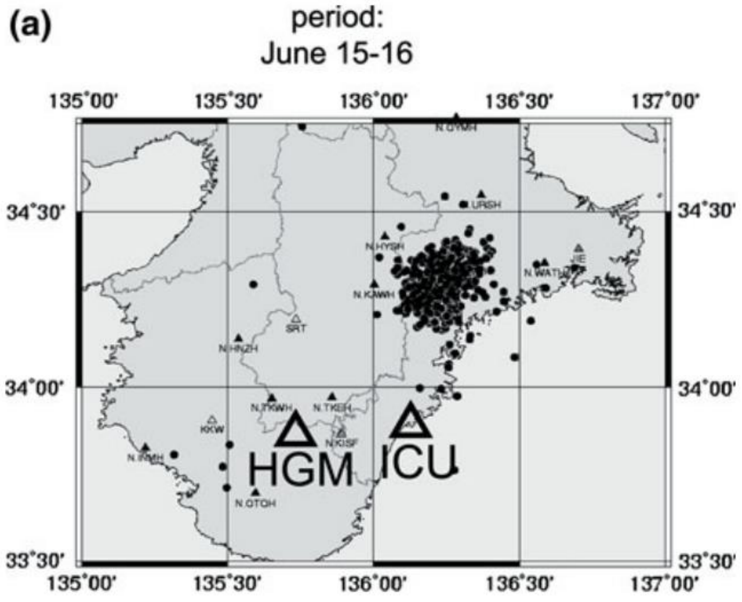


: slow-slip events (SSEs)

- During the SSEs, there were no large changes in groundwater level such as those that occurred prior to the 1946 Nankai Earthquake.
- During the fourth SSE in June 2008, strain changes at HGM1 and ICU1 were clearly recognized.

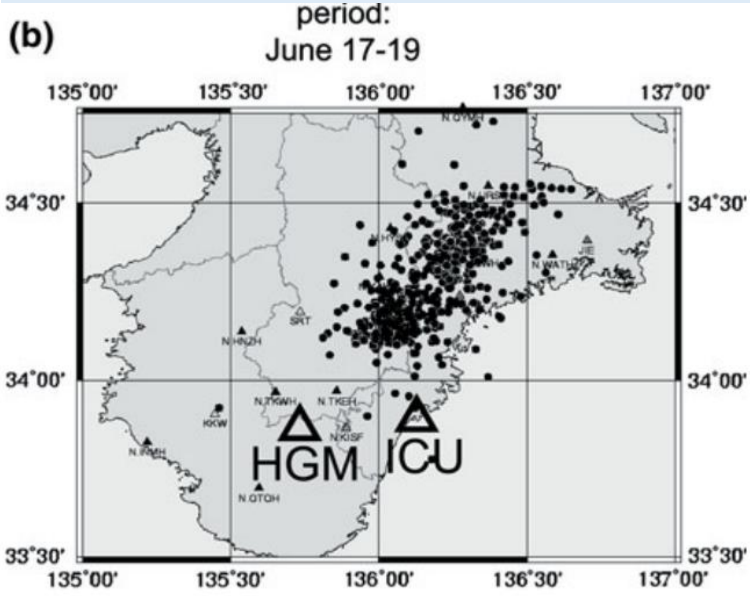
Epicenters of Tremors

A-period



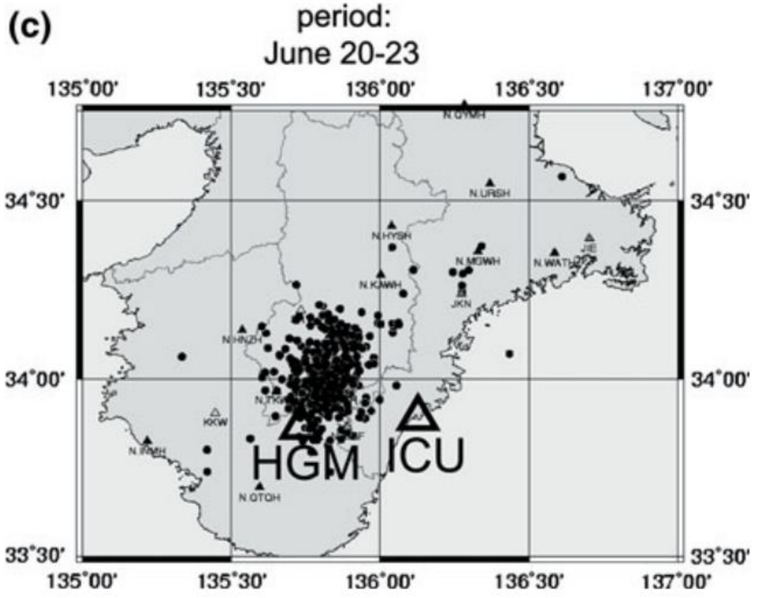
The tremors occurred a little further from ICU and HGM, and there were small strain changes in the horizontal components.

B-period



The area for tremors became larger and the southern part of the area was approaching ICU and HGM.

C-period



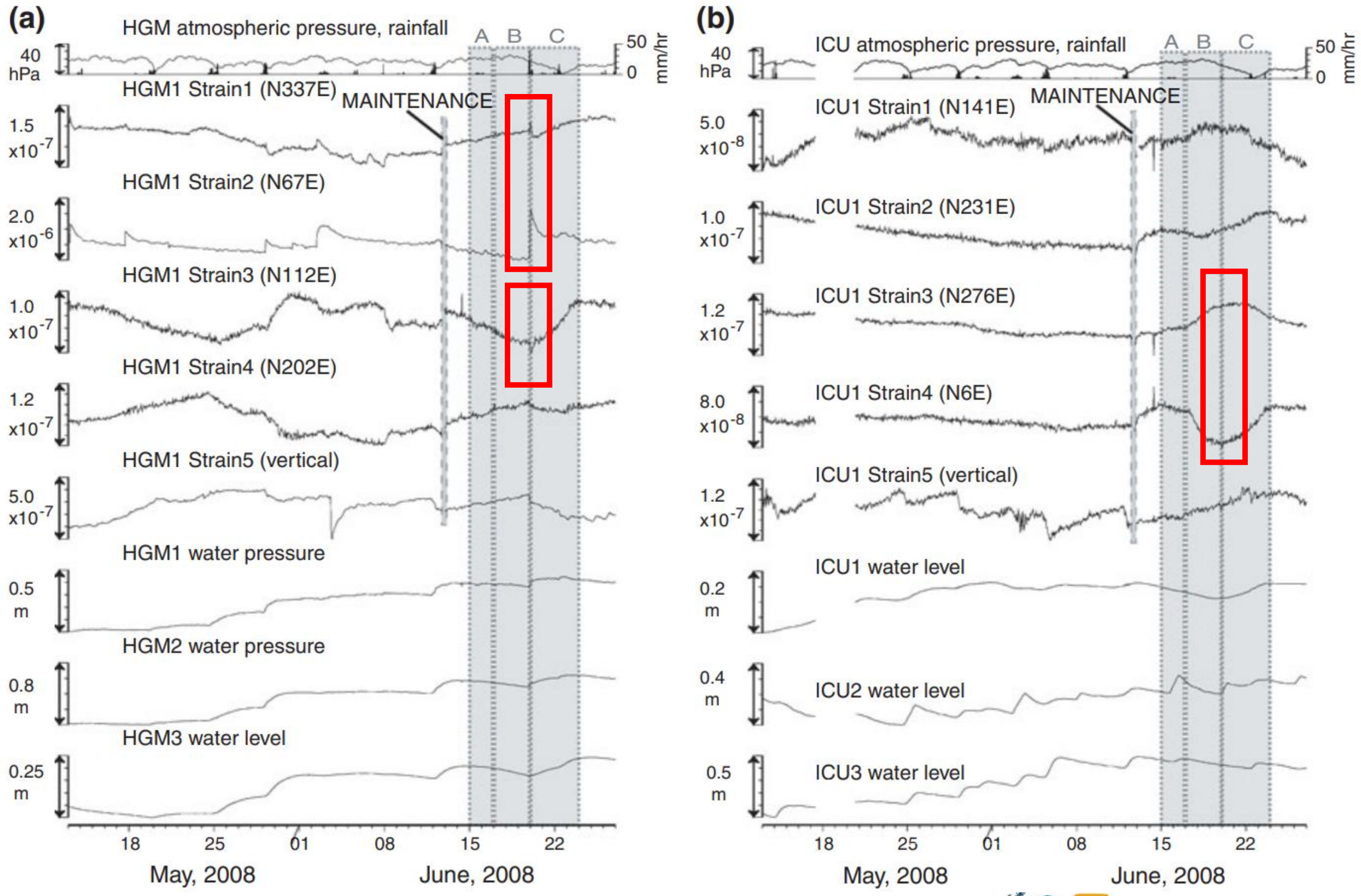
The tremor area was the nearest to HGM and ICU, and could be regarded as in the vicinity of HGM.

● : Epicenter of tremors

▲ : Observation points

△ : Observations stations (HGM & ICU)

Strain and Groundwater Changes in June 2008



- Observation period: May 13 – June 27.
- During the B-period: the strain changes were larger, especially in the N276E and N6E components at ICU.
- During C-period: At HGM, the strain changes were clearly recognized as Strain-3 (N112E). However, there were step-like changes at Strain-1 (N337E) and Strain-2 (N67E) on June 20.
- The groundwater levels or pressures showed no clear changes during periods A–C.

: slow-slip events (SSEs) and maintenance

Time?

Conclusions

Conclusions

- Past pre-seismic groundwater level changes:

The M 7.9 1944 Tonankai earthquake was preceded by pre-seismic crustal deformation and followed by co-seismic and post-seismic changes in groundwater levels. The M 8.0 1946 Nankai earthquake, followed 11 pre-seismic drops in groundwater levels.

- Strain and groundwater level changes from May 2007 to June 2008:

Strain changes caused by SSEs in June 2008 were detected at HGM and ICU, although related changes in groundwater levels were not clearly recognized.

Need future continuous observation to clarify groundwater changes related to the 1944 Tonankai and 1946 Nankai earthquakes.

Thank You

Sensitivity Analysis Progress