Integration of real time data and advanced simulation for disaster mitigation in Japan

Yoshiyuki Kaneda

1:Kagawa University

2:Japan Agency for Marine-Earth Science and Technology (JAMSTEC)

Seismicity and Volcanic front in Japan

- High Seismicity
- Many Volcanos

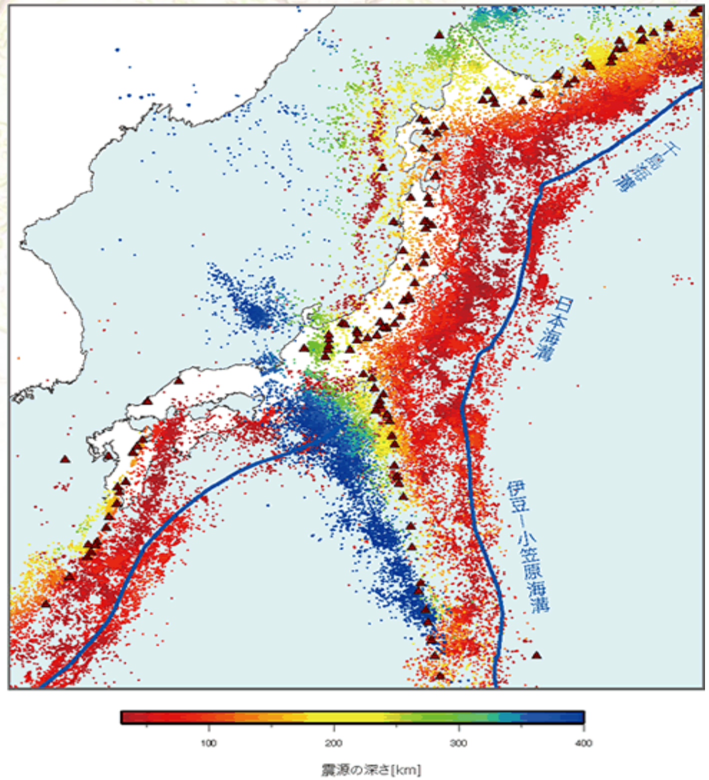
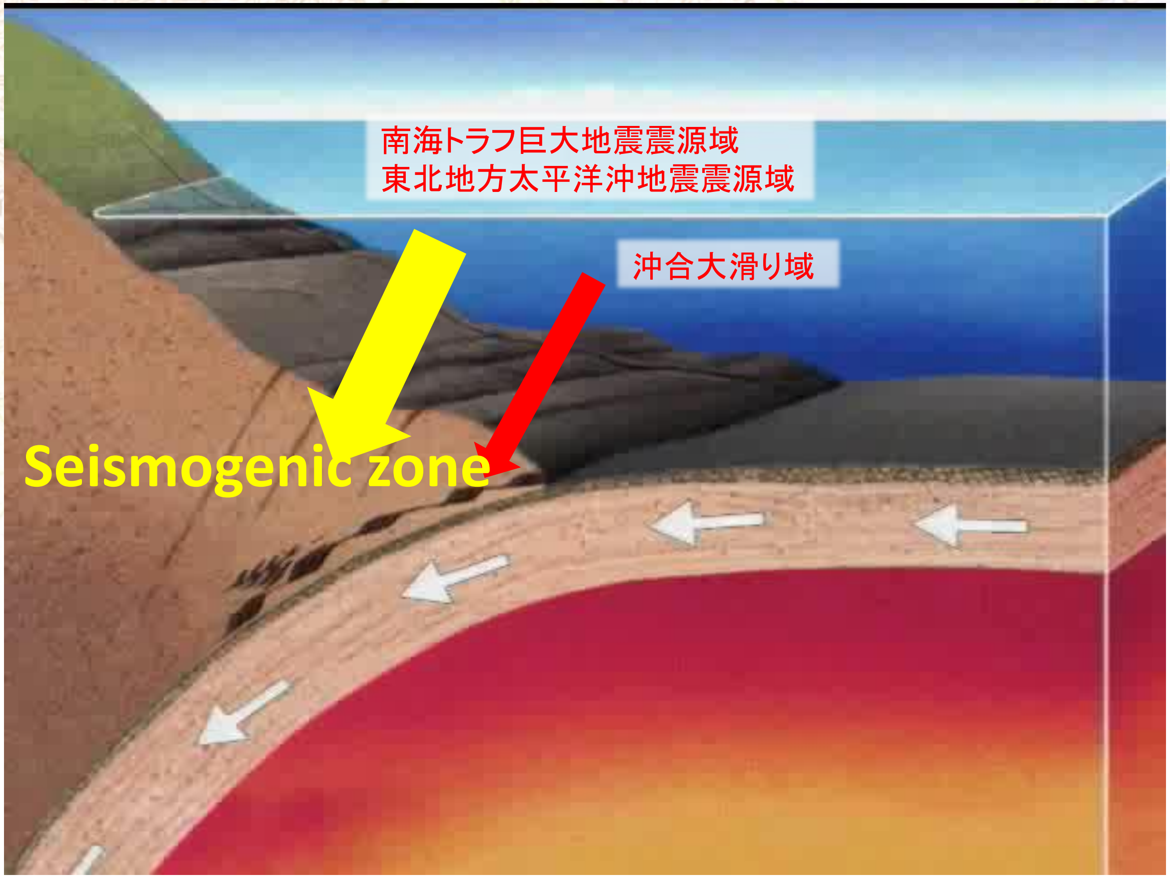


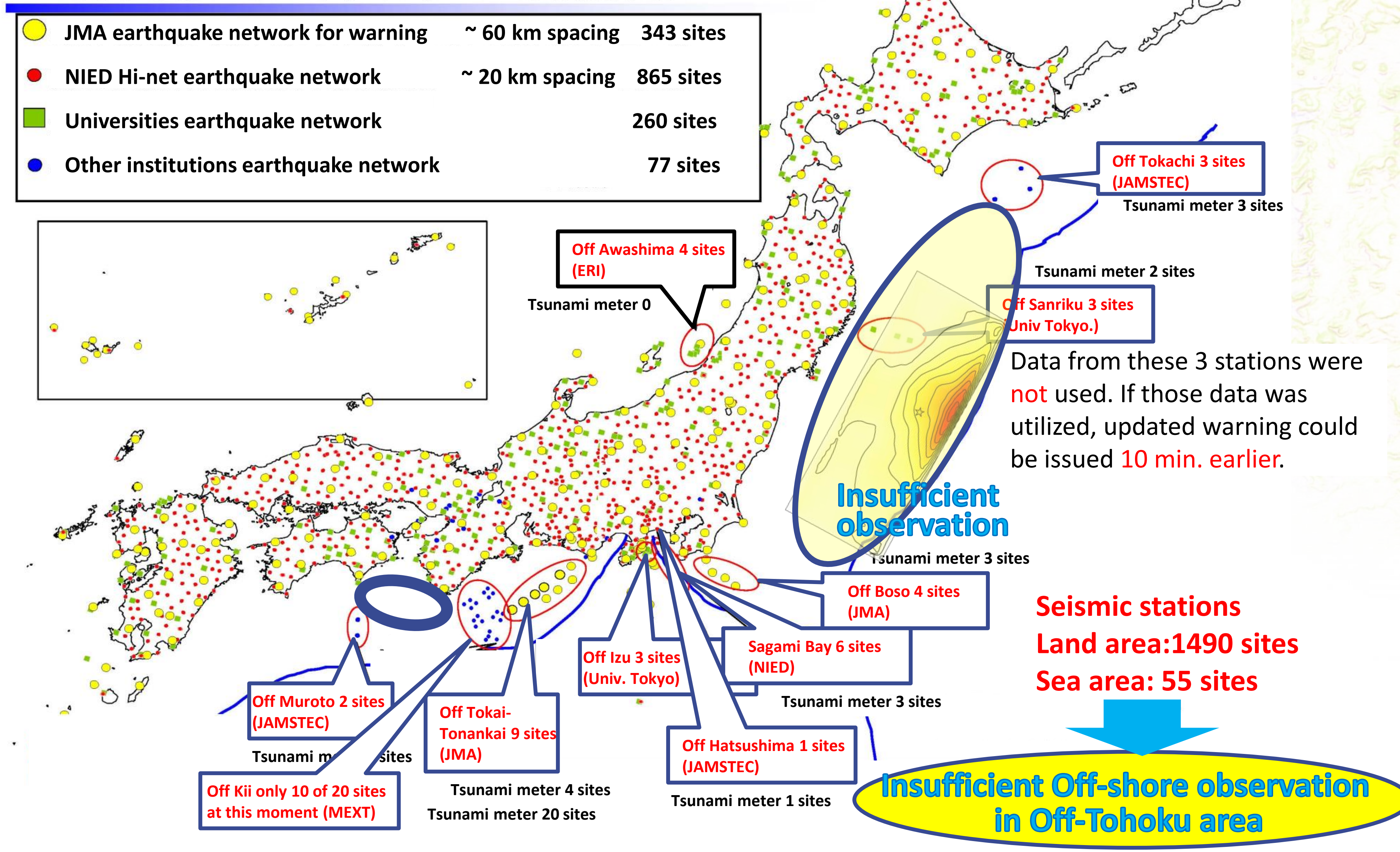
図１　活火山（▲）の分布
活火山は海溝と平行に並んでいる。点は震源を示し、色は震源の深さをあらわす。（気象庁一元化震源）

「Mega Thrust Earthquake



Earthquake and tsunami observation site in and around Japan

(At the time of the 2011 Tohoku Earthquake)



2013年7月6日　ケーブルタンク上のデッキに収納された地震津波計。手前の12台が茨城県鹿嶋市側から設置するもので、奥の10台が千葉県南房総市側から設置するものです。（提供：防災科学技術研究所）

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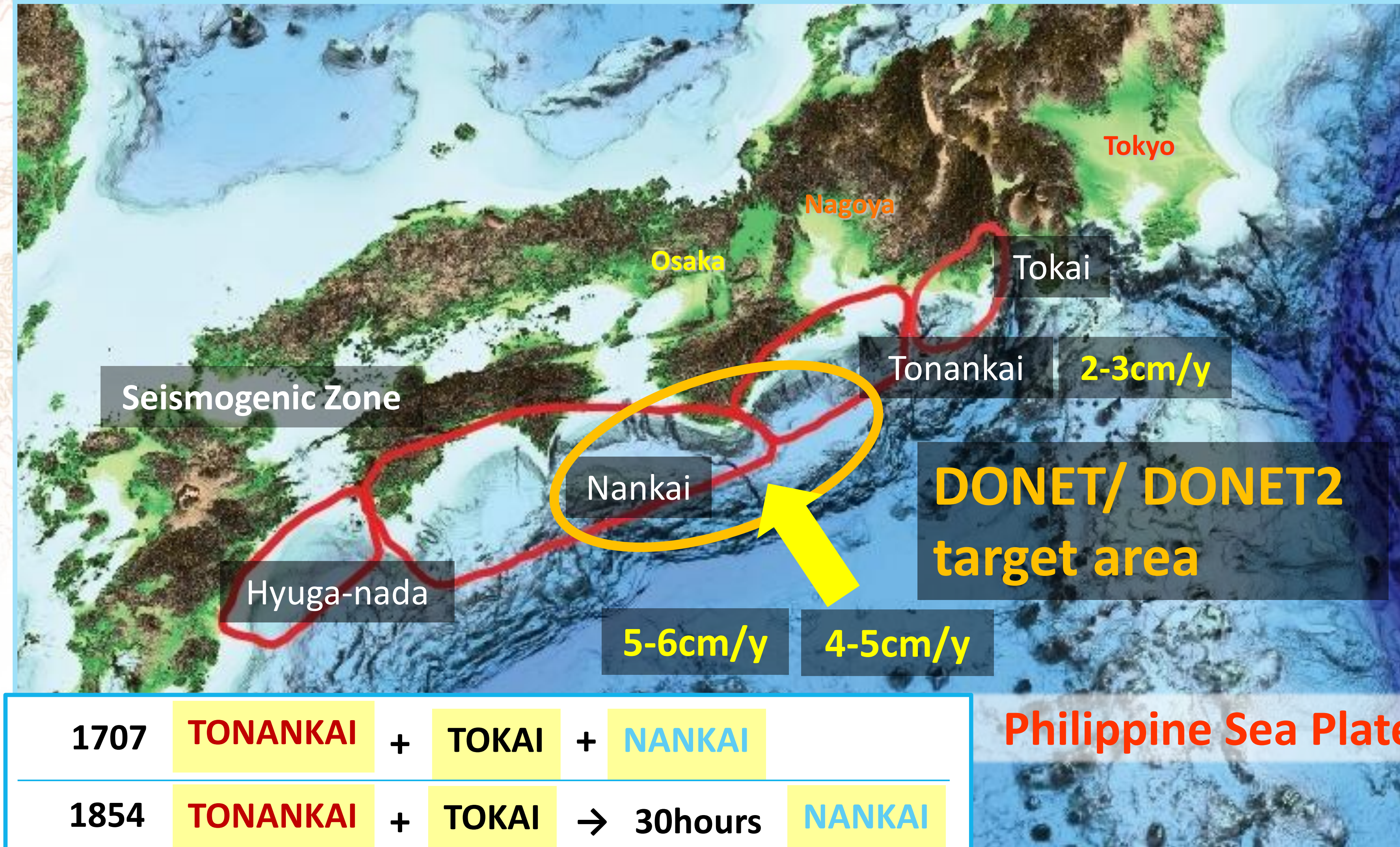
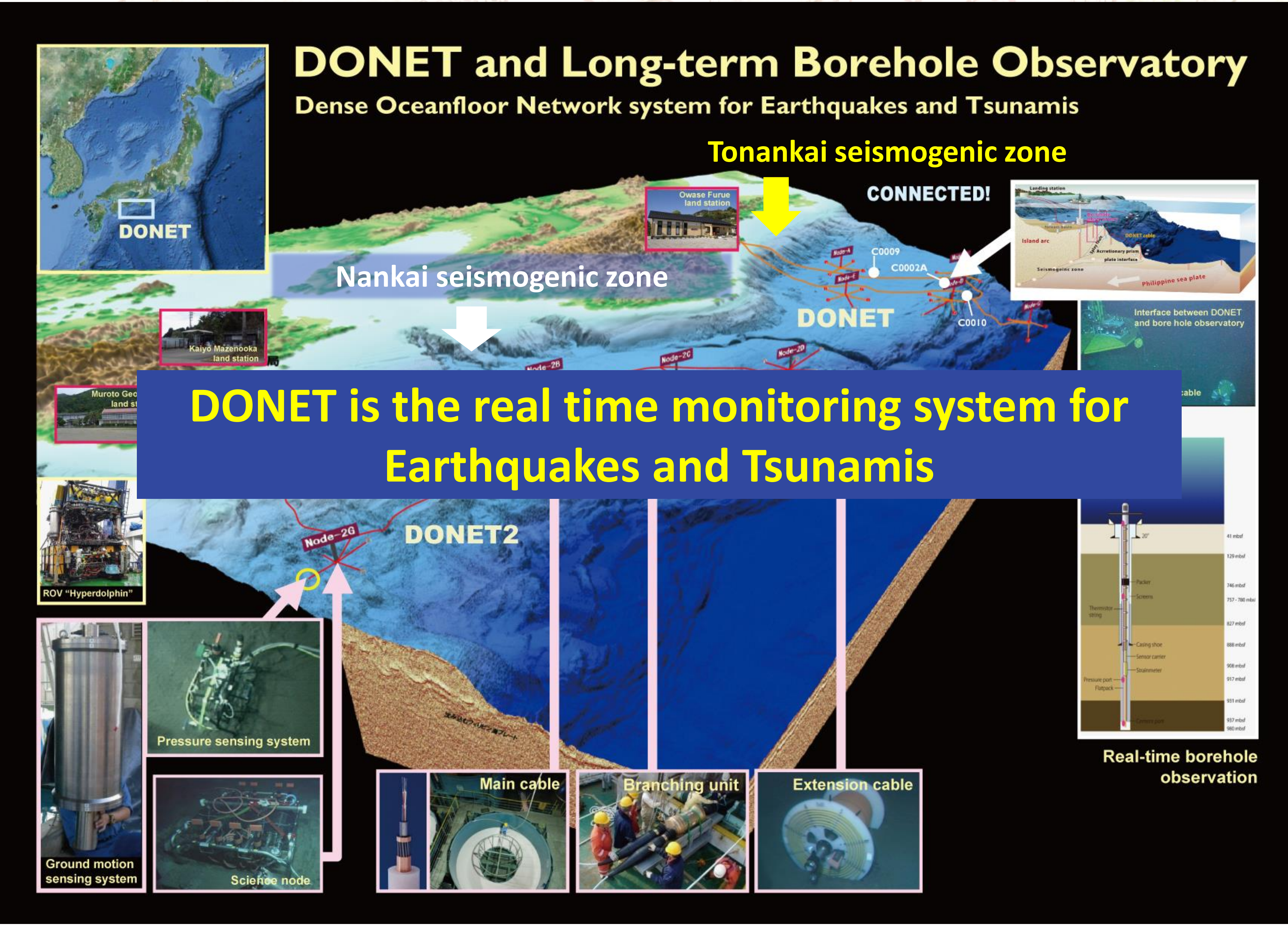
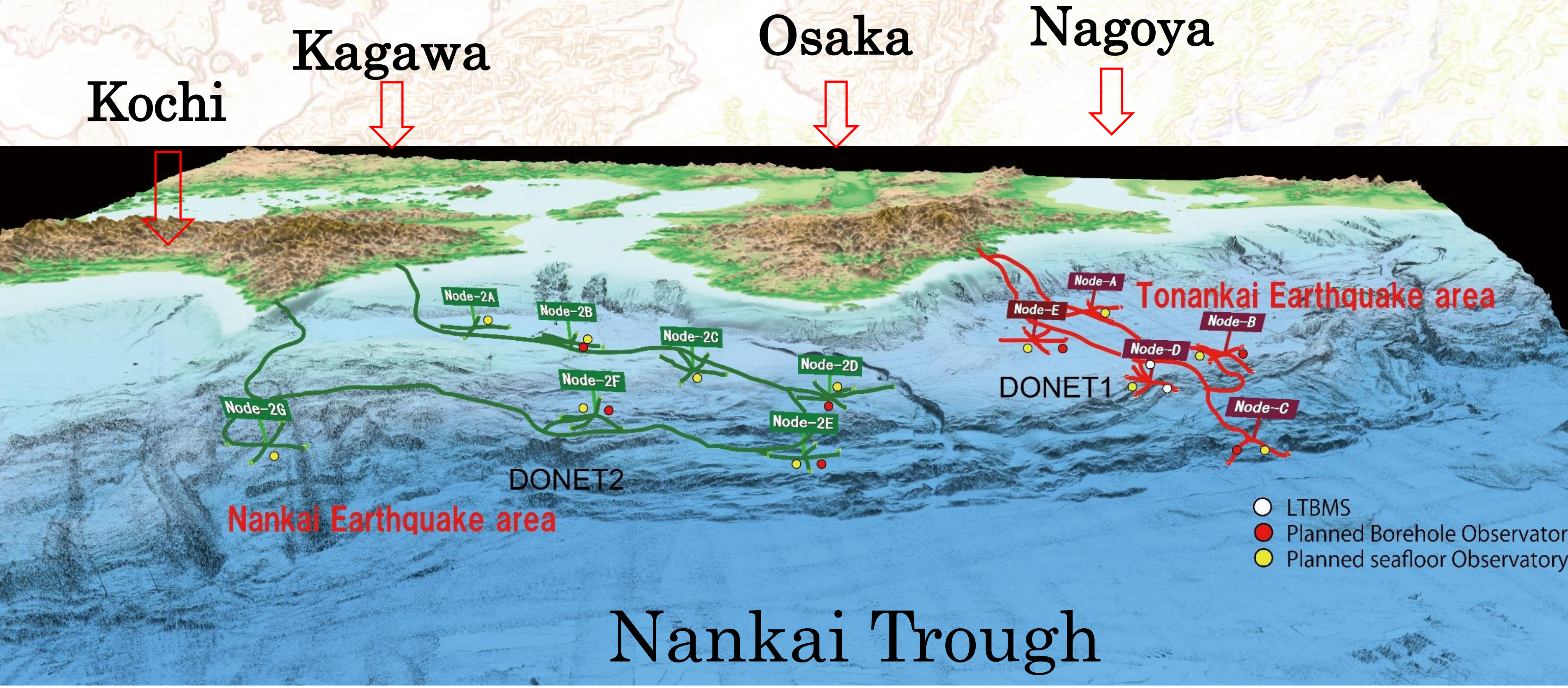
Target Region: Nankai Subdcution Zone



1707	TONANKAI	+	TOKAI	+	NANKAI	
1854	TONANKAI	+	TOKAI	→	30hours	NANKAI
1944 1946	TONANKAI			→	2years	NANKAI


DONET and Long-term Borehole Observatory
Dense Oceanfloor Network system for Earthquakes and Tsunamis
Tonankai seismogenic zone
CONNECTED!
Owase Furue land station
Nankai seismogenic zone
DONET
C0009
C0002A
C0010
Kaiyo Mazenooka land station
Island arc
Seismogenic zone
Philippine sea plate
Interface between DONET and bore hole observatory
DONET is the real time monitoring system for Earthquakes and Tsunamis
Node-2G
DONET2
ROV "Hyperdolphin"
Pressure sensing system
Ground motion sensing system
Science node
Main cable
Branching unit
Extension cable
Real-time borehole observation

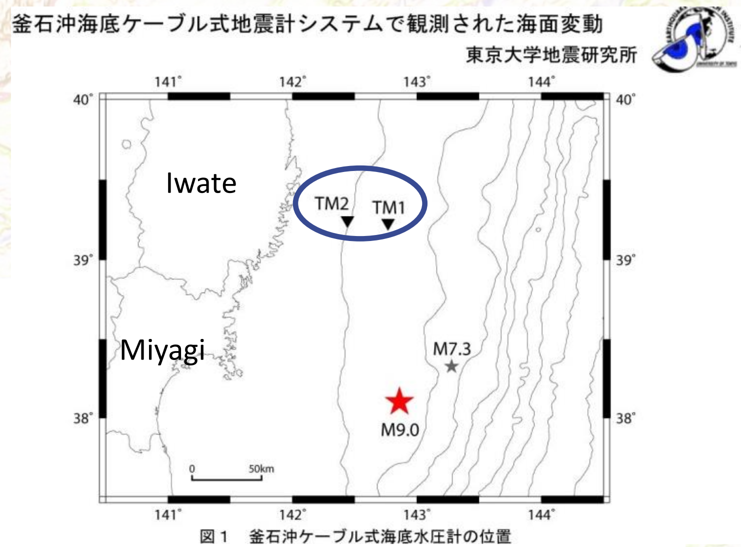
DONET Array

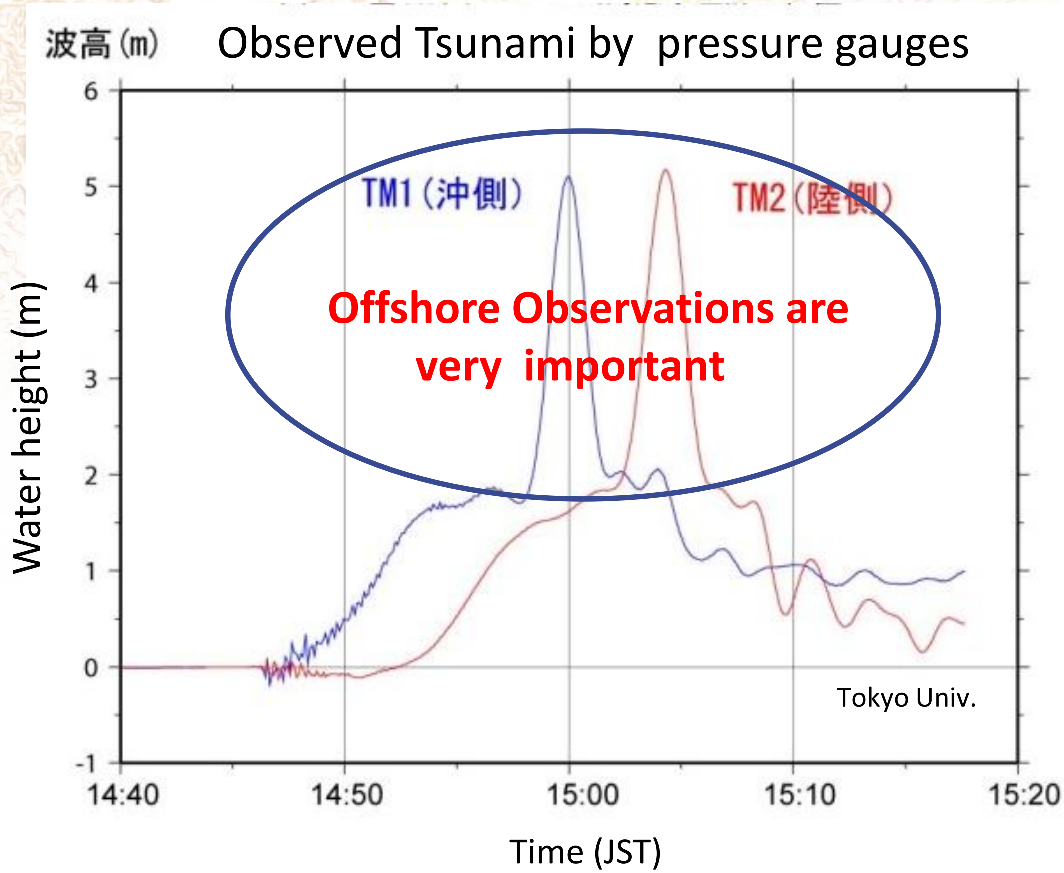

Kochi
Kagawa
Osaka
Nagoya
Node-2A
Node-2B
Node-2C
Node-2D
Node-2E
Node-2F
Node-2G
DONET2
Nankai Earthquake area
Node-A
Node-B
Node-C
Node-D
Node-E
DONET1
Tonankai Earthquake area
LTBMS
Planned Borehole Observatory
Planned seafloor Observatory
Nankai Trough

The March 11 Japan earthquake, 2011

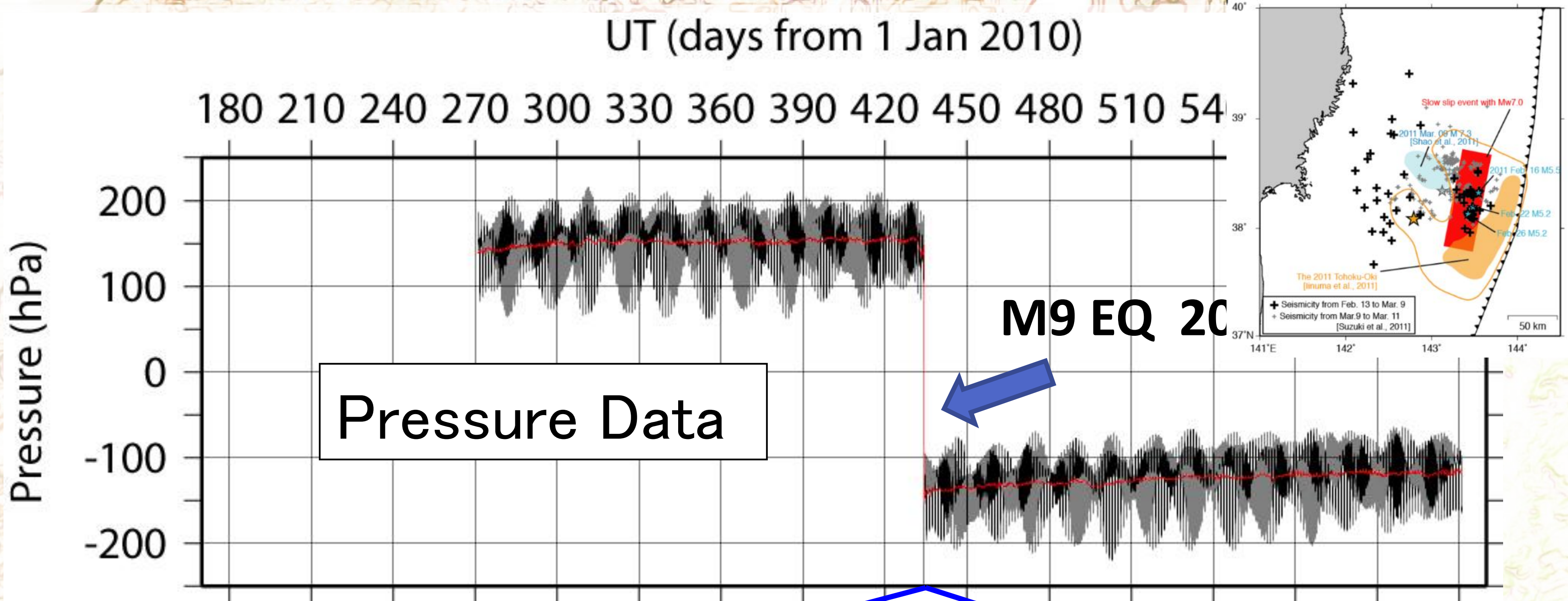
Offshore March 11 tsunami observed by a cabled observatory

Ocean bottom pressure gauge

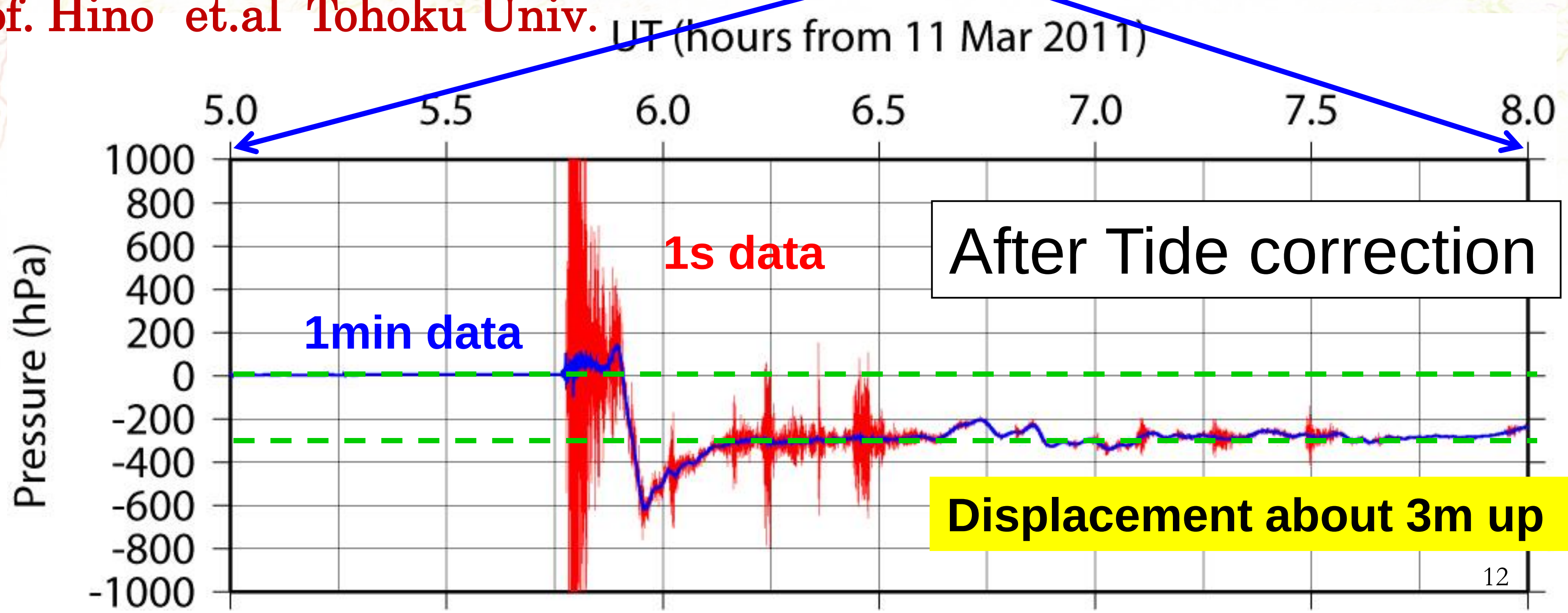




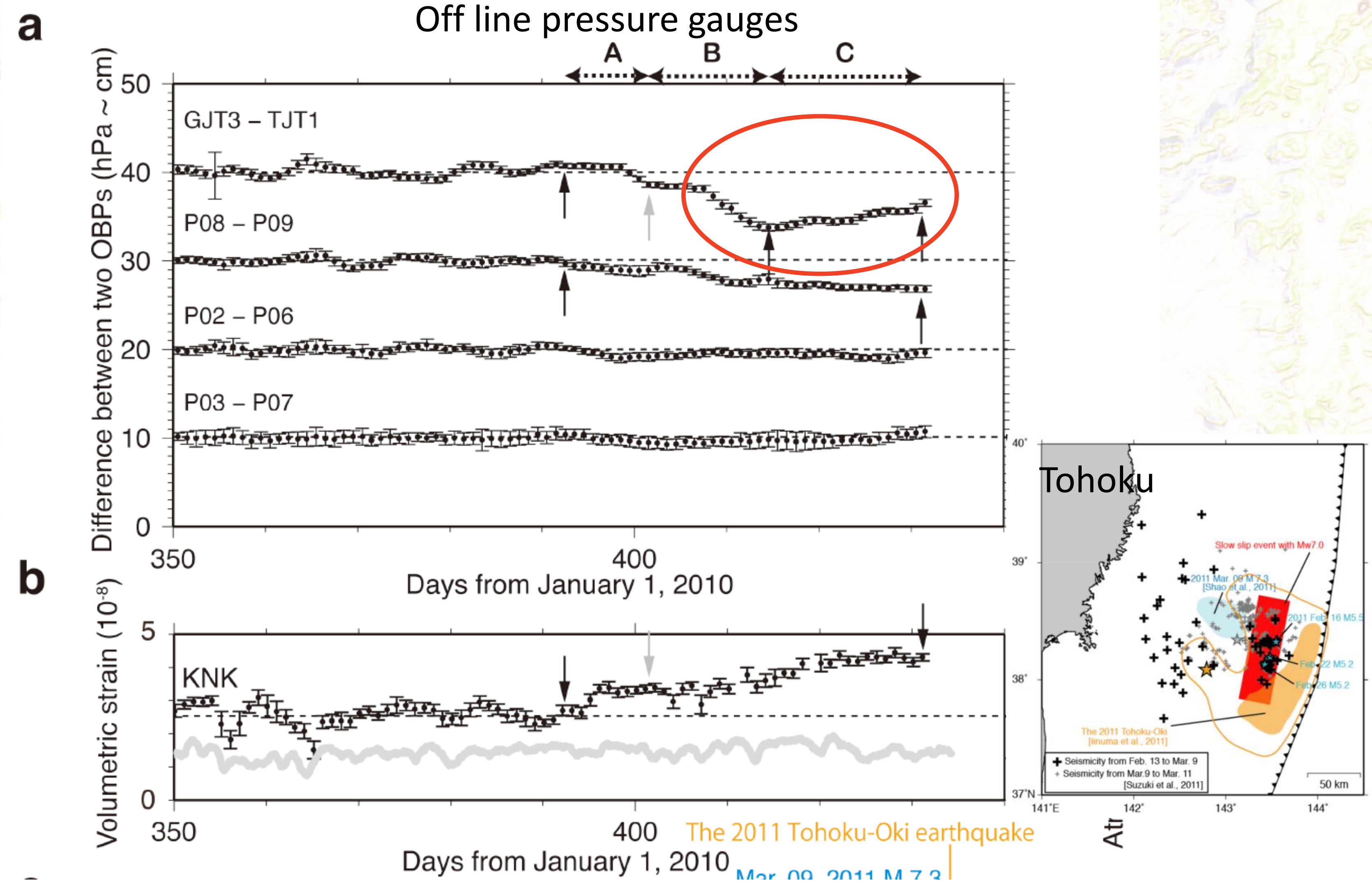
Simulation by Furumura (ERI, Tokyo)



Prof. Hino et.al Tohoku Univ.



Ocean floor deformation before Tohoku EQ.



This is very important data for the understanding of this EQ.

Prof.Hino et al. Tohoku Univ.

Outline

- Nankai Seismogenic Zone
- Dense Oceanfloor Network system for Earthquakes and Tsunamis (DONET1,DONET2)
- Large-scale Simulations for Disaster Mitigation

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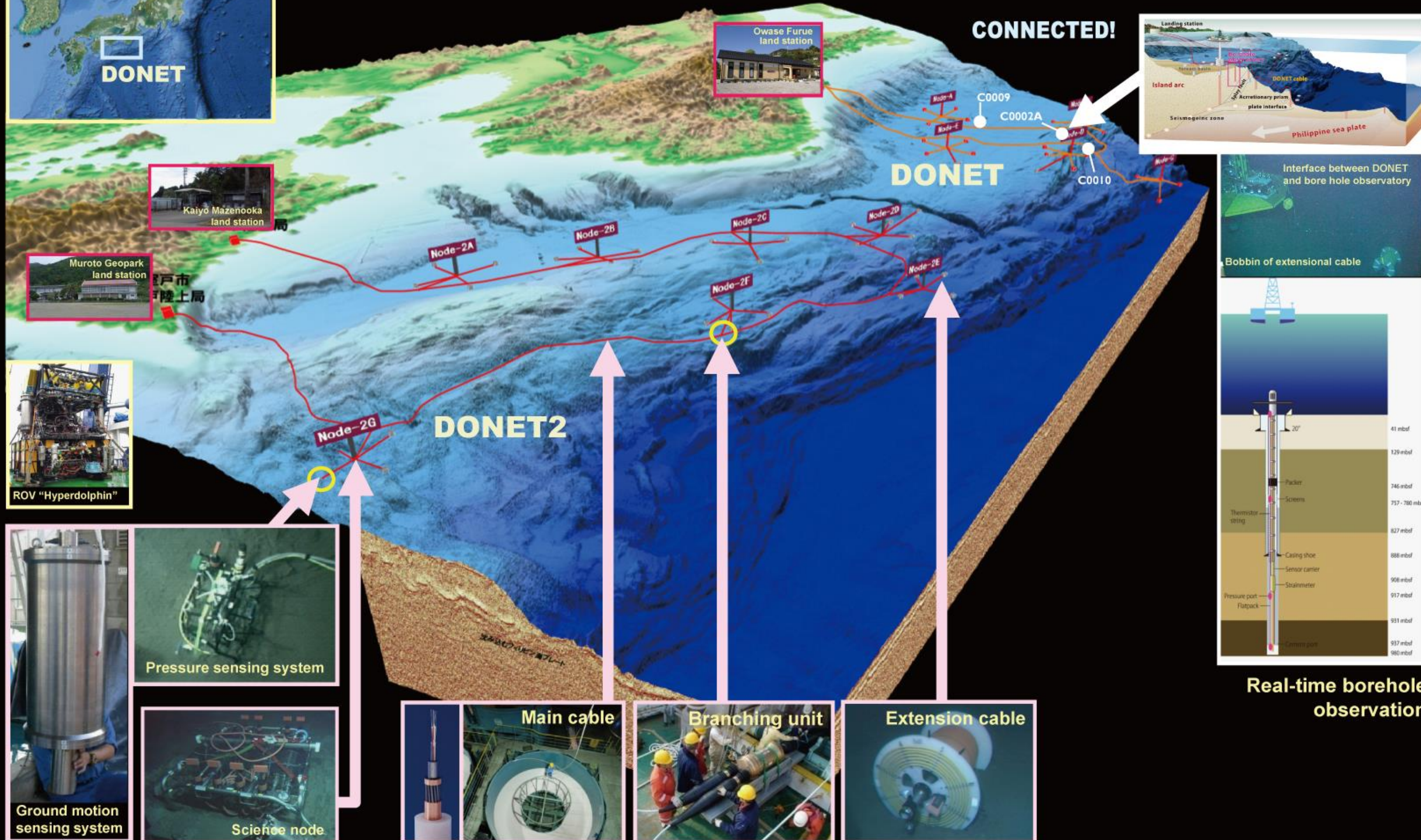
DONET and Long-term Borehole Observatory

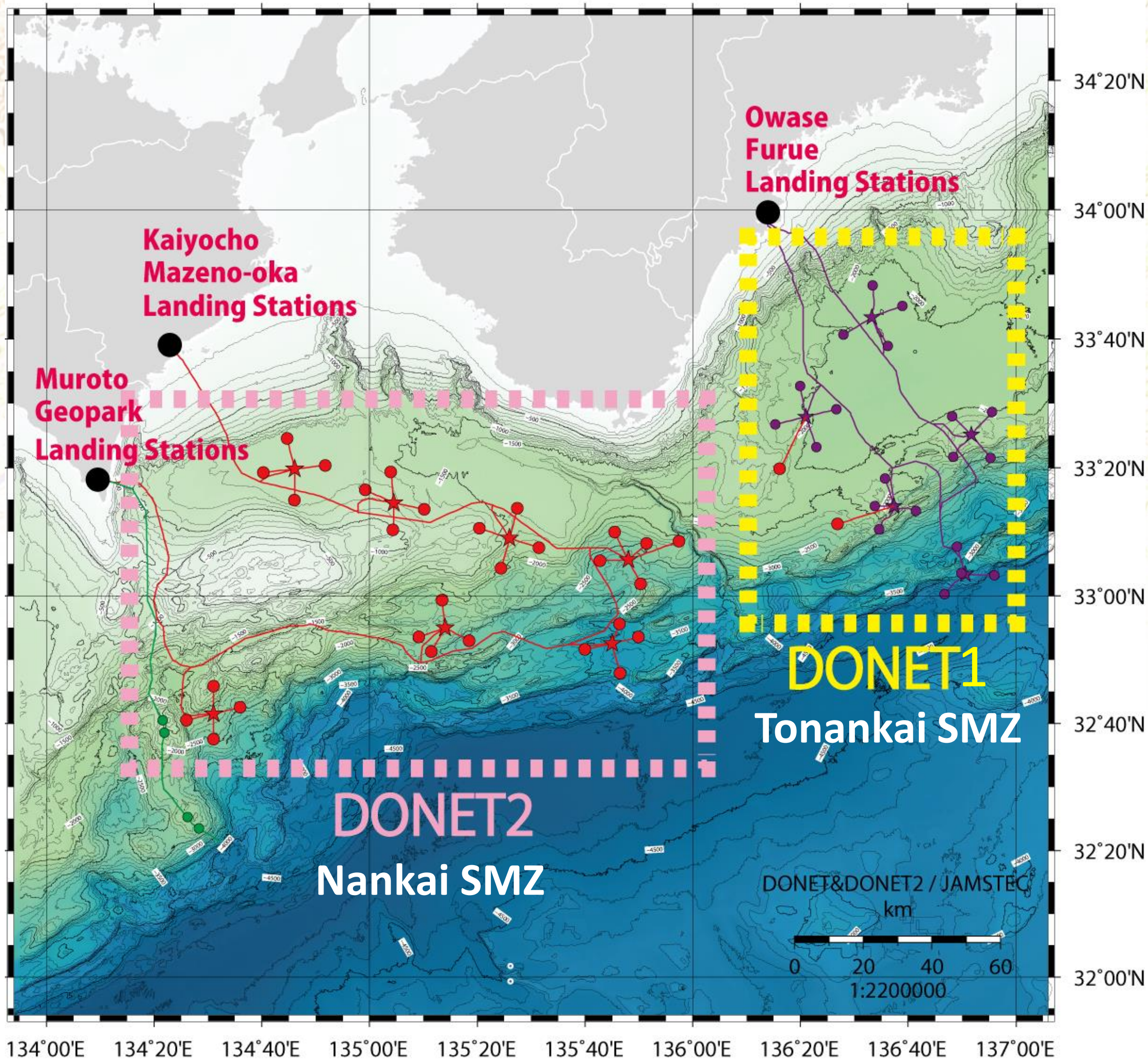
Dense Oceanfloor Network system for Earthquakes and Tsunamis

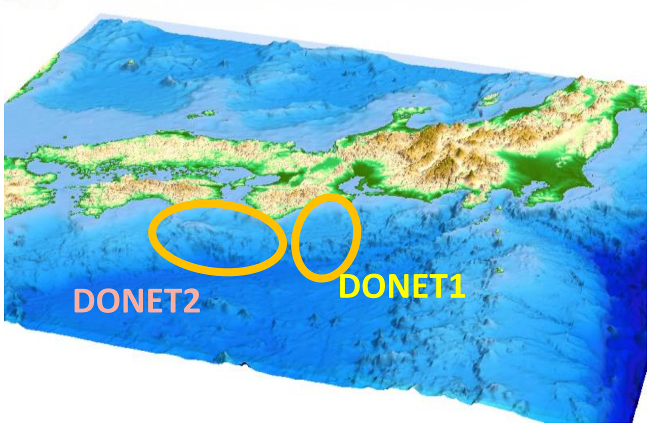


New Real-time Monitoring System in the Nankai Trough (DONET2)

DONET2 fact sheet
(in ( ) is DONET1)

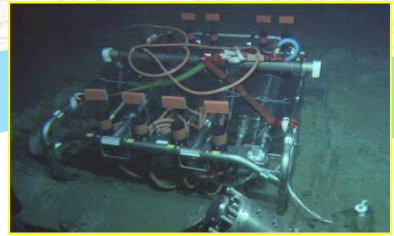
Backbone cable length : ~350km(~250km)
# of Branching Unit : 7 (5)
# of Node : 7 (5)
# of Observation system : 29 (20+2)
Total 51 Observatories



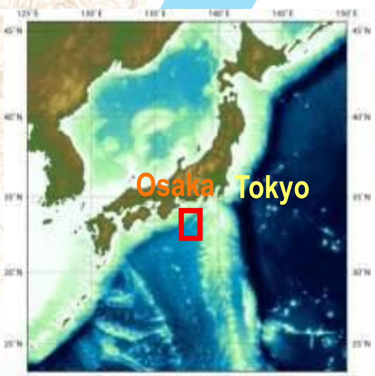


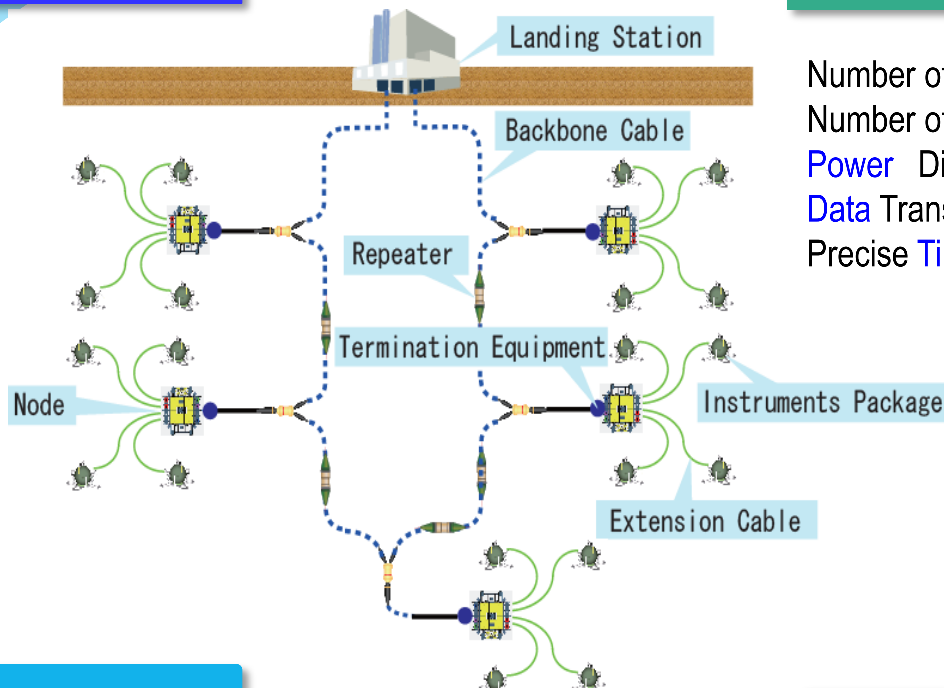
Novel functions of DONET

Redundancy:
Equipping redundant configuration on backbone cable and node

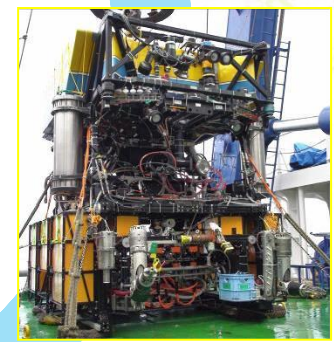


Expandability:
Branching unit and node enables wide-spread distribution of observation points.

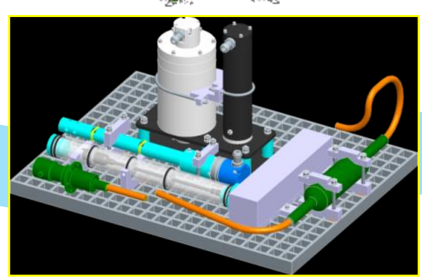




Number of Science Node : 5 Nodes
Number of User Interface : 8 ports / Node
Power Distribution : 30 W / Port
Data Transmission : 50 Mbit / s / Port
Precise Timing Control : < 1μsec



Replaceability:
Replacing observation unit at the seafloor by using underwater removable connector

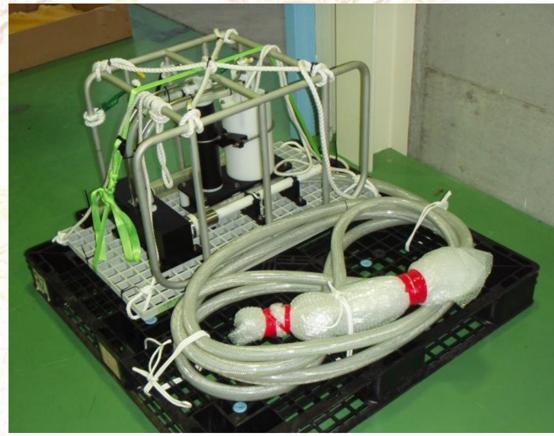


Maintainability:
Operation on the seafloor by using Remotely Operated Vehicle (ROV)

Sensing Systems to monitor Crustal activities in Real-time

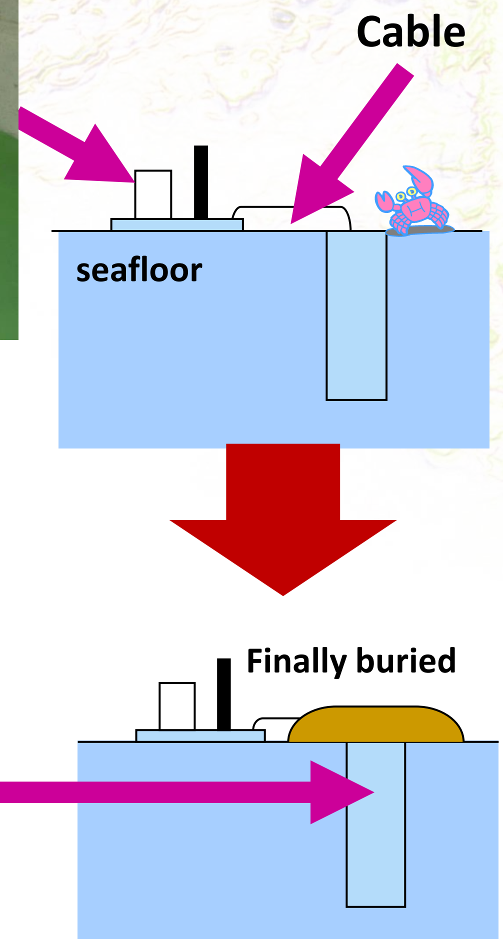
DONET stations have

- Strong motion sensor
- Broadband seismometer
- Pressure sensor
- Differential pressure sensor
- Hydrophone
- Thermometer



Pressure sensing system

Ground motion sensing system



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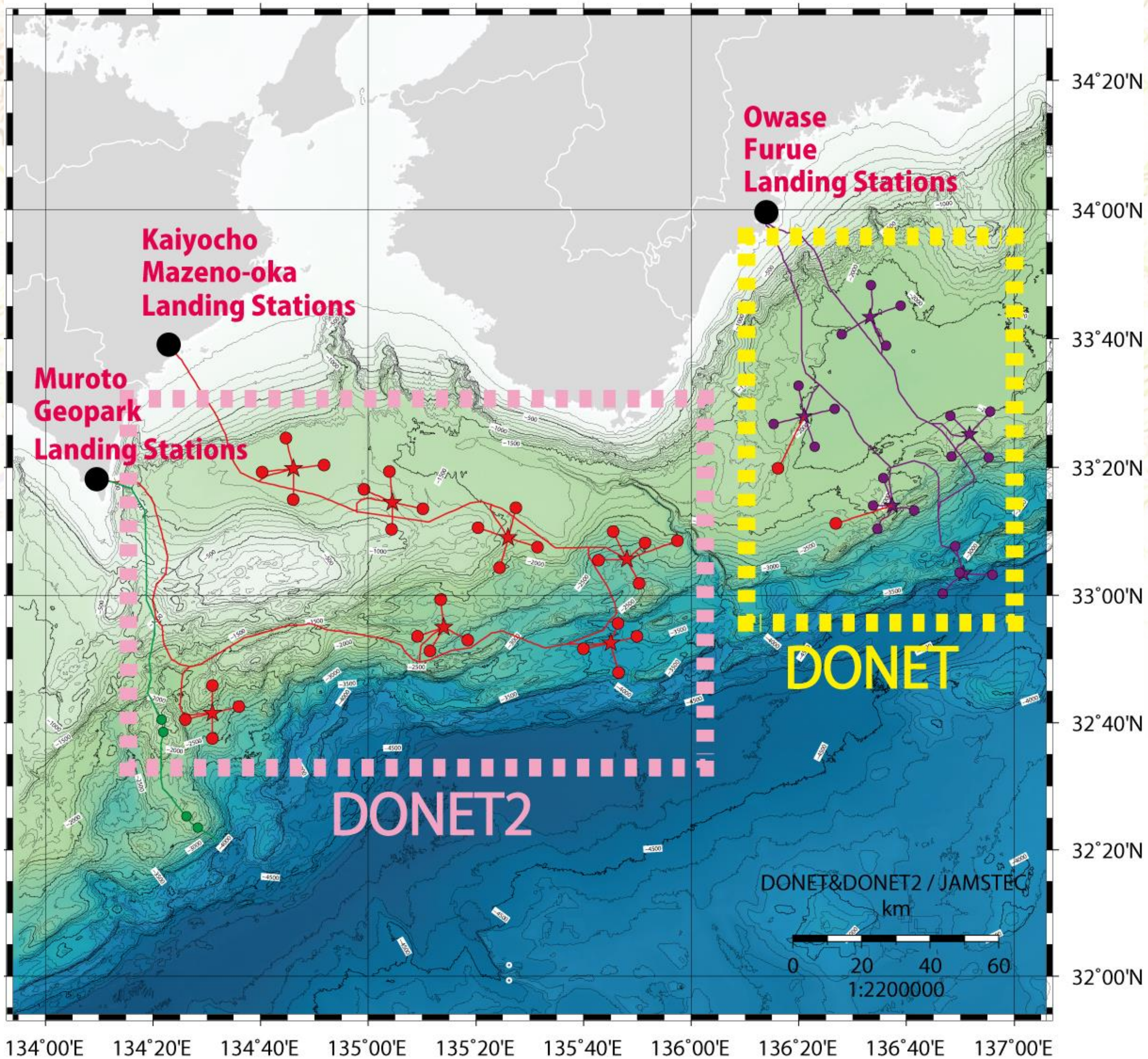
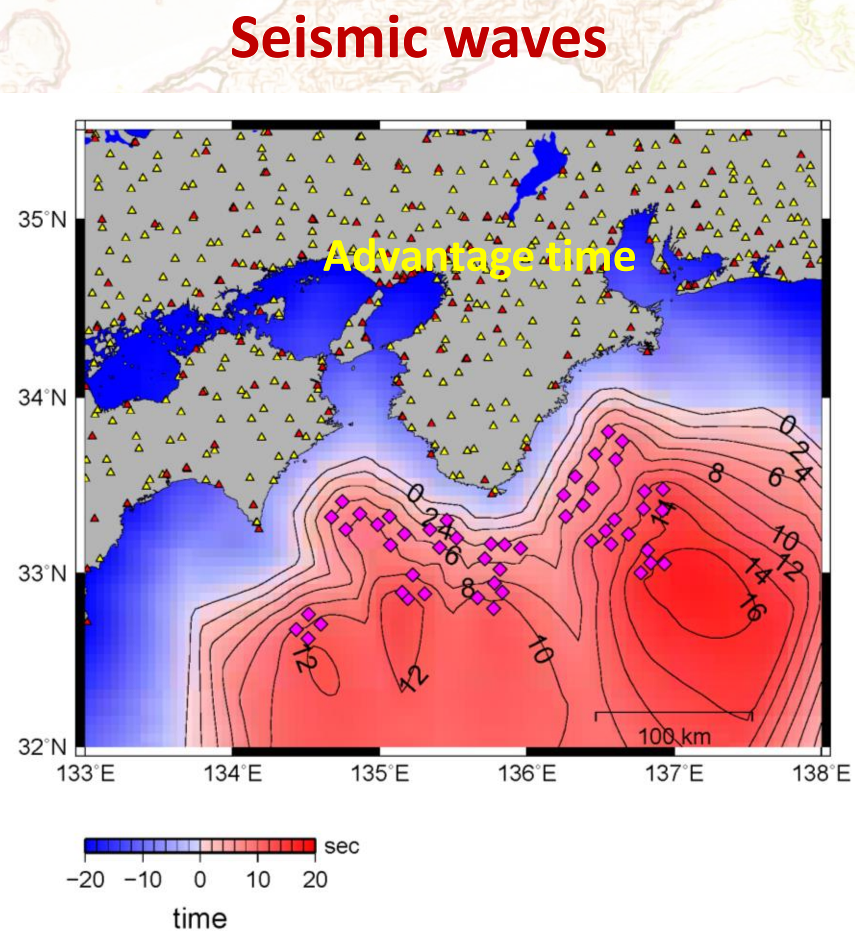
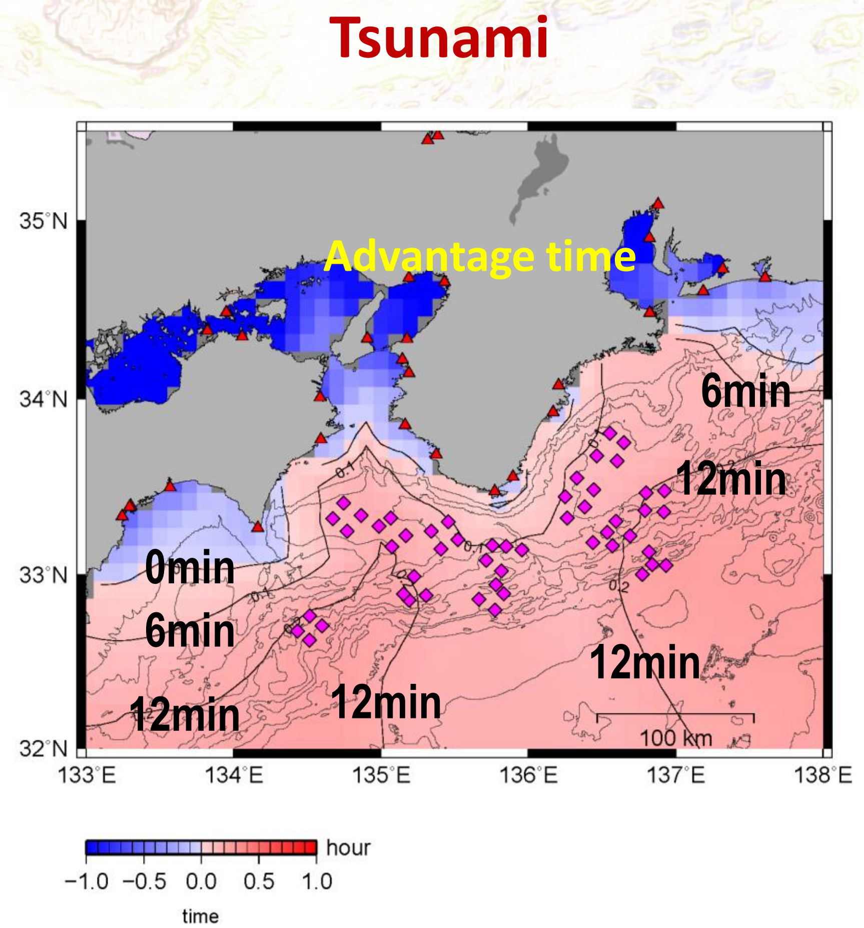


We got final route of a main cable

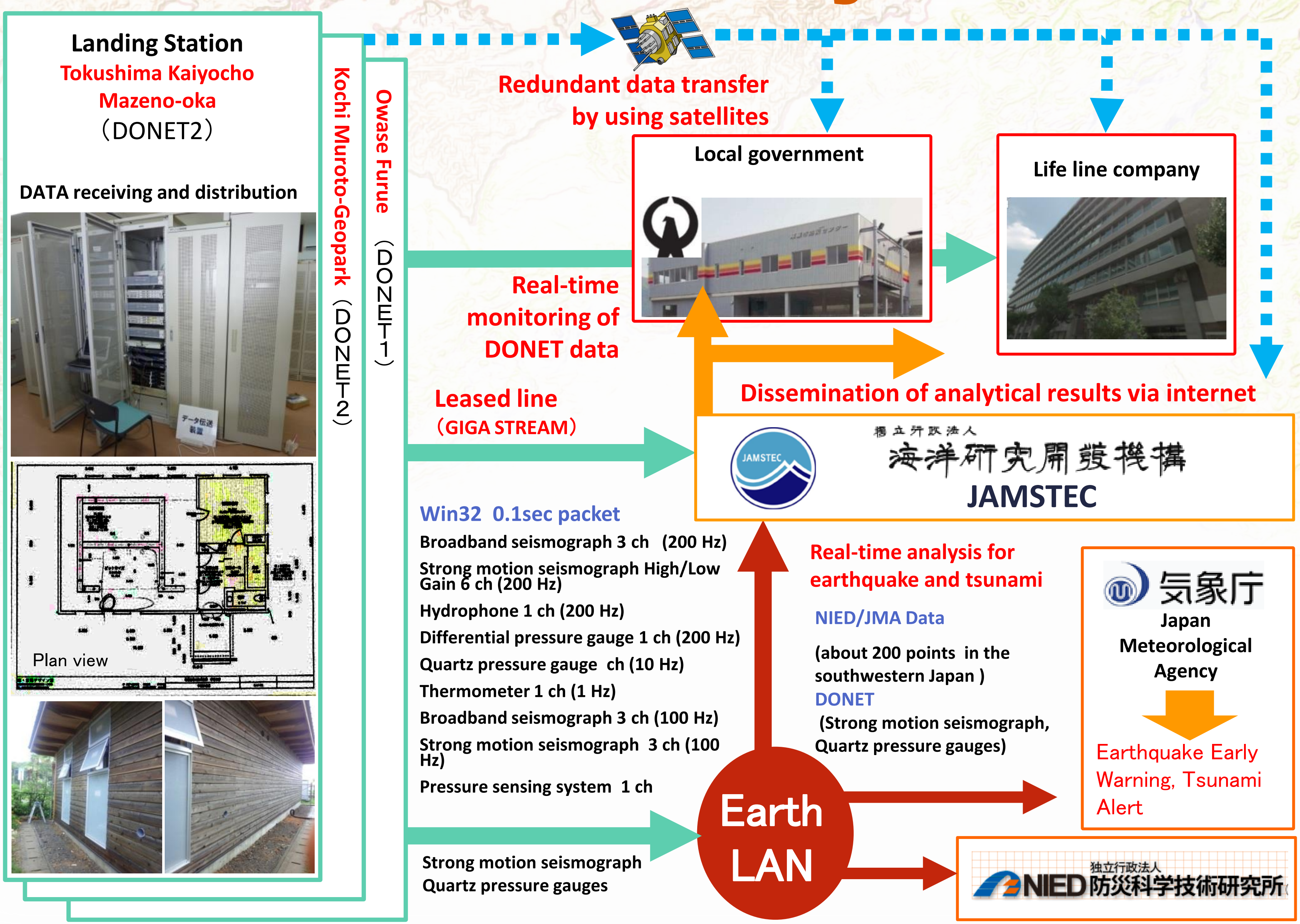
Early Detection of Earthquake and Tsunami by DONET1/DONET2



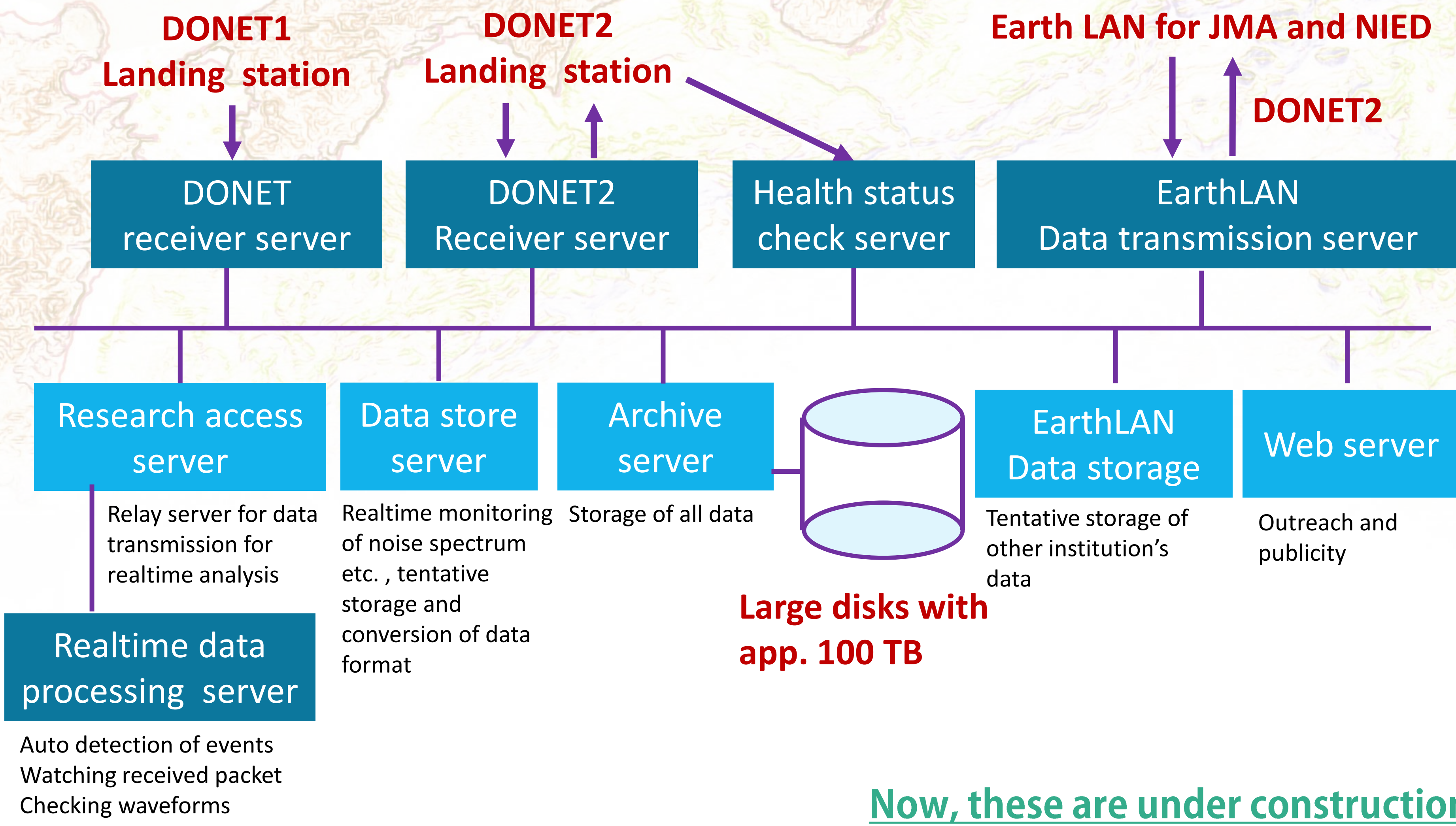


The red parts show the DONET/DONET2 detects earthquakes and tsunamis earlier than the land stations.

Data Transfer System

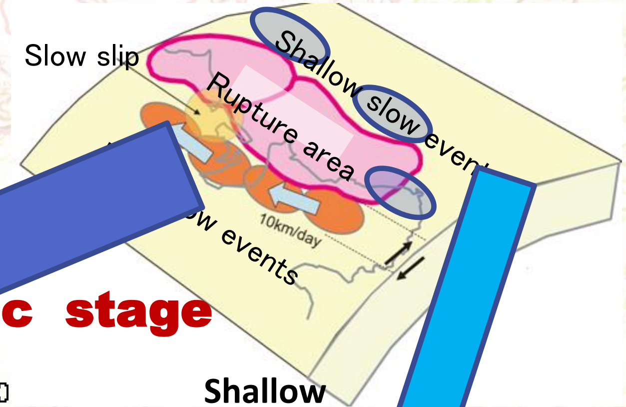


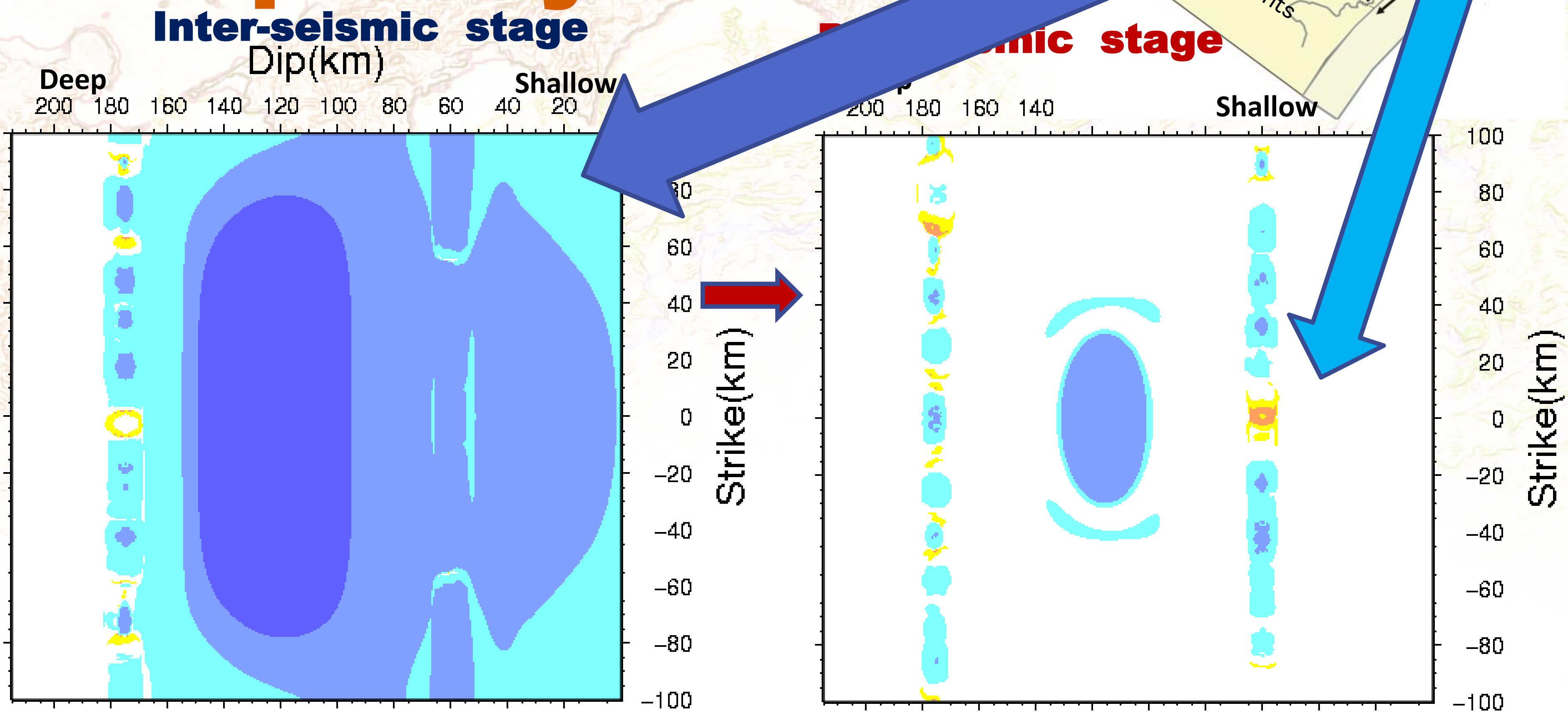
DONET database



Now, these are under construction

Monitoring of low frequency events



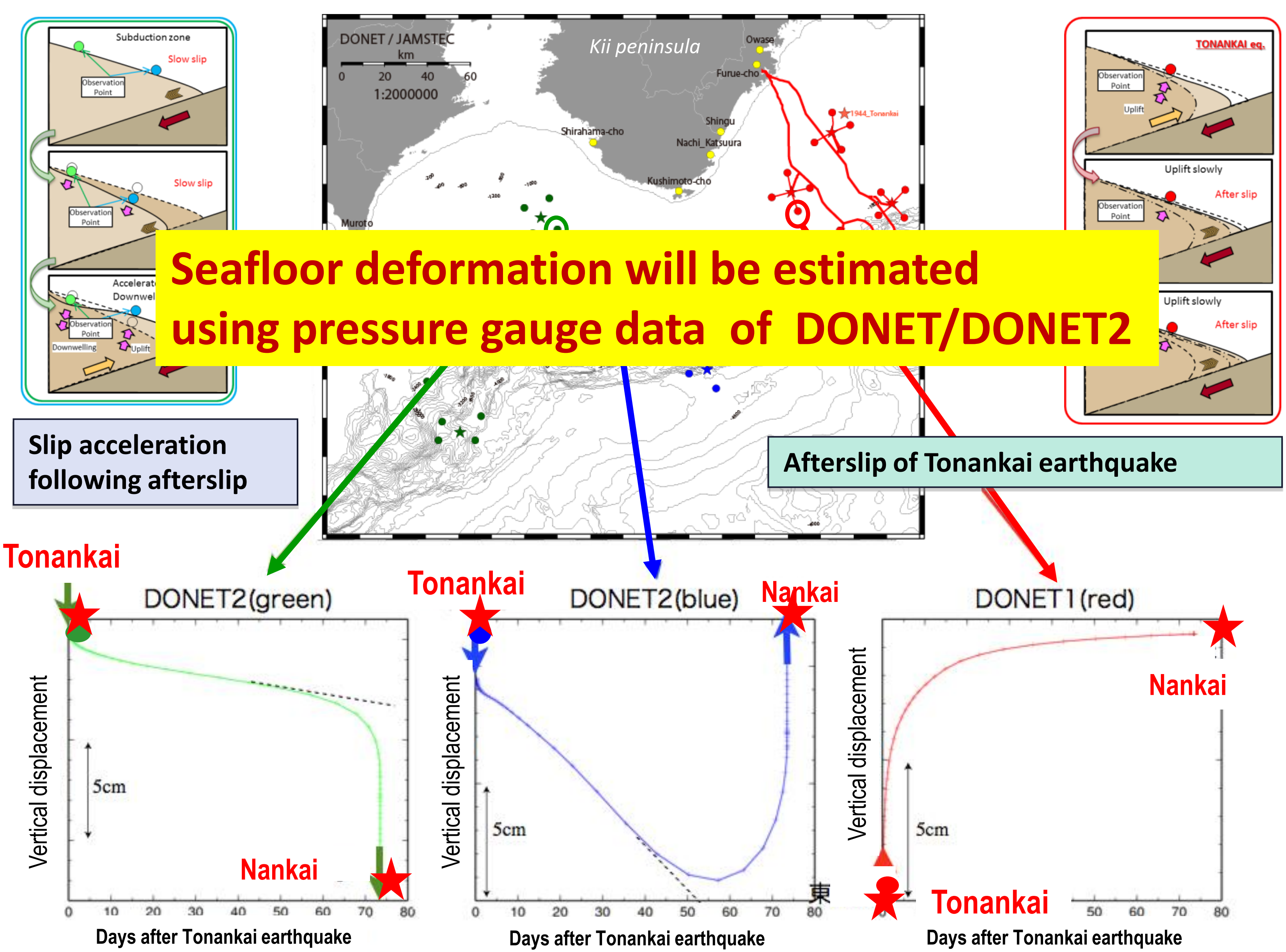


●Inter-seismic rupture cycle : Inactive shallow low frequency events

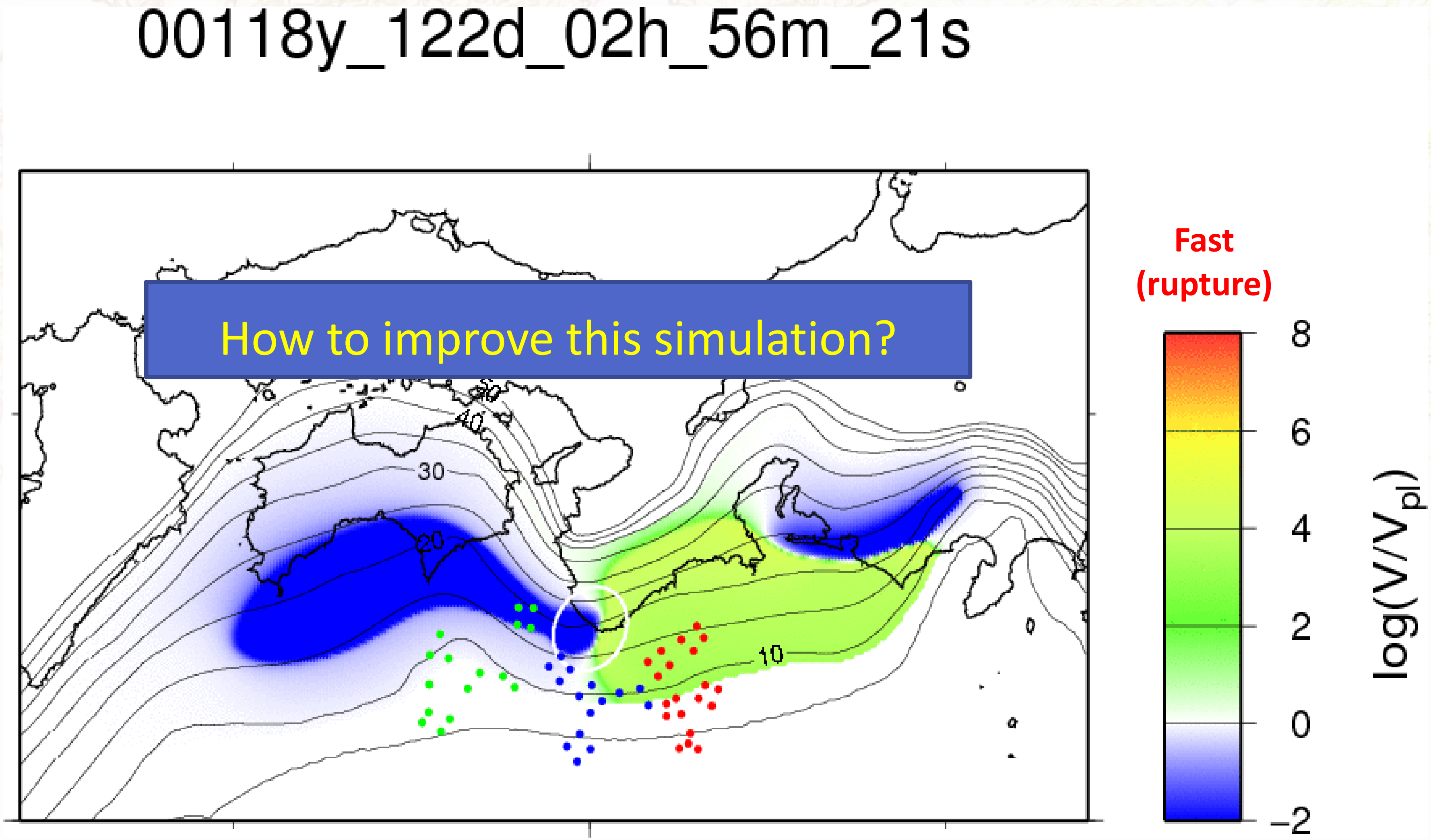
●Just before large earthquake: Change for seismicity of low frequency events in not only deeper area but also shallow area.

★ Monitoring of low frequency events → **One of informations for predictive researches**

Expected Seafloor Deformation after the Tonankai Earthquake



Expected Slow Slip after the Tonankai earthquake



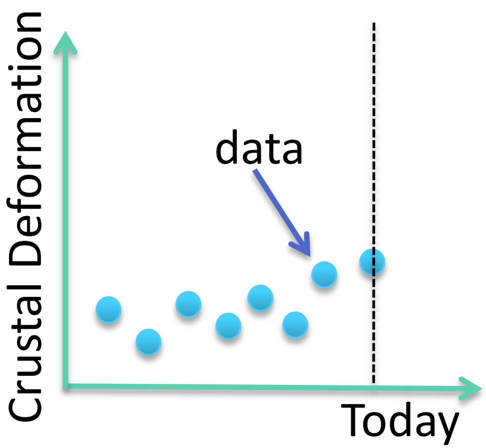
Afterslip of Tonankai earthquake propagates westward and triggers nucleation of Nankai earthquake starts

Basic concept of forecasting system

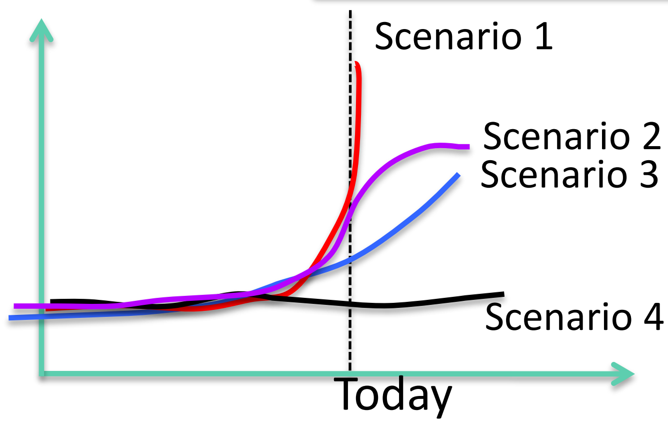
Key point①
prepare for the abrupt change in crustal deformation so that we can always compare obs. data with many scenarios.

Real Time Observation data − Huge number of simulation results → Output the forecast weighted by the consistency with observation data

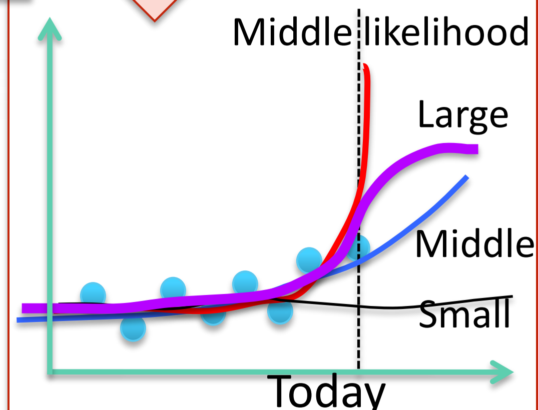
Evaluate likelihood based on the residual of obs. data and simulation



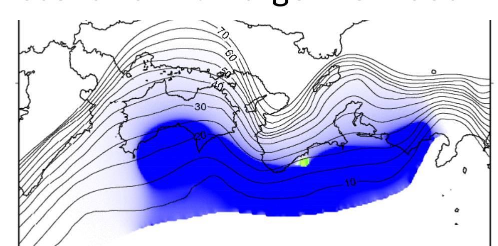
Observation database



Simulation database



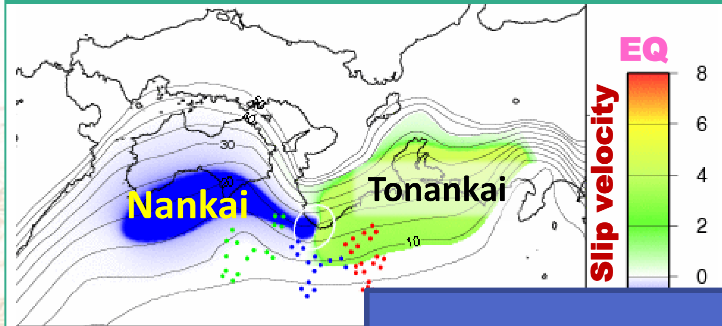
Display the animation of the scenario with large likelihood



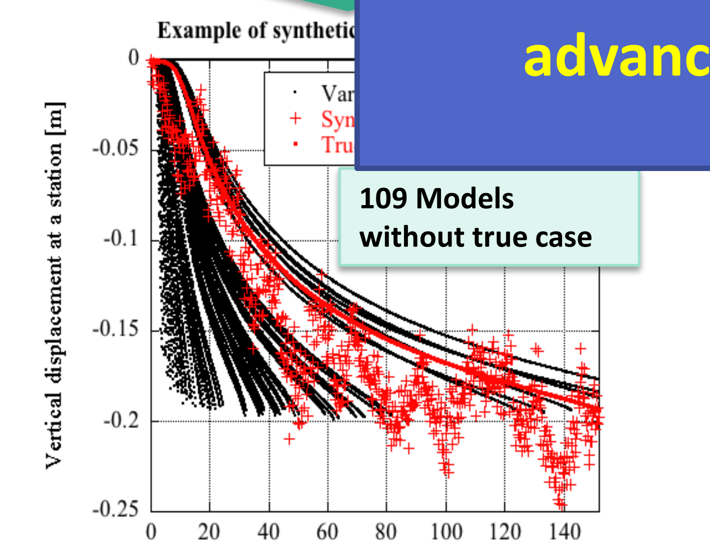
Key point②
To establish the system for forecasting.
(Increase of forecast accuracy is the next step)

Data assimilation test to estimate EQ time interval

Earthquake cycle simulation

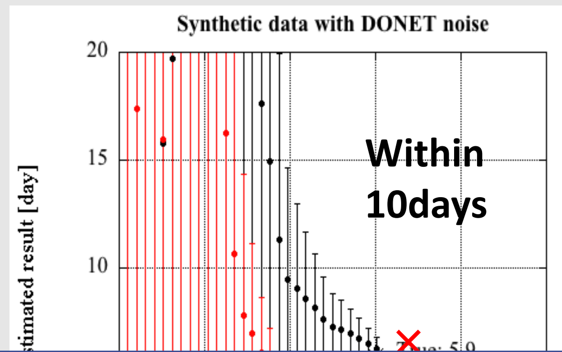


Many simulations of sea… from Tonankai to Nanka…



109 Models without true case

Comparison of synthetic data(+) and models(･) at one station

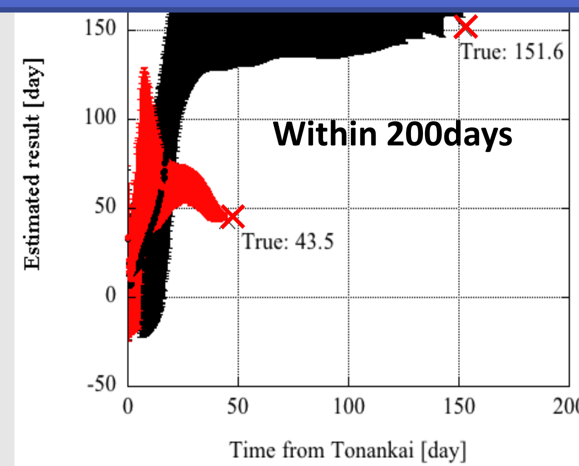


Estimation results

4 cases of synthetic data (different time interval)

…ation: DONET …ng) & DONET2 …tations

DONET/DONET2 data will be applied to data assimilation for advanced prediction researches



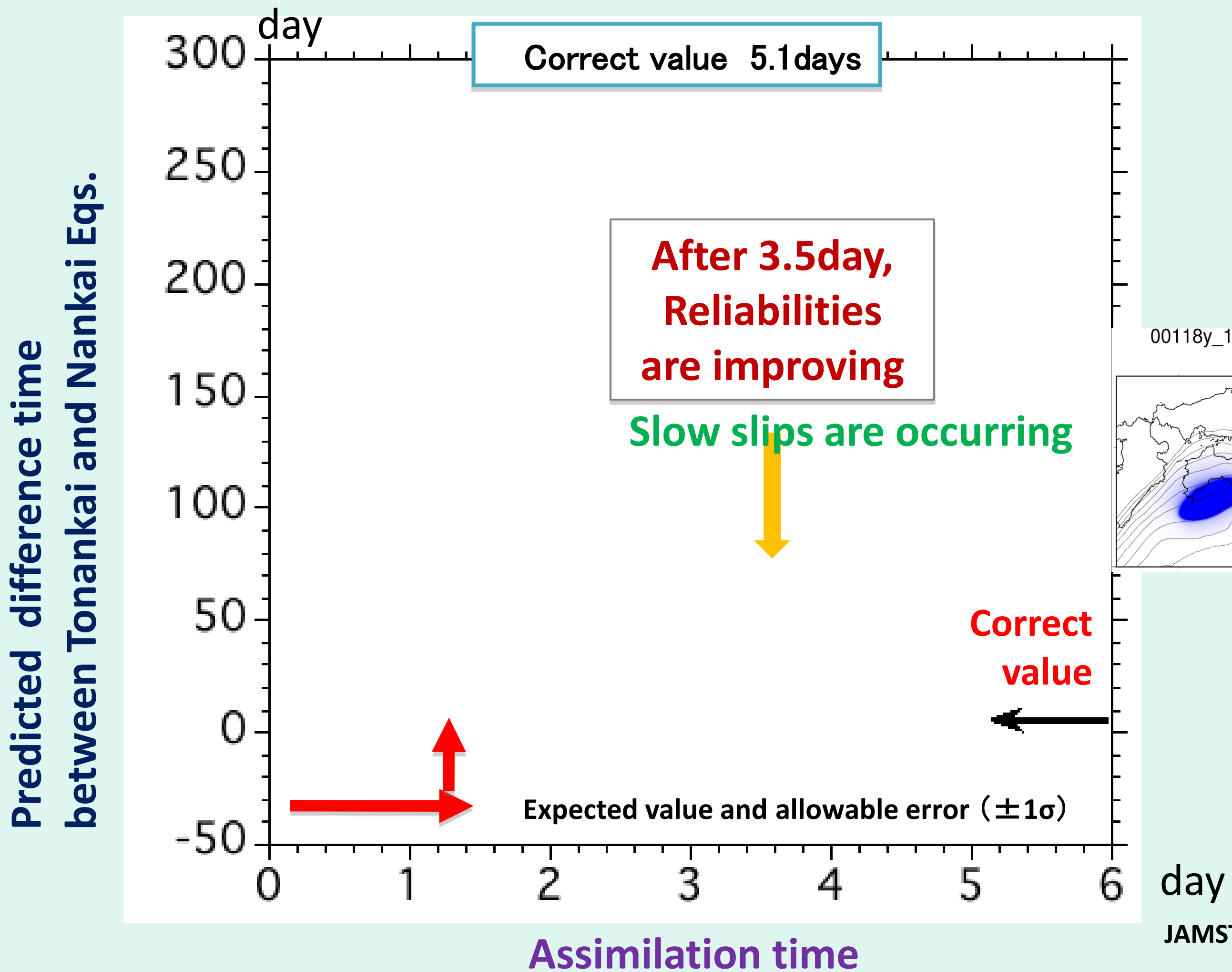
…nterval can be …ted properly in early stages because we use many observation points and models

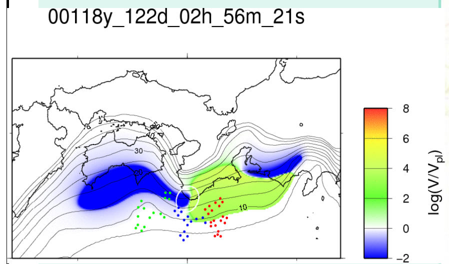
Next steps: apply the method to real data with interseismic period or SSE and improve the models based on likelihood

Numerical case study of Data assimilation

Initial condition:

The Nankai EQ. occurred 5days after the Tonankai EQ.

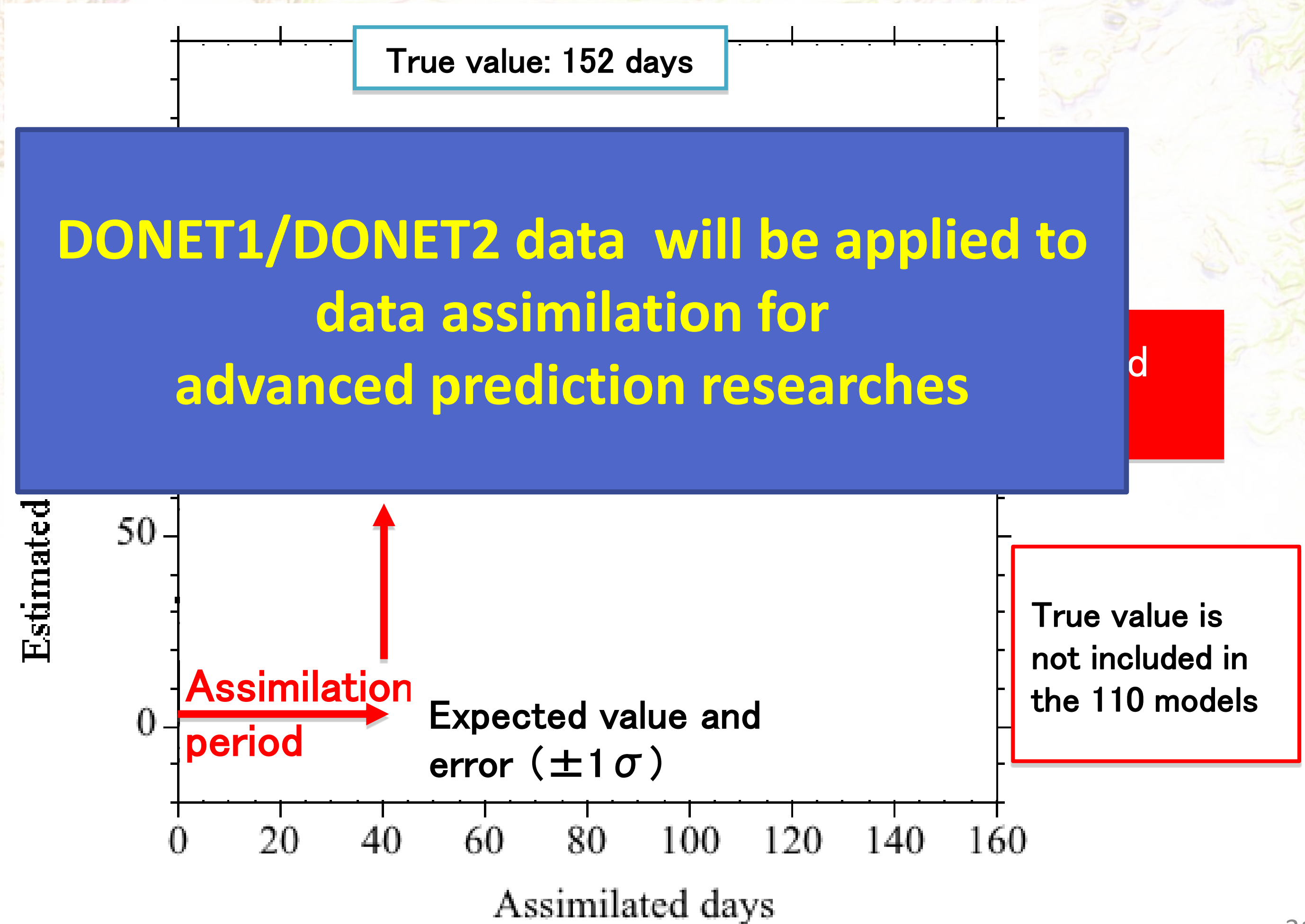




JAMSTEC Takane Hori SL

Numerical experiment of data assimilation

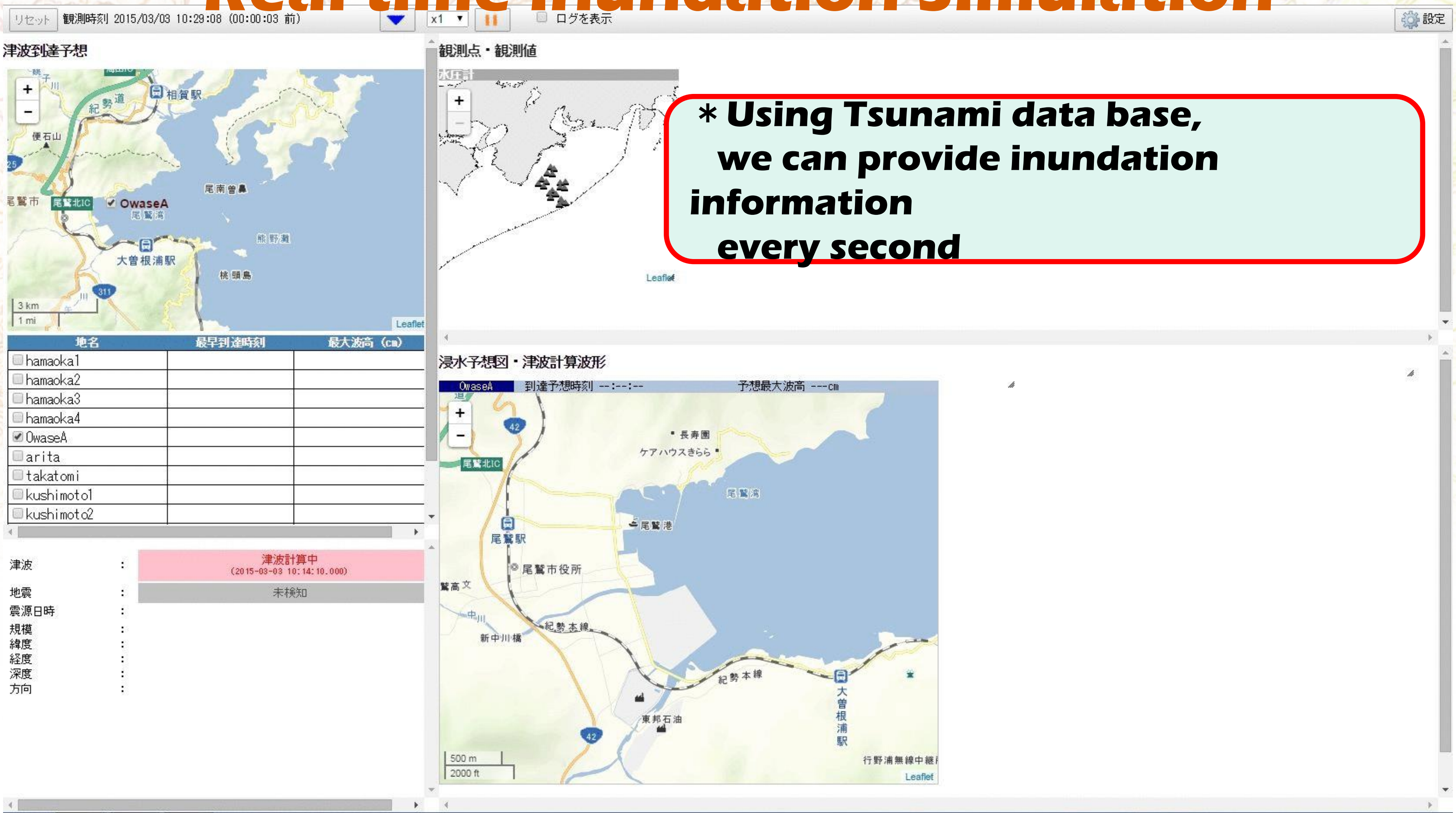
Results of the estimation from 110 models
for the case that Nankai earthquake occurs
152 days after the Tonankai earthquake



DONET1/DONET2 data will be applied to data assimilation for advanced prediction researches

Hori and Hyodo (JAMSTEC)

Utilization of DONET data
—Real time inundation Simulation—



＊Using Tsunami data base,
we can provide inundation information
every second

Display scale 100 times

A tsunami simulation code, JAGURS

- Written by FORTRAN90
- Hybrid parallelization by using openMP and MPI to run on PC, clusters, scalar/vector super computers
- Inclusion of dispersive term (Bussinesq term)
- Upgraded nesting algorithm suitable for Bussinesq modeling
- Inclusion of elastic earth deformation and seawater density stratification
- Inclusion of calculation of initial sea surface deformation with horizontal effect, and high-cut filter
- Simultaneous execution of multi-scenario
- Available via GitHub

logo

JAGURS stands for collaboratively developed by Jamstec, Anu, Awa (Tokushima), Geoscience australia, URs corporation, Satake)

JAGURS Governing Equations

$$\frac{\partial M}{\partial t} + \frac{1}{Rsin\theta}\frac{\partial}{\partial \varphi}\left(\frac{M^2}{d+h}\right) + \frac{1}{R}\frac{\partial}{\partial \theta}\left(\frac{MN}{d+h}\right) = -\frac{g(d+h)}{Rsin\theta}\frac{\partial h}{\partial \varphi} - fN - \frac{gn^2}{(d+h)^{7/3}}M\sqrt{M^2+N^2} \quad (1)$$

$$\frac{\partial N}{\partial t} + \frac{1}{Rsin\theta}\frac{\partial}{\partial \varphi}\left(\frac{MN}{d+h}\right) + \frac{1}{R}\frac{\partial}{\partial \theta}\left(\frac{N^2}{d+h}\right) = -\frac{g(d+h)}{R}\frac{\partial h}{\partial \theta} + fM - \frac{gn^2}{(d+h)^{7/3}}N\sqrt{M^2+N^2} \quad (2)$$

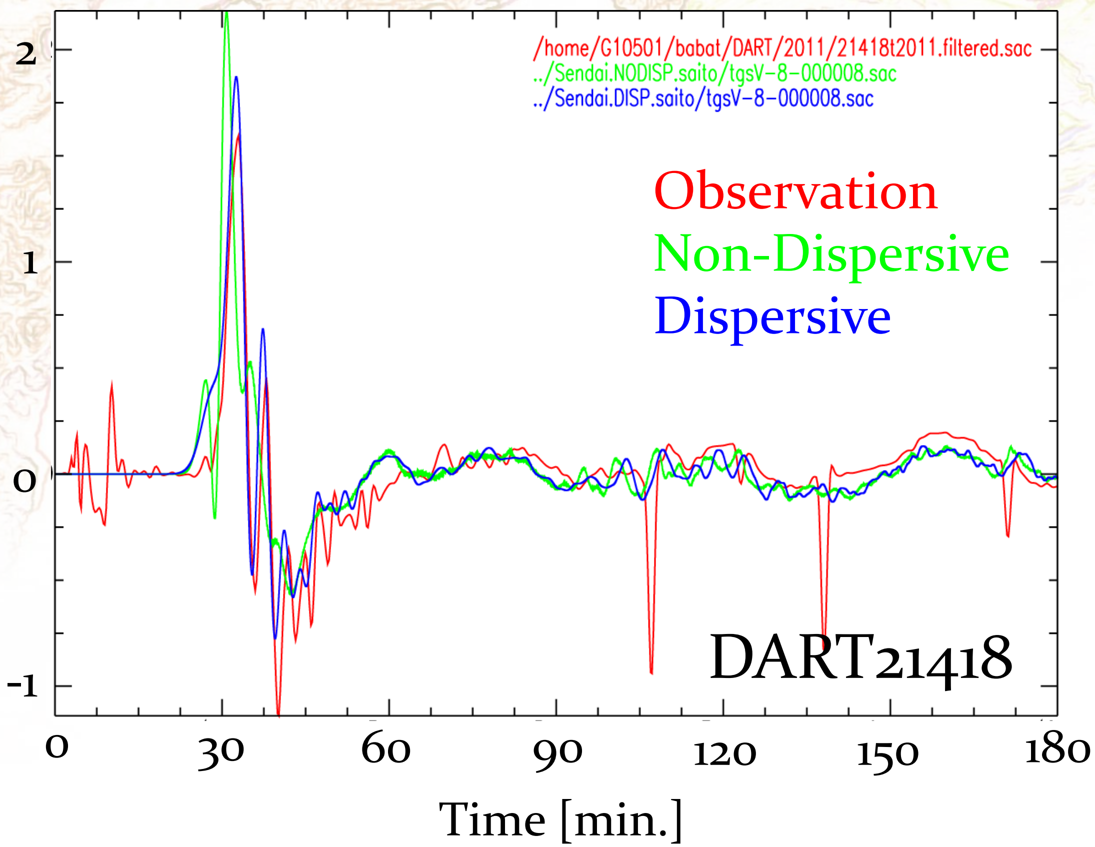
$$\frac{\partial h}{\partial t} = -\frac{1}{Rsin\theta}\left[\left(\frac{\partial M}{\partial \varphi} + \frac{\partial (Nsin\theta)}{\partial \theta}\right)\right] \quad (3)$$

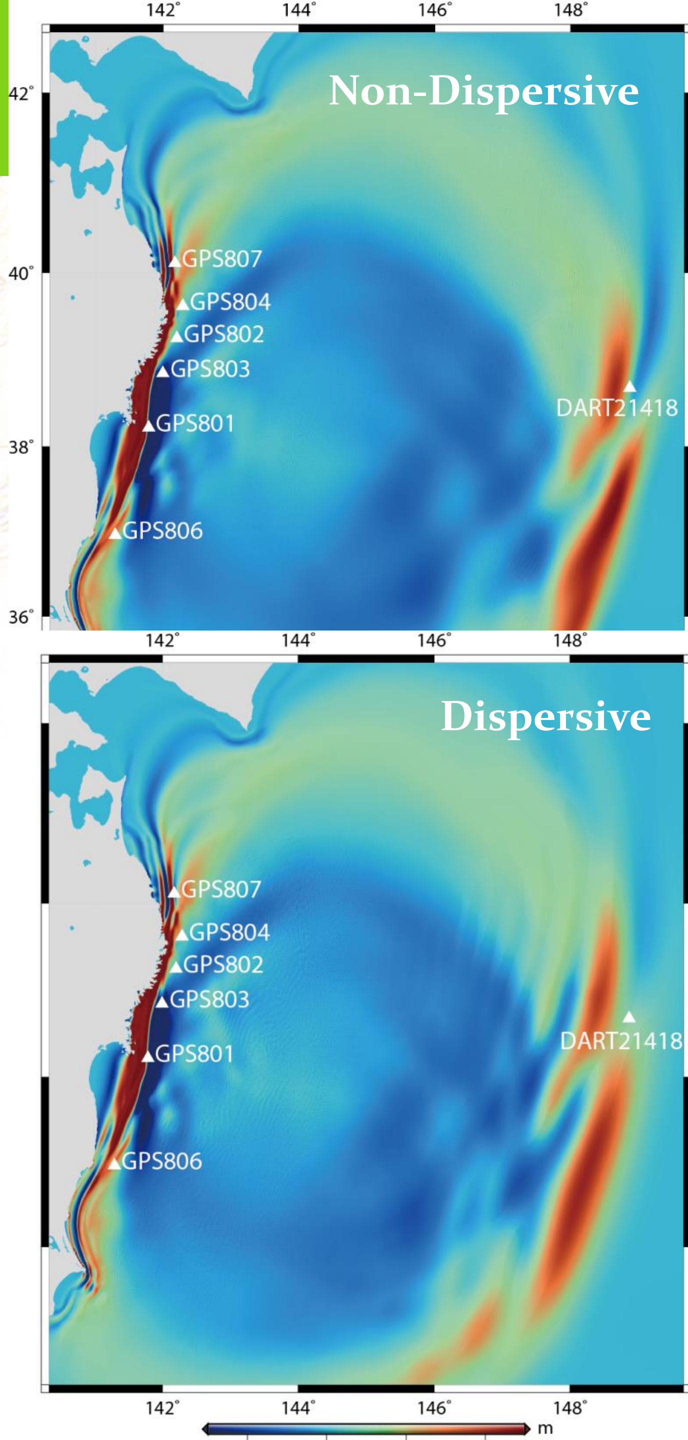
Symbol	Meaning
t	Time
R	Earth Radius
Φ	longitude
θ	co-latitude
M	Depth integrated velocity along Φ
N	Depth integrated velocity along θ
d	Water depth
h	Water deviation
g	Gravity acceleration
n	Manning's coefficient
f	Coriolis parameter
ρ_d	Sea water density at bottom
ρ_{ave}	Sea water density in average
ξ	Earth deformation due to tsunami load

Staggered grid, Leap-Frog method, 1st order upwind difference for advection terms, no breaking wave

Prof. Baba Tokushima Univ.

Waveform at DART 21418





Prof. Baba Tokushima Univ.

JAGURS Governing Equations

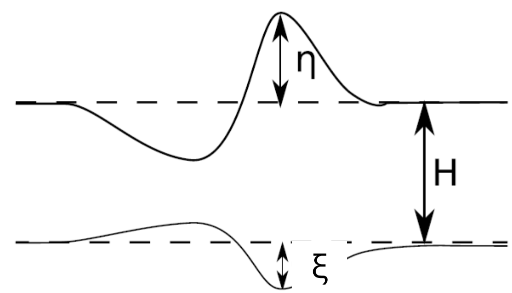
$$\frac{\partial M}{\partial t}+\frac{1}{R\sin\theta}\frac{\partial}{\partial\varphi}\left(\frac{M^2}{d+h}\right)+\frac{1}{R}\frac{\partial}{\partial\theta}\left(\frac{MN}{d+h}\right)$$
$$=-\frac{g(d+h)}{R\sin\theta}\frac{\partial h}{\partial\varphi}-fN-\frac{gn^2}{(d+h)^{7/3}}M\sqrt{M^2+N^2}$$
$$+\frac{d^2}{3R\sin\theta}\frac{\partial}{\partial\varphi}\left[\frac{1}{R\sin\theta}\left(\frac{\partial^2 M}{\partial\varphi\partial t}+\frac{\partial^2(N\sin\theta)}{\partial\theta\partial t}\right)\right] \qquad (1)$$

$$\frac{\partial N}{\partial t}+\frac{1}{R\sin\theta}\frac{\partial}{\partial\varphi}\left(\frac{MN}{d+h}\right)+\frac{1}{R}\frac{\partial}{\partial\theta}\left(\frac{N^2}{d+h}\right)$$
$$=-\frac{g(d+h)}{R}\frac{\partial h}{\partial\theta}+fM-\frac{gn^2}{(d+h)^{7/3}}N\sqrt{M^2+N^2}$$
$$+\frac{d^2}{3R}\frac{\partial}{\partial\theta}\left[\frac{1}{R\sin\theta}\left(\frac{\partial^2 M}{\partial\varphi\partial t}+\frac{\partial^2(N\sin\theta)}{\partial\theta\partial t}\right)\right] \qquad (2)$$

$$\frac{\partial\ h}{\partial t}=-\frac{1}{R\sin\theta}\left[\left(\frac{\partial M}{\partial\varphi}+\frac{\partial(N\sin\theta)}{\partial\theta}\right)\right] \qquad (3)$$

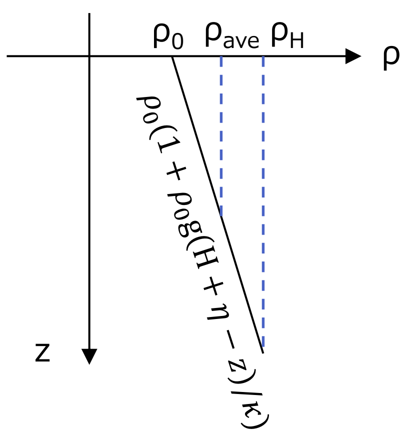
Staggered grid, Leap-Frog implicit method, 1st order upwind difference for advection terms, no breaking wave **Prof. Baba Tokushima Univ.**

1. **Elastic loading**



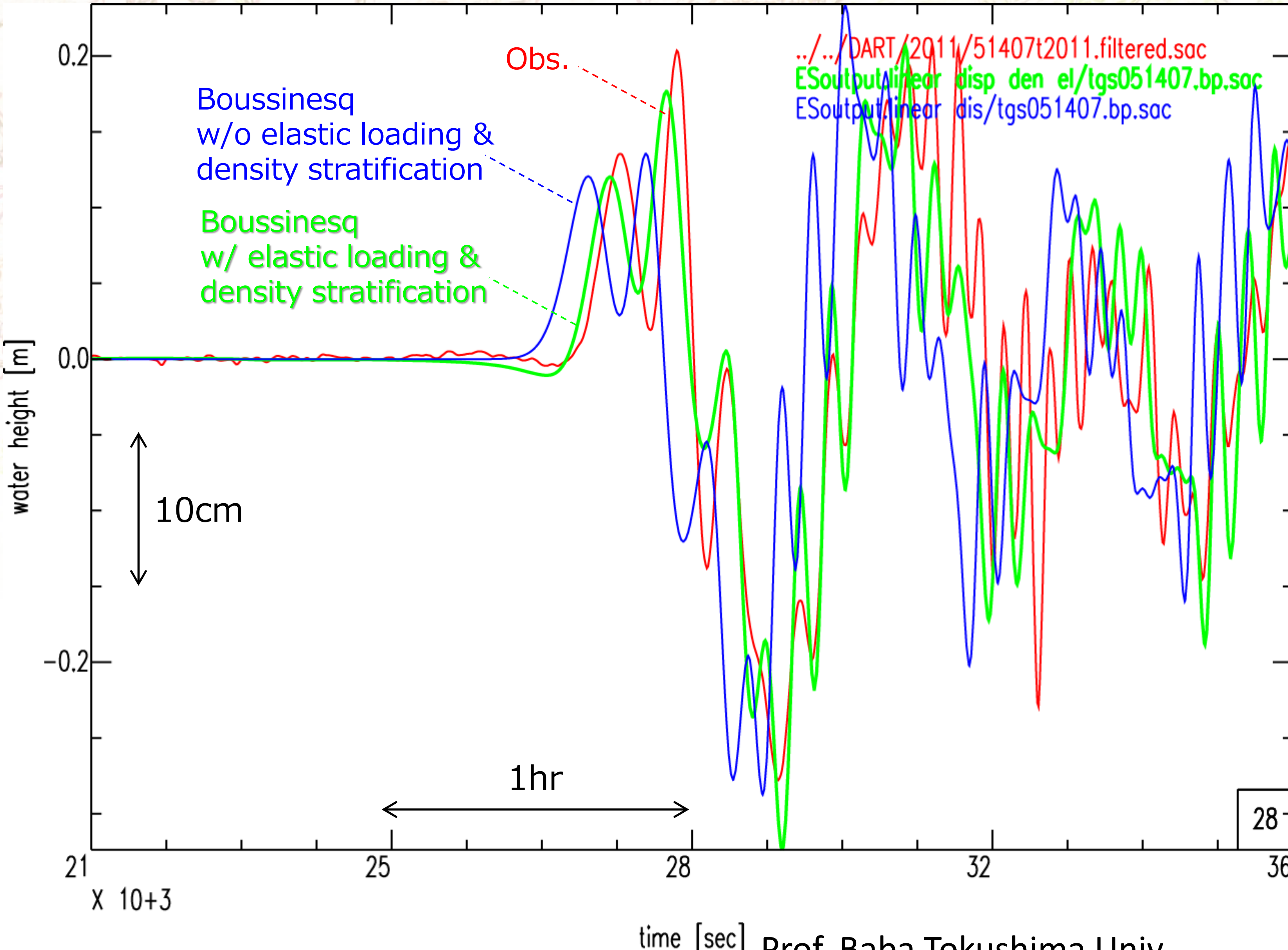
ξ can be calculated using Green's function that describes the response to a unit mass load concentrated at a point on its surface.

2. **seawater density stratification**



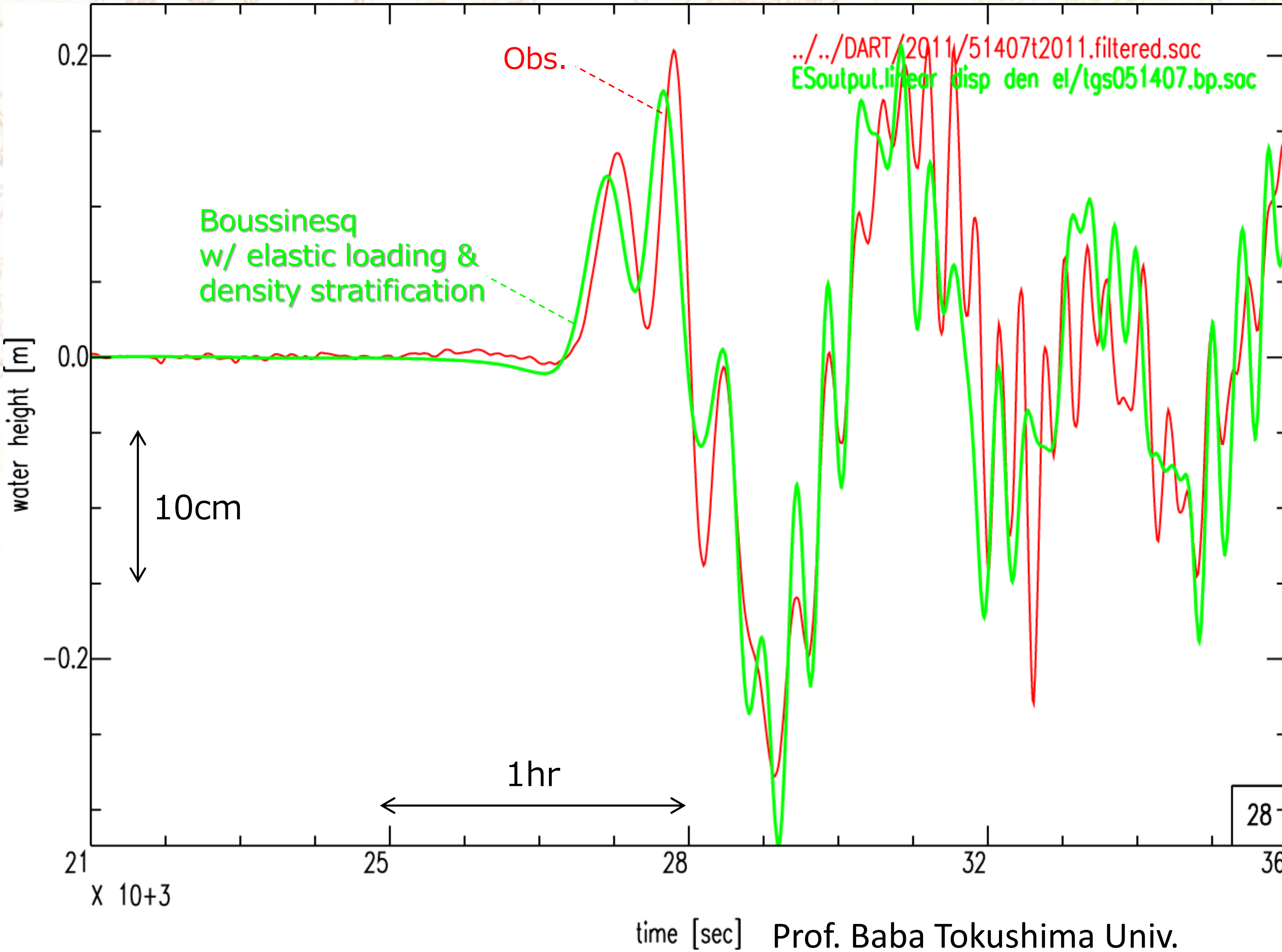
Allgeyer and Cummins (2014)

Site 51407 (Hawaii)



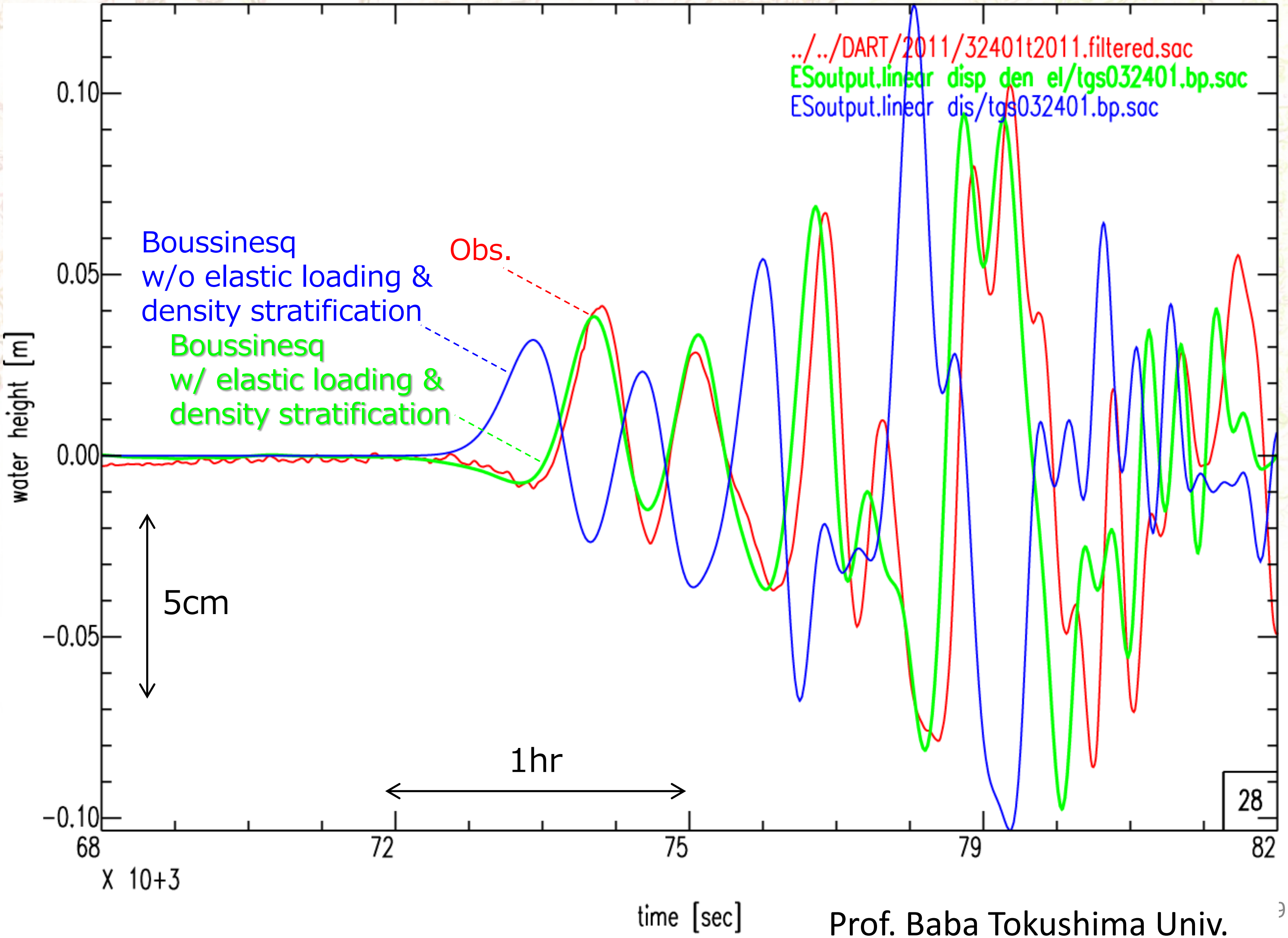
Prof. Baba Tokushima Univ.

Site 51407 (Hawaii)



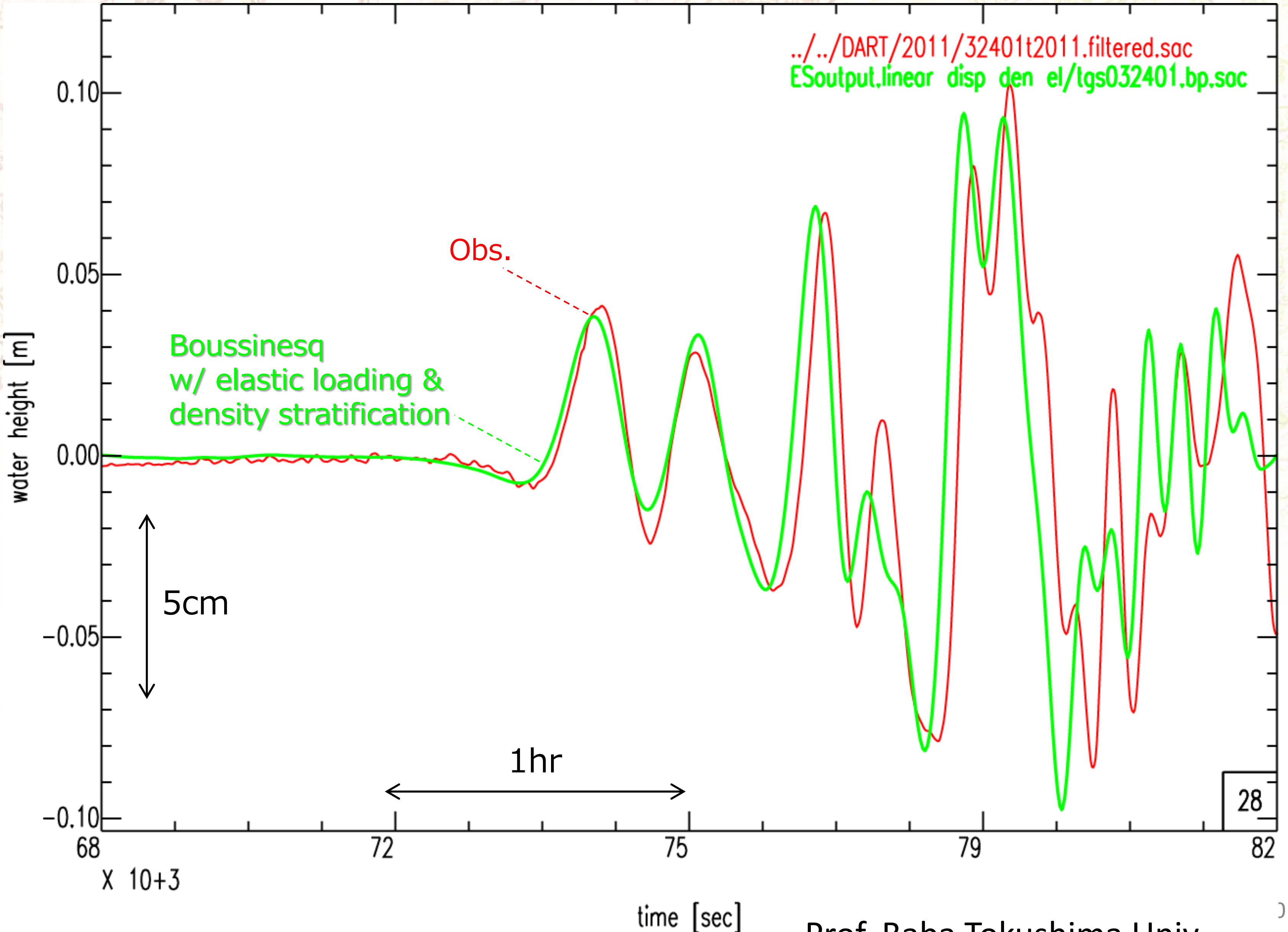
Prof. Baba Tokushima Univ.

Site 32401 (Chile)



Prof. Baba Tokushima Univ.

Site 32401 (Chile)



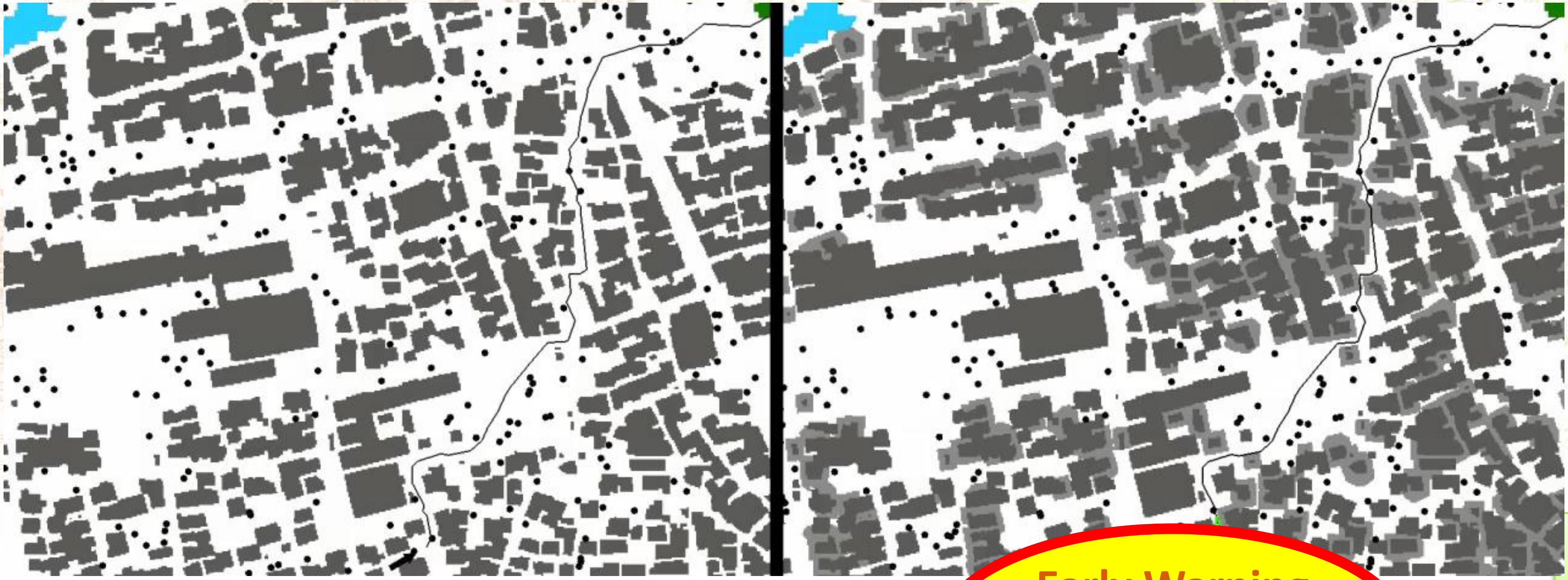
Prof. Baba Tokushima Univ.

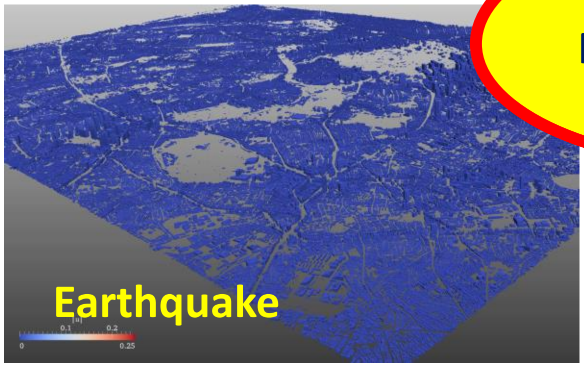
Navigation in damaged environment with EQ. and Tsunami

Dr.Lalith Univ.of Tokyo

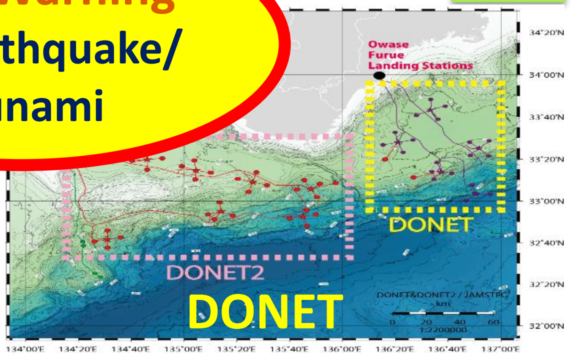
Undamaged Environment

Damaged Environment





Early Warning
For Earthquake/ Tsunami



Outline

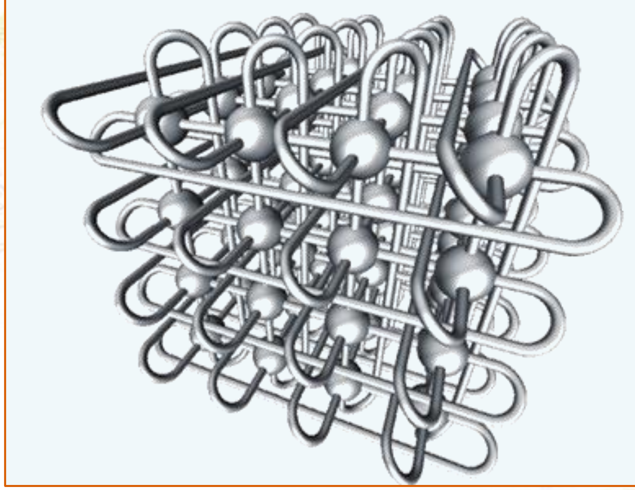
- Nankai Seismogenic Zone
- Dense Oceanfloor Network system for Earthquakes and Tsunamis (DONET1,DONET2)
- Large-scale Simulations for Disaster Mitigation

“K”(京) Computer

京 means 10^{16} : 10 to the 16th of power

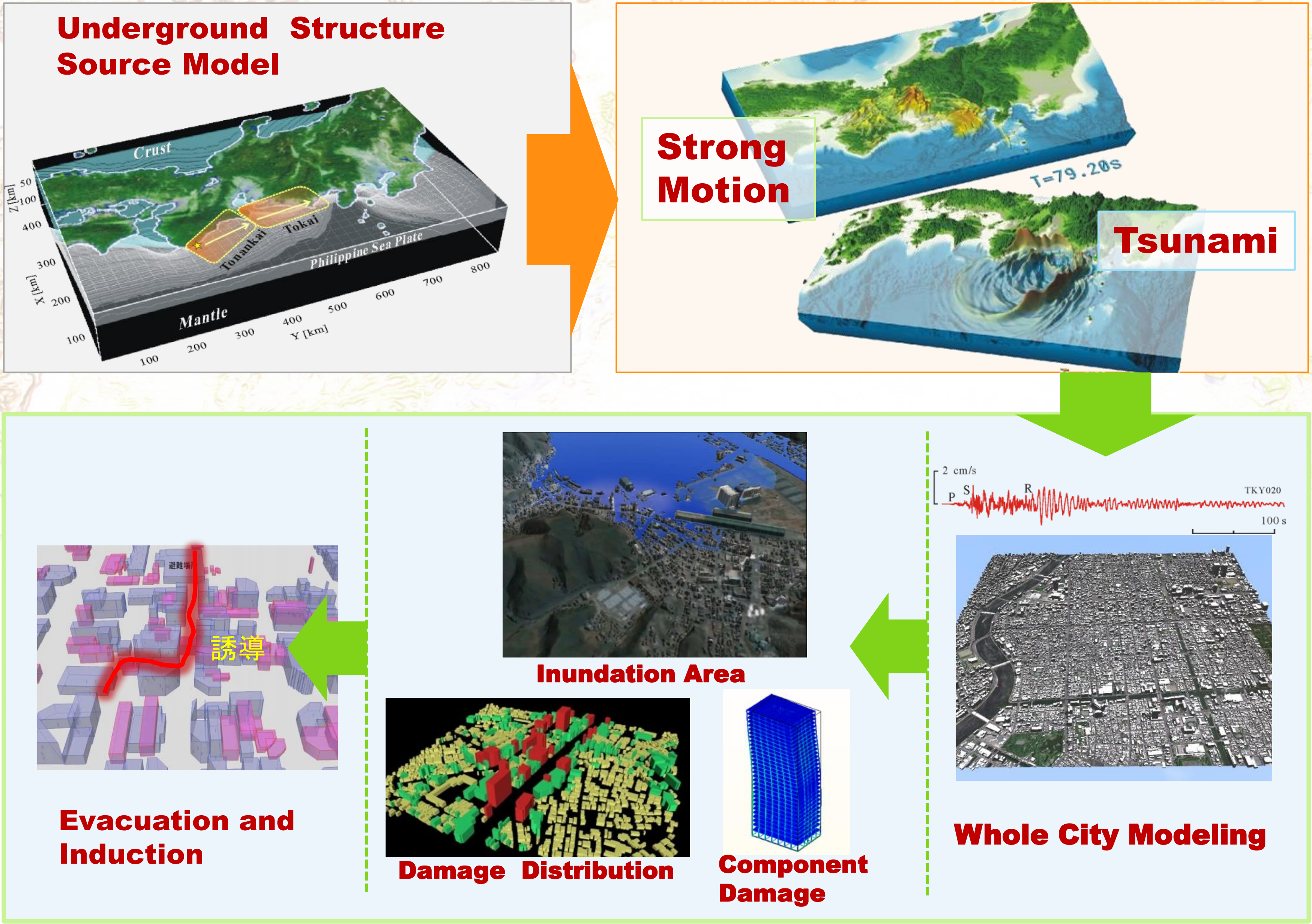
Total Performance : 10.62PFLOPS
Total Memory : 1.26PB（16GB/Node）
Computational node network :
Innovative ″6-Dimensional Mesh/Torus″ Topology Network Technology
Performance/CPU : 128GFLOPS（16GFLOPSx8cores）
Number of CPU : 82,944CPU （663,552cores）

Innovative "6-Dimensional Mesh/Torus" Topology Network Technology



Machine	Performance
Titan	17.59 PFLOPS
Sequoia	16.32 PFLOPS
K	10.62 PFLOPS
ES2	131 TFLOPS
ES（初代）	40 TFPLOPS
Intel core i7 (Sandy Bridge)	168 GFLOPS

High-advanced Simulation from Earthquake Source Process to Damage Evaluation on the K computer



S-net :Seafloor Observation Network for Earthquakes and Tsunamis along the Japan Trench

First dense real-time observation network in the ocean（6 segments & 150 observatories）

- Total length of the ocean bottom fiber optic cable: 5,700 km.
- Covers the wide area of Japan Trench from Kanto to Hokkaido.
- At least one observatory in a source region of M7.5 earthquake.
- Nodes are planned to install every
  - 30 km in a direction cross to trench
  - 50 - 60 km along direction to the trench

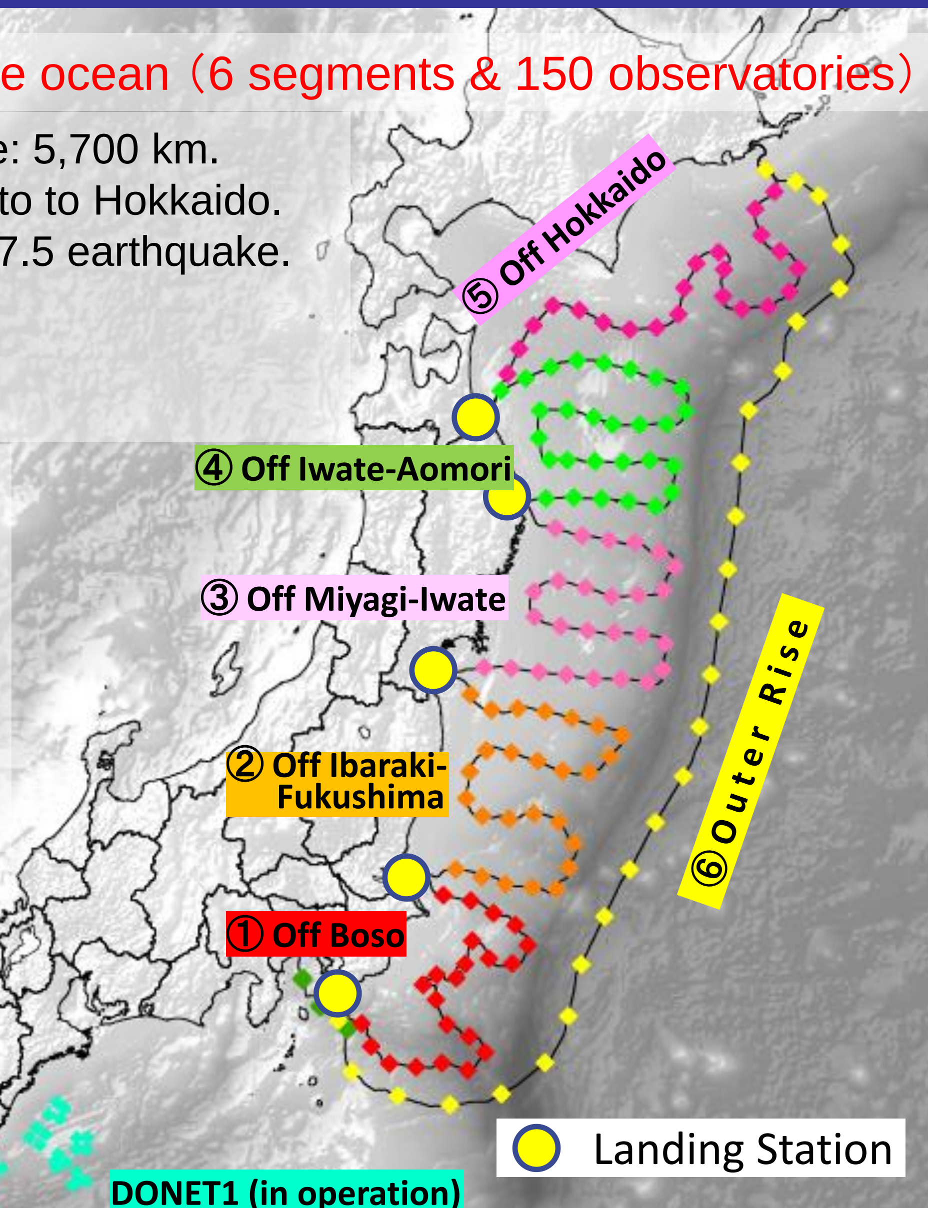
Objectives

Real time ocean bottom pressure measurements for the next-generation tsunami warnings which estimate coastal tsunami heights precisely .

Real time ocean bottom seismological measurements for a much earlier JMA Earthquake Information.

Investigation of a large earthquake generation process in the vicinity of Japan Trench associated with subducting Pacific plate.

Investigation of ocean bottom crustal movements (vertical component).



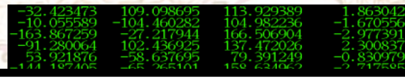
DONET2 is now constructed by JAMSTEC.A.

Authority of those two networks will be transfer to NIED.

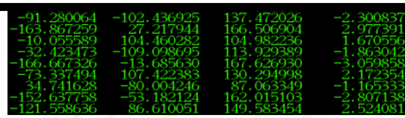
Prediction Researches

- Sparse modeling
- Dimension reduction analysis

Sparse modeling



高次元観測データ
$\boldsymbol{y}$



スパース原理

（自然界のデータは
0が多い. →圧縮可能）

潜在的な構造
物理法則
$\boldsymbol{x}$

Image Compression

.bmp 649KB

jpeg

.jpg 102KB

Components of image are remained JAMSTEC Kuwatani et.al

Data Science

- Sparse modeling ⇒ **Model　Unknown**
  - Lasso・AIC・モデル選択・ Principal Component Analysis
- Bayesian inference
  - モデル選択・ク **Model known** ズ推定・状態空間モデル・ Monte Carlo method ・Data Assimilation

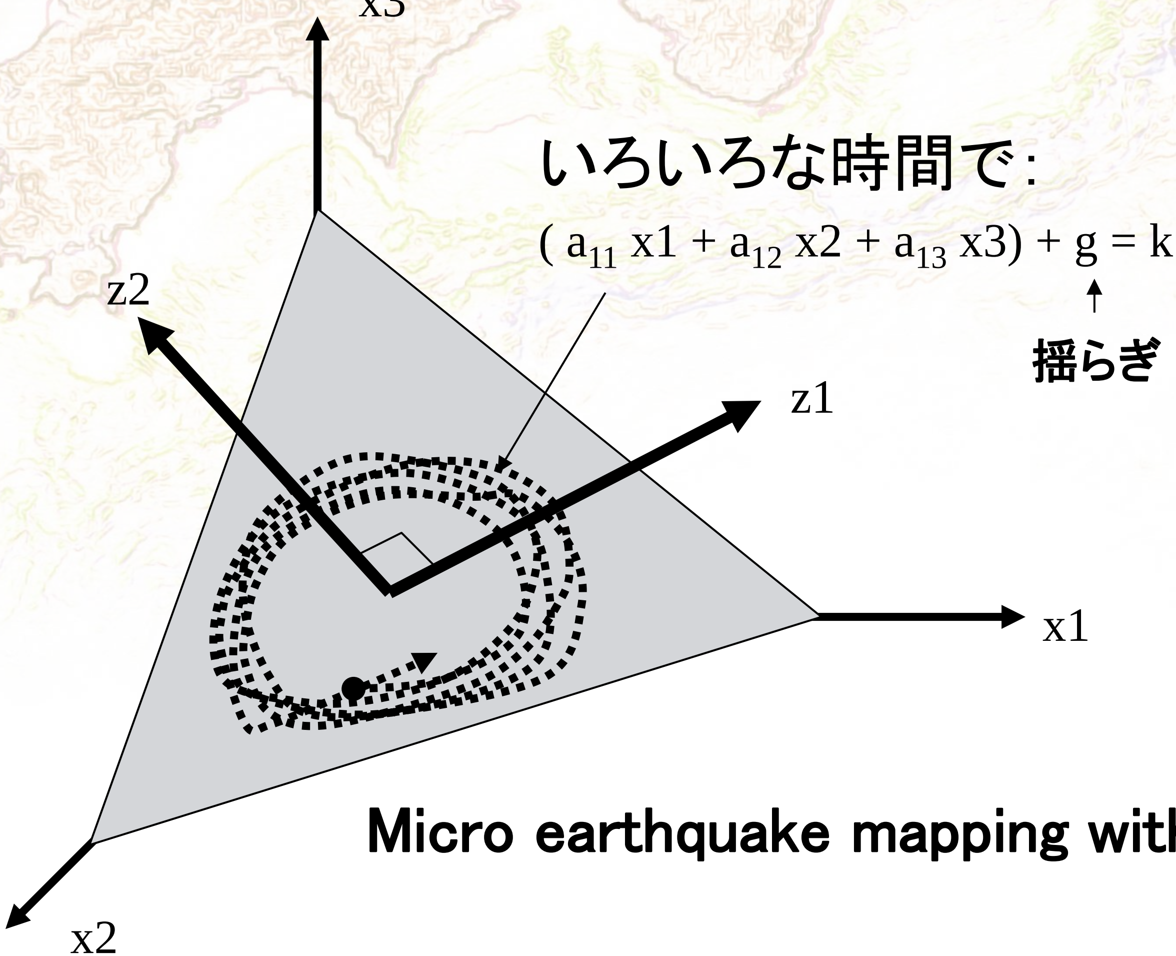
Geoscience data：High dimension data　＋
Time special data　　↑

↑　　Sparse modeling

Bayesian inference

JAMSTEC Kuwatani et.al

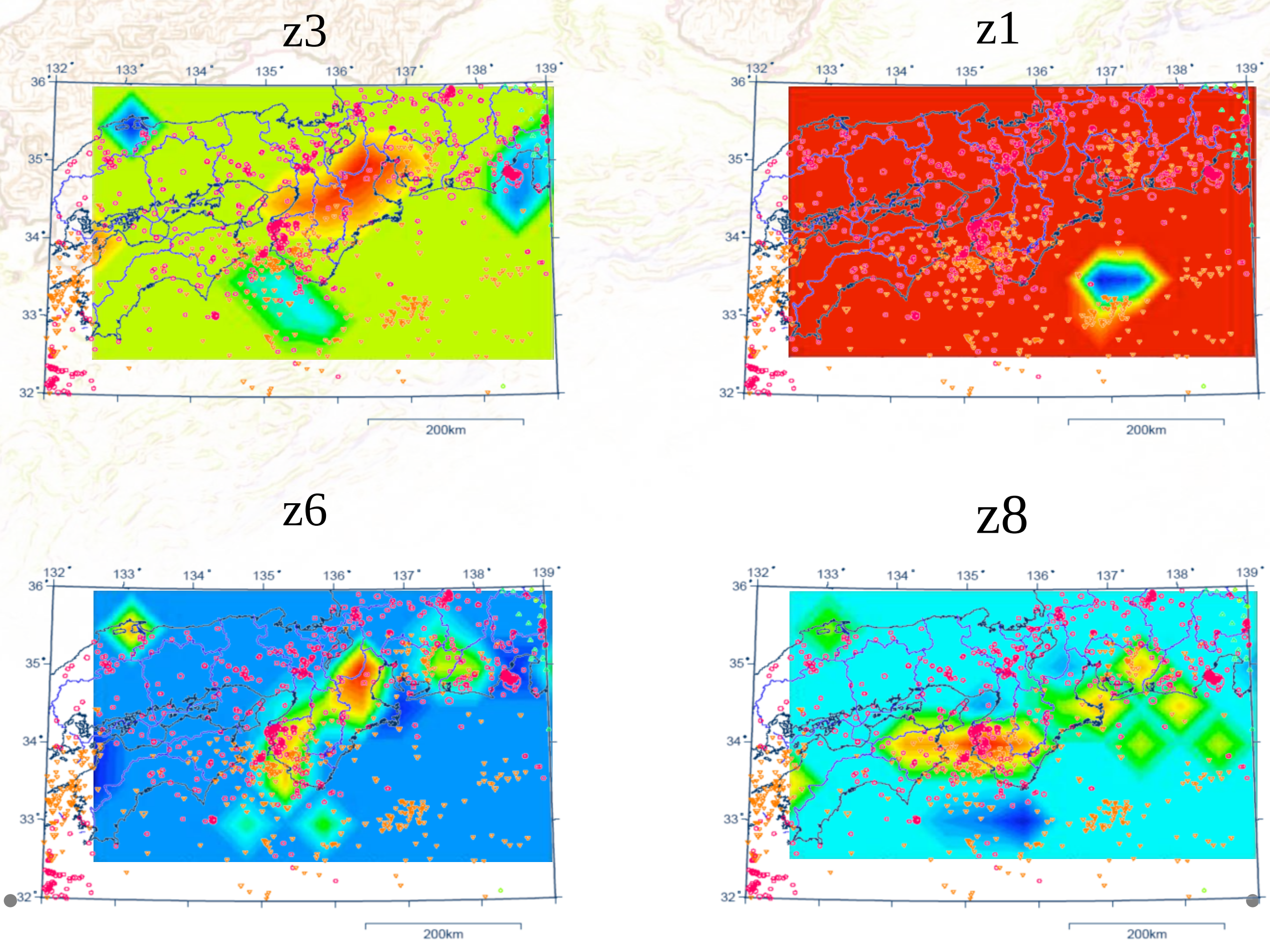
Dimensionality reduction → Time-Spatial information mapping



Micro earthquake mapping with PCA

JAMSTEC Kuwatani et.al

Results of dimension reduction analysis using micro Eqs. using PCA
Dominant modes are shown as Z1,Z3,etc.
Finally, we apply AI to estimate dominant mode as the anomalies



Focus on Nankai trough seismogenic zone

JAMSTEC Kuwatani et.al

Feature Extraction of Global Seismicity by Principal Component Analysis

<u>Akihisa Okada</u> Toyota Central R&D Labs., Inc.

Mitsuhiro Toriumi Japan Agency for Marine-Earth Science and Technology

Yoshiyuki Kaneda Kagawa University

Overview

Final Goal

Predicting earthquake activity for mitigating the resulting damage

Purpose of This Study

Obtaining features of **global** earthquake activity

Method

Data-driven (statistical) approach

Data

Open data catalog of earthquakes

Outline

Introduction

- Prediction & Control
- Earthquake

Method

- Data for Analysis
- Principal Component Analysis

Results

- Extracted Features
- Seismicity Index

Summary & Perspective

- Summary
- Perspective

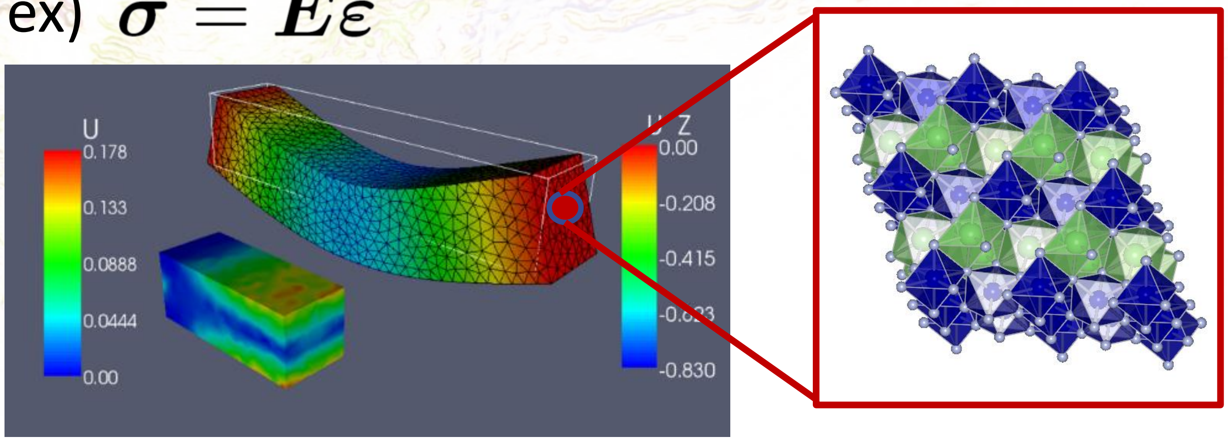
Prediction & Control

Traditional Way

discover <u>physical law</u>

relations between a few kinds of features

ex) $\boldsymbol{\sigma} = \boldsymbol{E}\boldsymbol{\varepsilon}$



https://fenicsproject.org/

Microscopic view

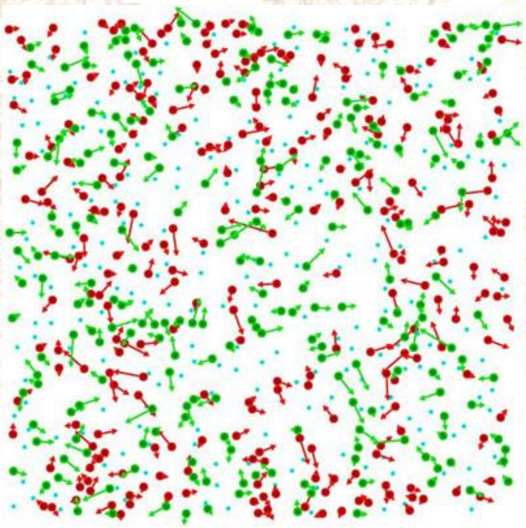
tremendous number of variables!

Gap between a physical law and microscopic information

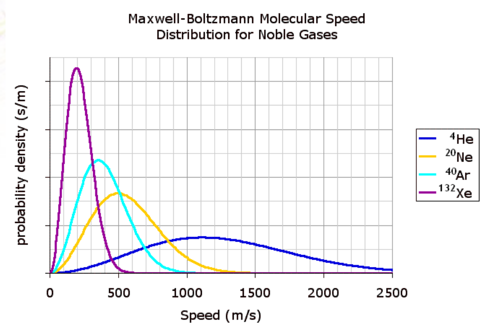
Prediction & Control

Statistical Physics solved this gap

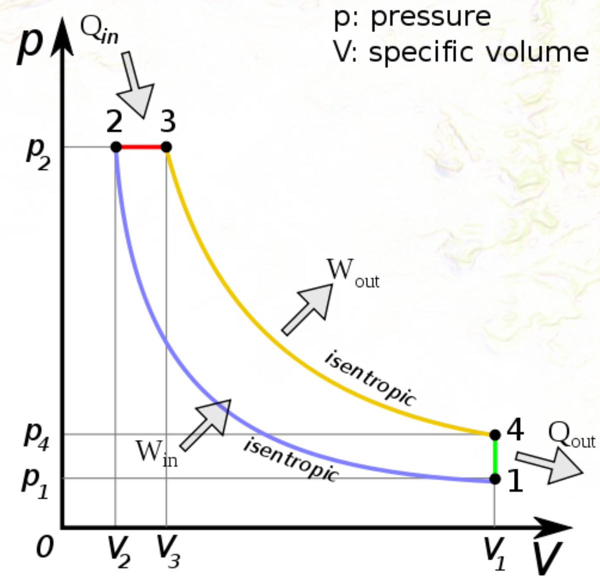
Microscopic



Distribution of state



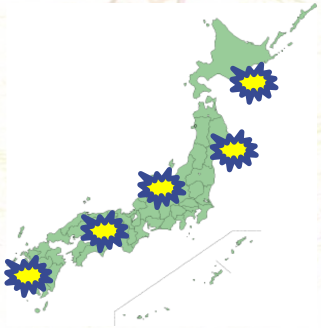
Macroscopic

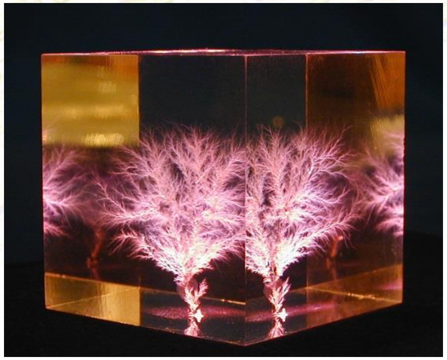


Statistics enable to grasp physical view by dimensionality Reduction → prediction & control

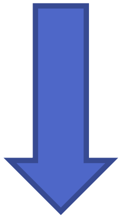
Earthquakes

Predicting earthquake activity is
needed for saving lives,
but difficult due to the complexity.





“Microscopic” : individual earthquakes



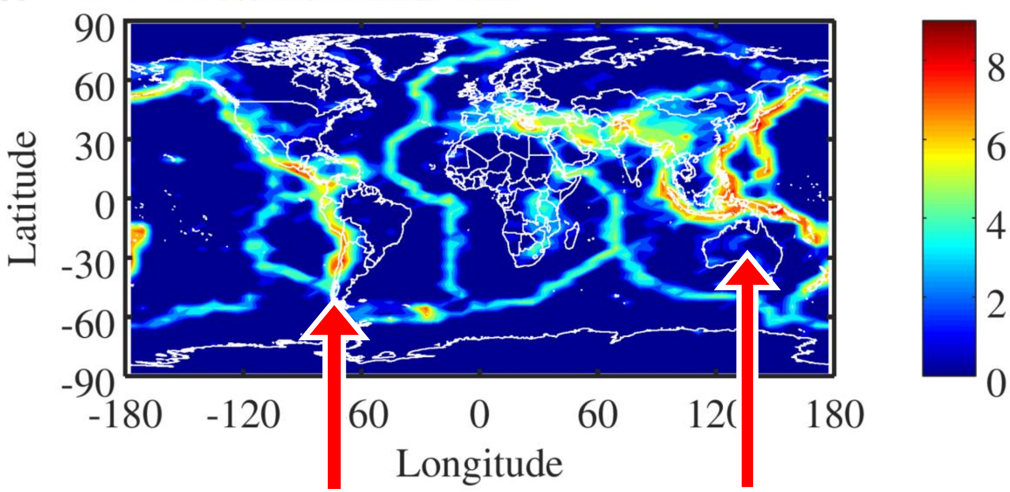
Statistical Approach

“Macroscopic” : Features of earthquake activity?
Model of earthquake activity?

Data for Analysis

Data Source the United States Geological Survey
Period 1990/1/1-2016/12/31
Magnitude Greater than or equal to 4, less than 5
Depth of epicenter 0-200km
Total 208,614

Integrated counts shown as log(1+N)



Discretization 3600 parts
Unit region
Latitude Δ3 deg.
Longitude Δ6 deg.

Active at plate boundary in Pacific Rim

Principal Component Analysis

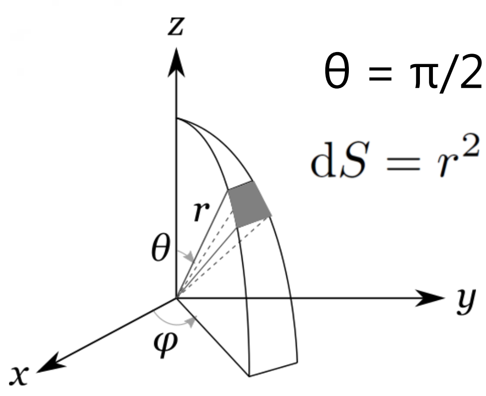
Earthquake occurrence rate $X_k(t)$

count per unit area S and unit time T

$$X_k(t) = \frac{N(t)}{ST}$$

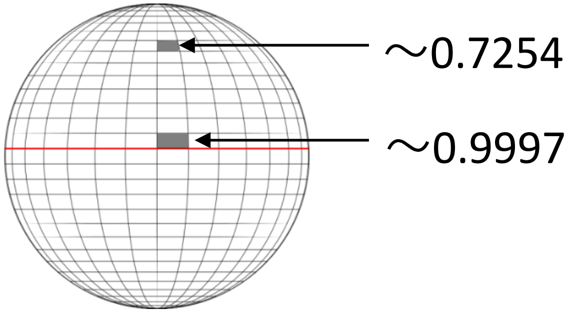
k : Regional label
S : Surface of unit region on the equator
T : 1 month

* : Lat. dependence of S is ignored (following results didn't differ so much)



θ = π/2 – Lat.

$$\mathrm{d}S = r^2 \sin\theta \; \mathrm{d}\theta \mathrm{d}\varphi$$



Earth as Sphere

Principal Component Analysis

New features extracted by PCA

region k as dimensionality (m), time t as sample (n)

m×n matrix *X* consists of $X_k(t)$

$$X = \begin{pmatrix} X_1(t_1) & X_1(t_2) & \cdots & X_1(t_n) \\ X_2(t_1) & X_2(t_2) & \cdots & X_2(t_n) \\ \vdots & \vdots & \ddots & \vdots \\ X_m(t_1) & X_m(t_2) & \cdots & X_m(t_n) \end{pmatrix}$$

eigenvalue decomposition

$$\Sigma = \frac{1}{m} X X' \Rightarrow U$$

Then, adopt only j_{min} vectors

$$\frac{\sum_{l=1}^{j_{\min}} \lambda_l}{\sum_{i=1}^{m} \lambda_i} > c$$

dimensionality is reduced!

Seismicity Index

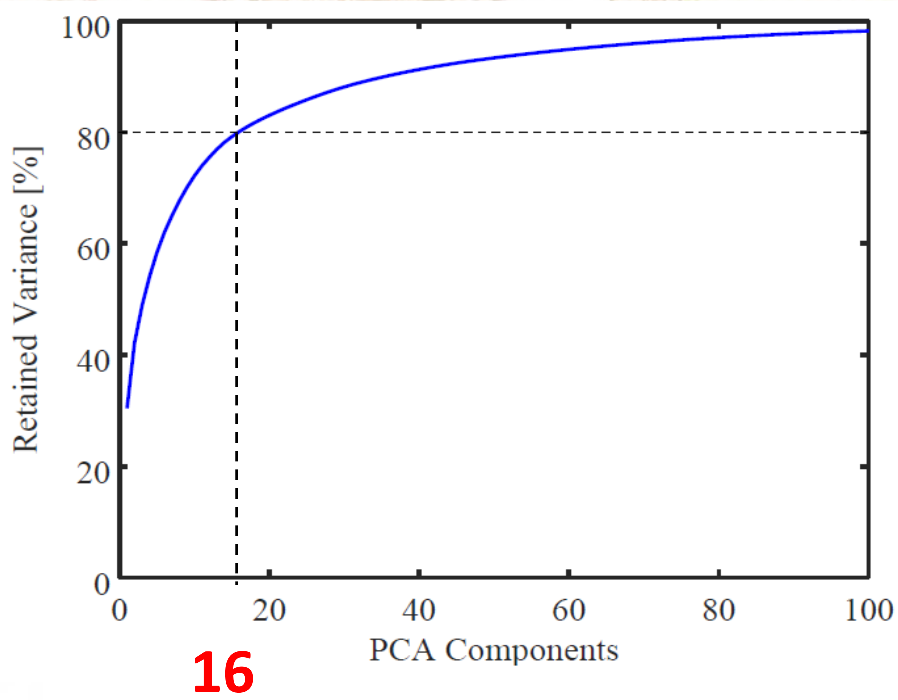
$$Y_i = \sum_{k=1}^{j_{\min}} U_{ik}$$

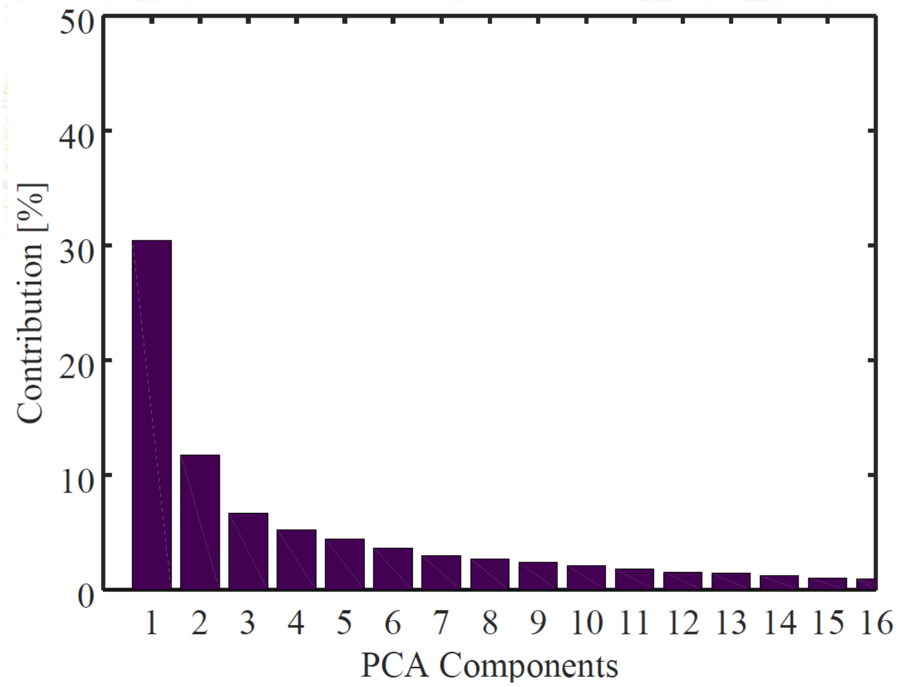
k : principal component
i : region label

Active regions are emphasized.

Extracted features

80% of variance is retained by 16 components





Dimensionality

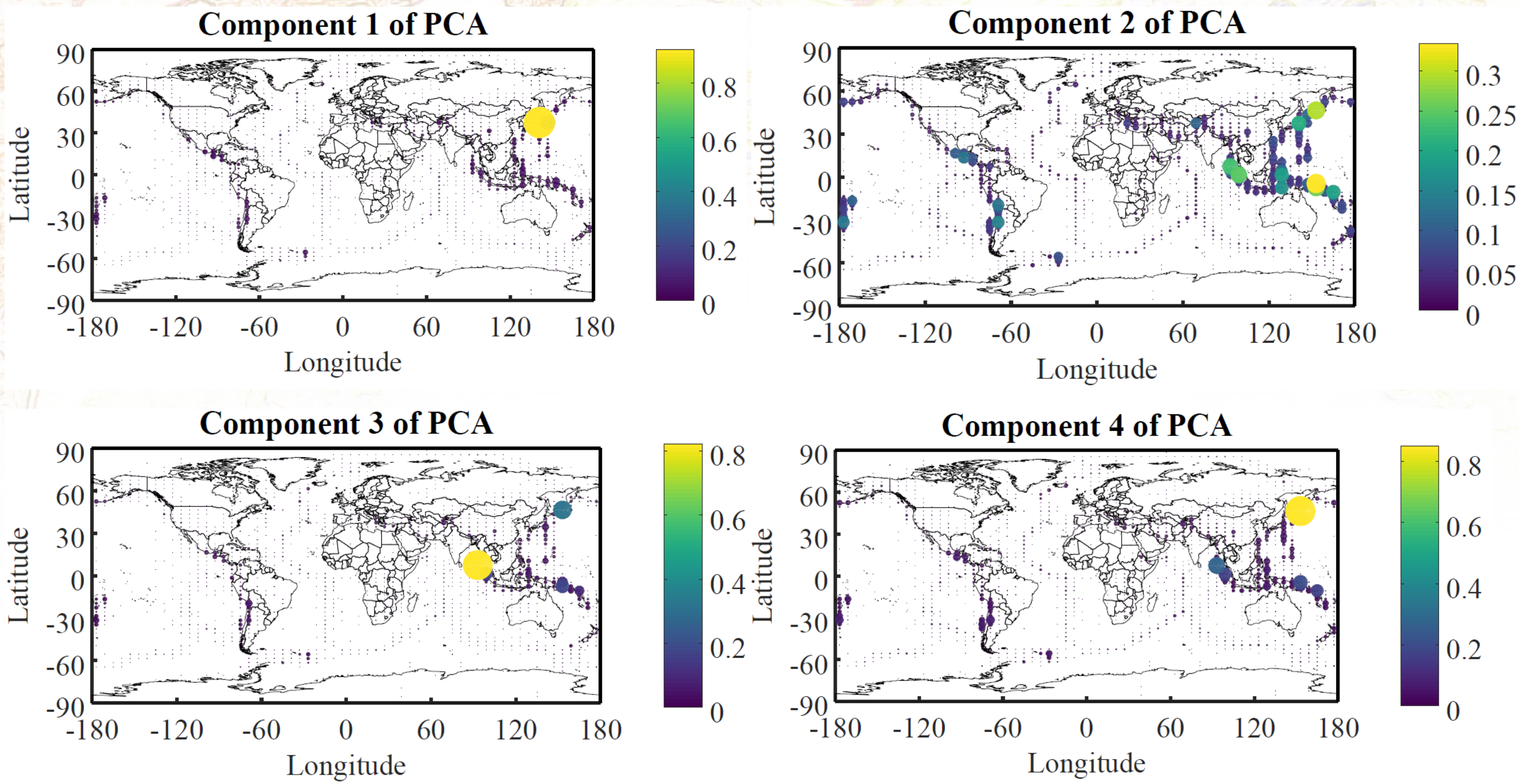
original : 3600

reducted : 16

$$\frac{\sum_{j=1}^{16} \lambda_j}{\sum_{i=1}^{3600} \lambda_i} > 0.8$$

Extracted features

Spatial Distribution in Global scale



Perspective

Not global but local Analysis will reveal more detailed tendency in specific region

- Epicenter movement in active area
  - ex. Indonesia
- Silent area nevertheless past massive earthquake.
  - ex. Canada offshore

Machine learning will be an candidate for extracting features of earthquake activity from plate moment.

Earthquake

1. Plate tectonics
2. Strain rise
3. Occurrence

Neuron

1. Diffusion of ion
2. Voltage rise
3. Firing

Unit model for NN

Thank you for your attention