Tsunami Scenarios in the Northeast Pacific from Stress Diffusion caused by the Tohoku Event

Dave Yuen (School of Environmental Studies, CUG, Wuhan , China, University of Minnesota, USA, Helen Jing (Mechanical Engineering, Ningbo University, Zhejiang China) and Dave Lloyd George USGS, Vancouver, Washington, U.S.A.

Shige Maruyama, ELSI, Titech, Japan

Two different Ideas are presented

- **STRESS REDISTRIBUTION** FROM LARGE EARTHQUAKeS AND CONSEQUENCES OVER SHORT TIMESCALE, 10 to 25 years
- **Landslides accompanying Large earthquakes** near the coast, as a mechanism for tsunami excitation

Stress Diffusion

- Following large earthqukaes, stress field released by the rupture is redistributed by the visco-elastic nature of the lithosphere-asthenosphere system. This physical idea was first brought to the fore by Walter Elsasser in the late 1960's. He showed that this process follows a diffusion-like process, with a diffusion time-scale which depends on ***the elastic and viscous*** parameters of the lithosphere and asthenosphere system

Much work on this idea followed

- Non-Newtonian rheology (Jay Melosh, 1976)
- Diffusion time can be as short as few years
- Finite-element modelling (Melosh and Rafesky, 1980)
- Influences of surrounding 3-D slab geometry (M. Matsu'ura from Dept. of EPS, Univ. Tokyo)
- Transient rheology from Burger's body or Maxwell element (R. Burgmann, R. Sabadini and myself, L.Fleitout)

John B. Rundle, my classmate from UCLA , 1970’s

- He is **no**t a friend of Robert J. Geller from Todai
- He has developed advanced pattern recognition techniques, based on statistical physics. Hot-spots of earthquakes
- http://www.openhazards.com/blogs/John

- Chichi Jima and Iwo Jima are two hot-spots to watch for in the next few years.

One of our goals here is

- To study by numerical simulations tsunami waves coming from the Izu-Bonin trench, where these hot-spots are located and also from Nankai trench, which do not exhibit these hotspots of stress enhancement

Strong Evidence for link between large M8 earthquakes coming from Great Sumatran M 9.3 earthquake of December 26, 2004

- French group at ENS, Paris, under Fleitout and Vigny have provided good evidence from modelling that the 5 most recent large earthquake from 2005 to 2012 were due to the stress diffusion emanating from the Boxer Day event earhtquake, they found the viscosity of the asthenosphere was around 10^17 to 10^18 Poise (not the same viscosity for plate motions over long tiem scale)

Stress Redistribution following very large earthquakes

- Computationally very challenging because it involves three-dimension and complicated slab goemetry and many uncertainties about the rheology of the asthenosphere in the short timescale
- Matsu'ura san's work has employed rather simple maxwellian rheology with a linear behavior, as compared to the french group who used non-Newtonian and Burger's like rheology for shorter time-scales. It is unfortunate he has retired and not go on with this important work.

Second idea for tsunami modelling

- Possilble influences from landslides (shio-shio)
- First discussed by George, Maruyama, myself in AOGS presentation in Taipei in 2011
- Dan Mc Kenzie and Jackson in EPSL, 2012 found
- that slumping from gravitational collapse played a major role in Tohoku- earthquake ‘s tsunami excitation
- Stephane Grilli from Rhode Island University also has echoed this idea from a different standpoint
- This new idea has angered many seismologists, especially from Caltech (pico-pico model, cherished by
- Kanamori –san)

GEOCLAW

- HYPerbolic systems, wave propagation
- Nonlinear waves

- Brief Review of Geoclaw software

- Examples of current Geoclaw capabilities

Hyperbolic Problems in Geophysics

- Many problems in geophysics present common computational challenges
- Multiscale, large domians with small-scale features
- Evolving scales small-scale features move throughout
- Discontinuities: Irregular geophysical features
- Hyperbolic operators: shocks and discontinuities

GEOCLAW CAN HANDLE THESE PROBLEMS

- Governing PDES are hyperbolic or mixed with hyperbolic operators
- Mixed elliptic-hyperbolic or parabolic-hyperbolic, split the PDES and use best methods for each part
- Geoclaw developed by George for his PHD thesis is tailored for hyperbolic problems such as tsunamis , landslides
- Debris flows, floods, and surges along coast

Hyperbolic systems

$$q_t + \mathcal{A}^1(q)q_x + \mathcal{A}^2(q)q_y + \mathcal{A}^3(q)q_z = \psi(q, x, y, z),$$

where $q \in \mathbb{R}^m$, and $\mathcal{A}^{1,2,3} : \mathbb{R}^m \to \mathbb{R}^{m\times m}$ and $\psi \in \mathbb{R}^m$.

e.g., the shallow water equations:

$$h_t + (hu)_x + (hv)_y = 0,$$

$$(hu)_t + (\frac{1}{2}gh^2 + hu^2)_x + (huv)_y = -ghb_x,$$

Numerical methods have been developed already

- AMR (adaptive mesh refinement) have been tailored for these hyperbolic systems
- Algorithms for resolving moving features
- Resolve shocks and discontinuties
- Optimal time-stepping to satisfy CFL conditions involving spatial grid criteria

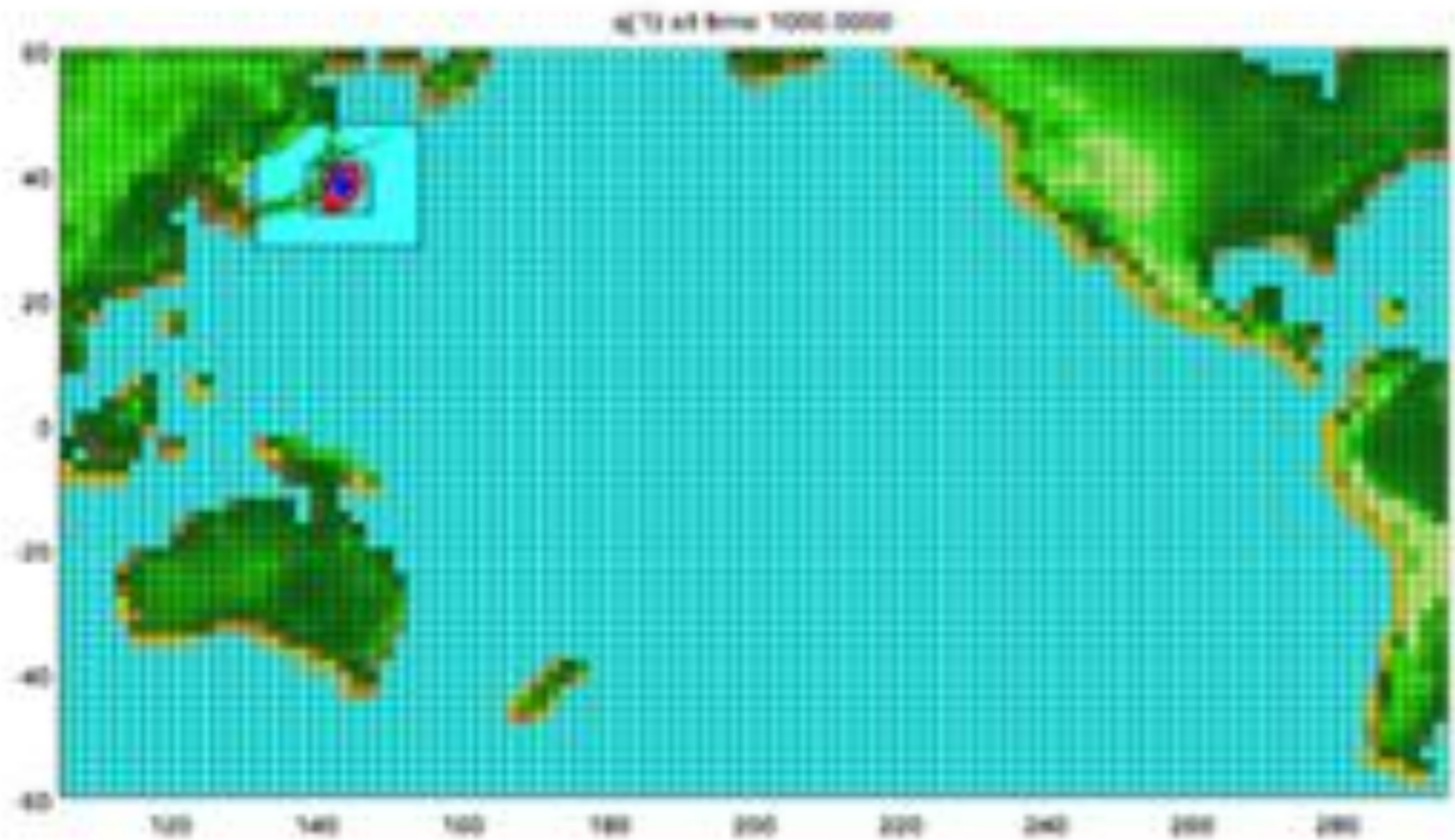
Software description

- Open source package for general hyperbolic systems
- Finite volume on rectangular grids
- High-resolution (TVD) shock capturing methods
- Robust Riemann solvers for fronts
- Block structured adaptive mesh refinement
- Available at www.clawpack.org

Tsunami Modelling

- Requires solving extreme multiple scales
- Global scale simulation domain
- Deep ocean wave propagation, wavelength around 100 km
- Wave propagation throughout the domain
- Near shore wave compression and topographic features => multiscale resolution needed for inudation
- Grid resolution is highly spatially and temporarily dependent

March 11, 2011

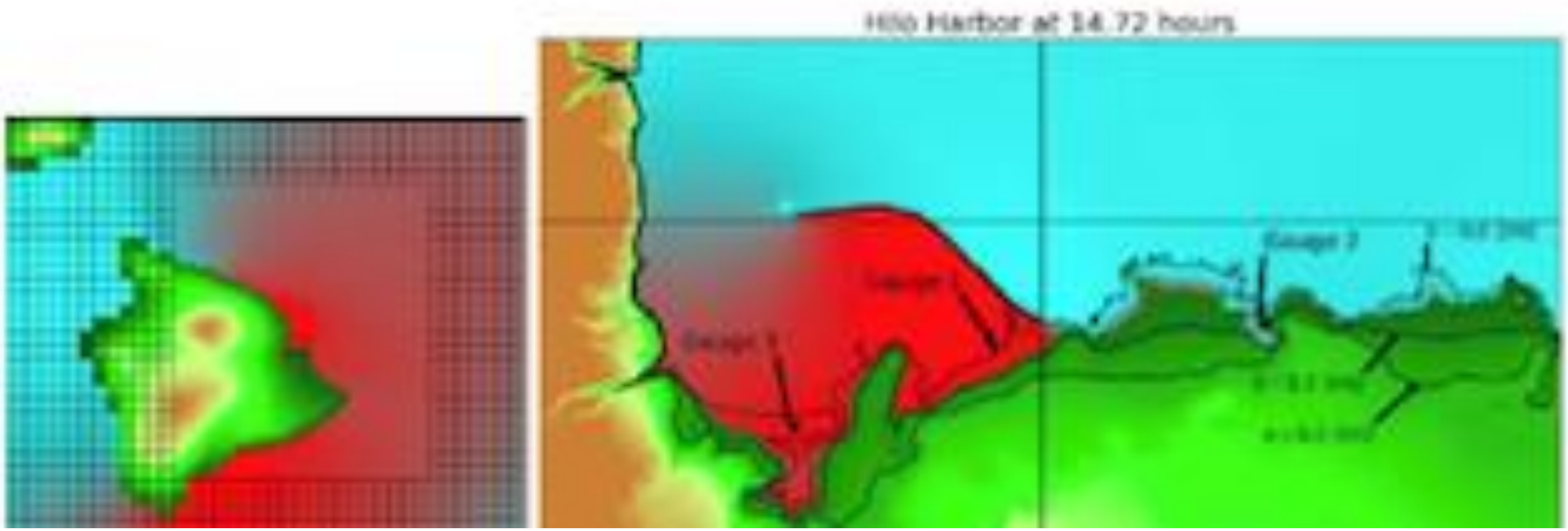


Inudation Model for Hilo, hawaii

refinement, with ratios: 8, 4, 16, 32.

Resolution ≈ 160 km on Level 1 and ≈ 10m on Level 5.

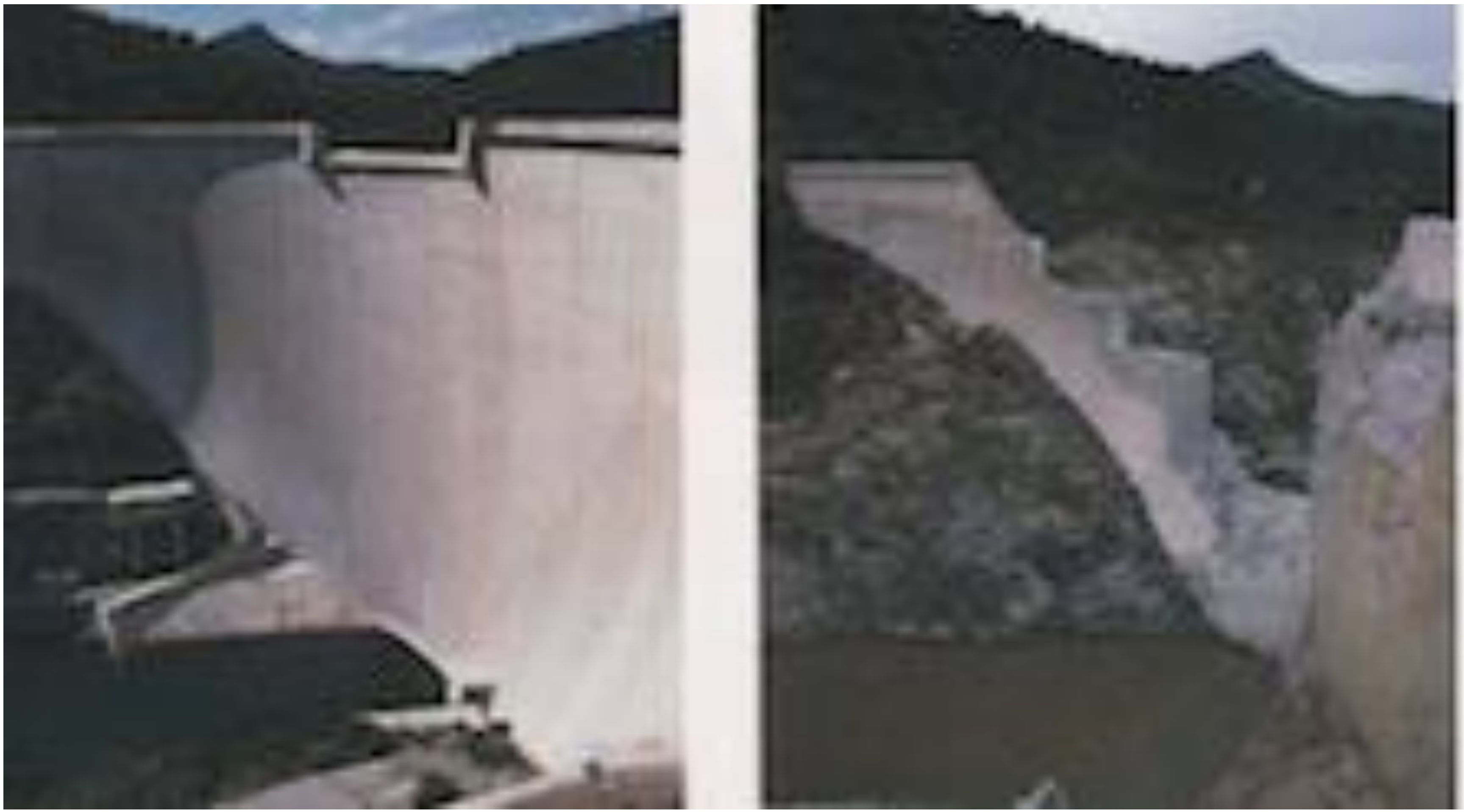
Total refinement factor: 2^{14} in each direction!



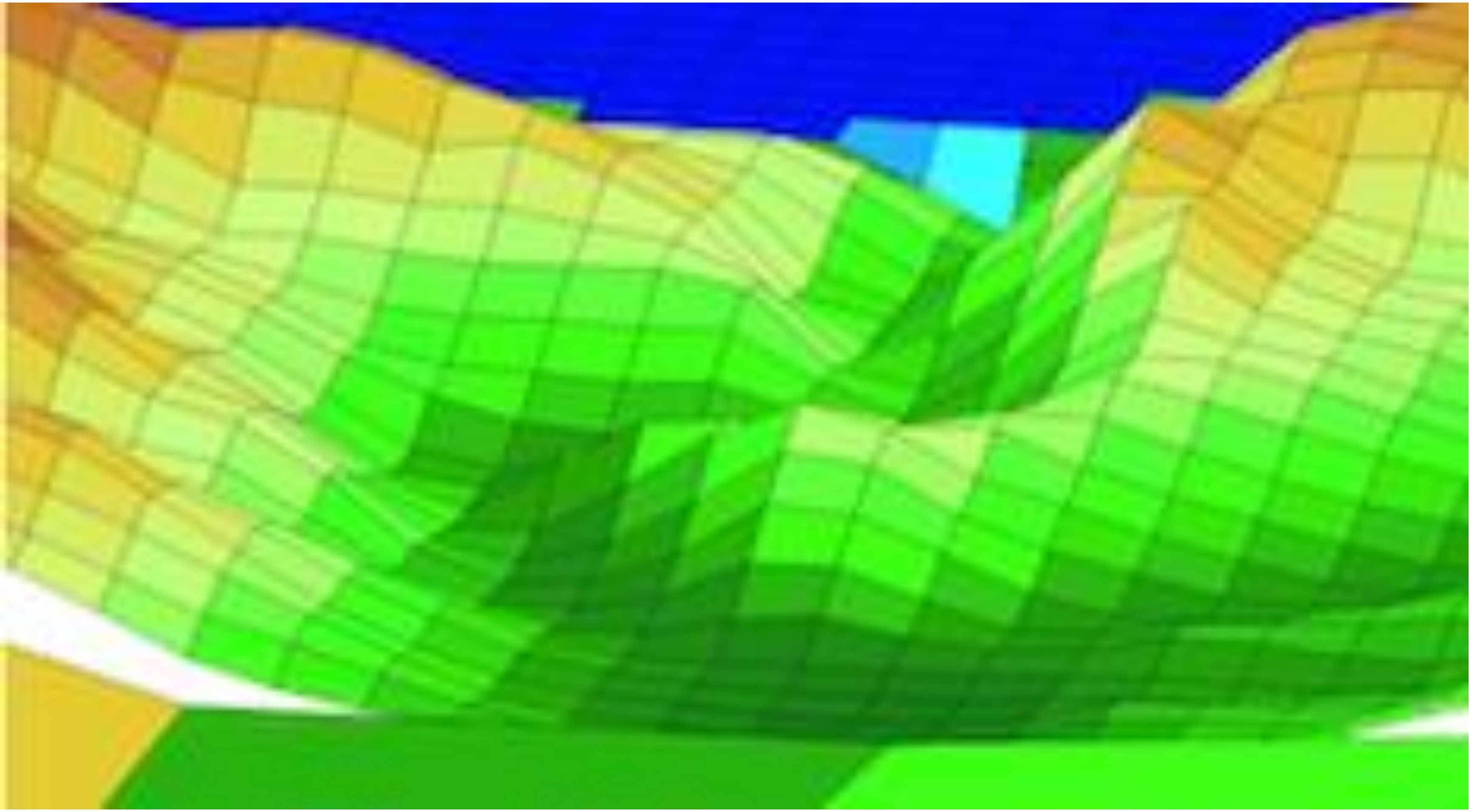
Overland Flow modelling (landslides)

- Floods, debris flows, mudslides, lahars
- Often serpentine unpredictably through domain around 100 km ^2
- Can require meter or submeter scale resolution
- Flow strongly influenced by topographic gradients
- Rheology is a big issue, plastic flow
- AMR is needed to track flow waves on evolving grids

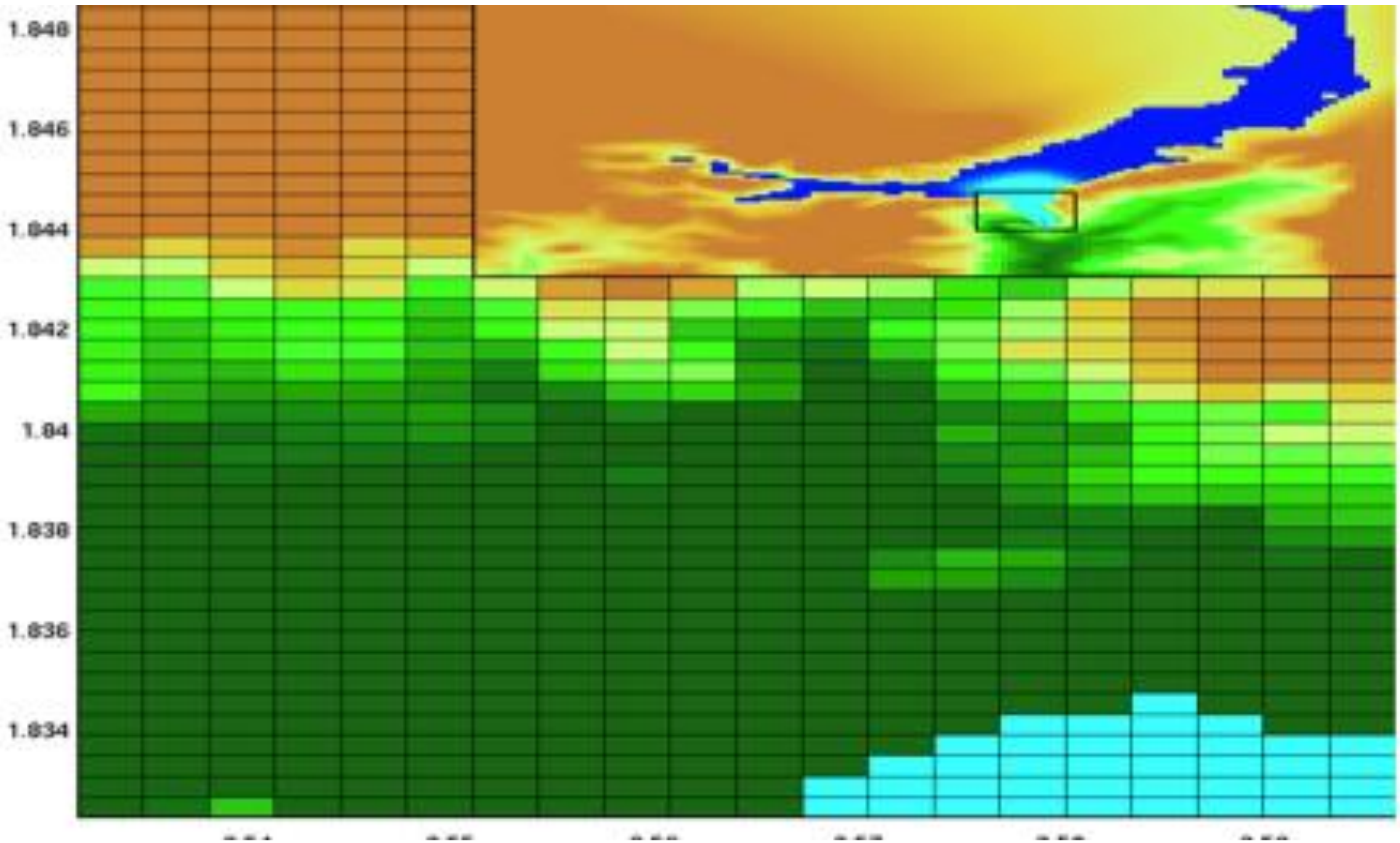
Overland Flooding, Malpasset Dam, France, 1959



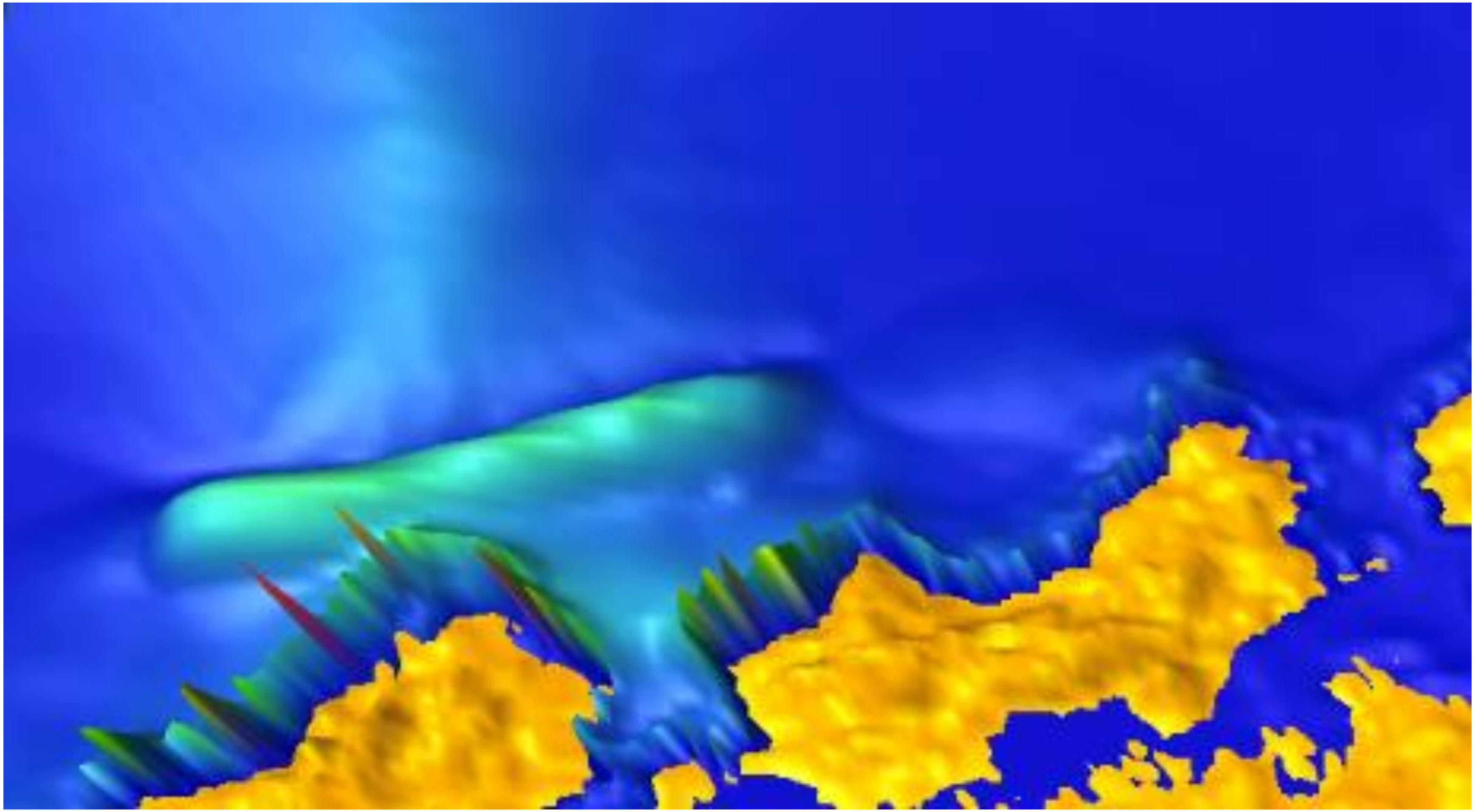
Overland Flooding, France



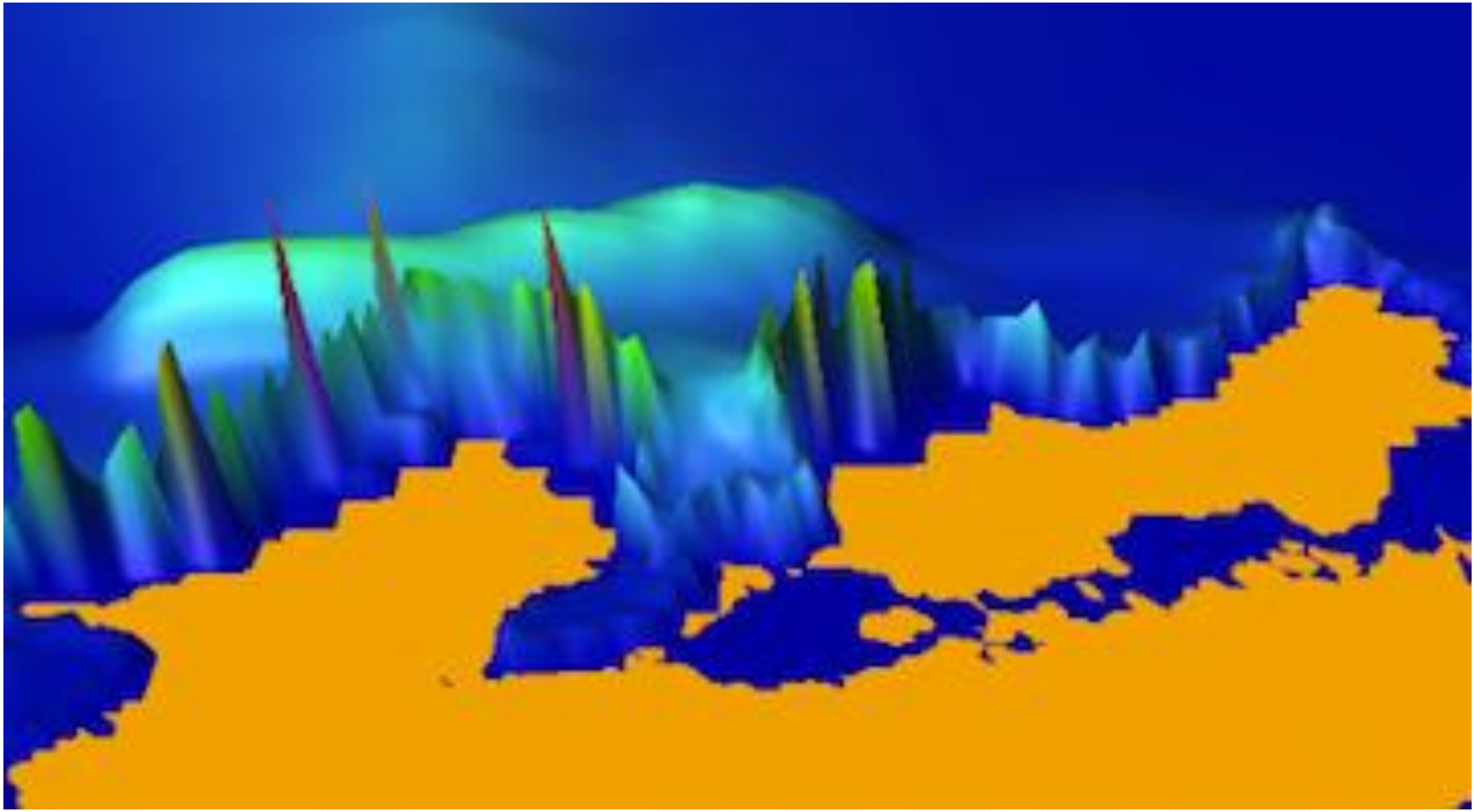
Malpasset Dam Flooding, 1959[1]



Run-up from M8.5 off Nankai Trough



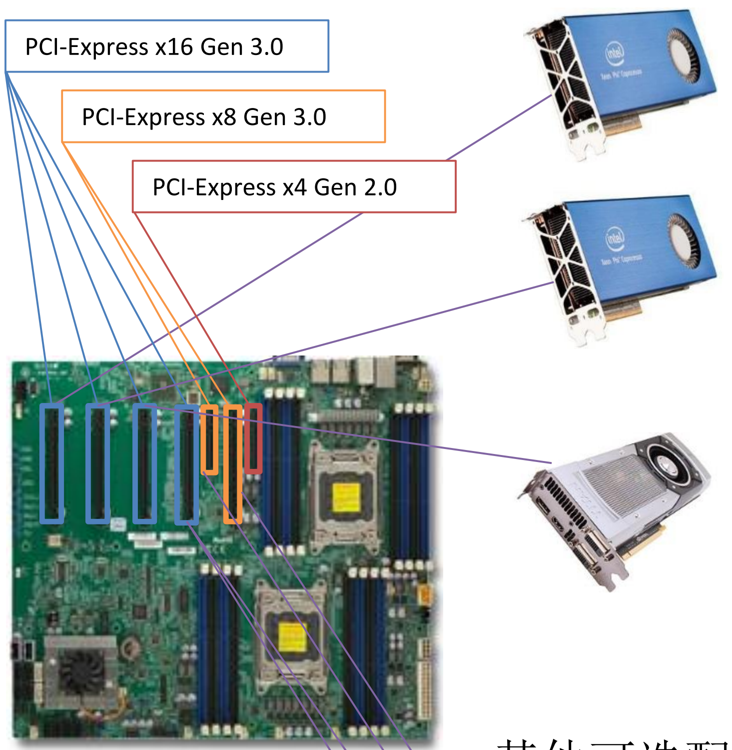
RUNUPS (depend a lot on local geography)



GEOCLAW allows high resolution using relatively meagre computing facilities

- We do not need to **use K** Computer at Riken, Kobe
- A powerful workstation which costs
- 800,000 Yen can do the job
- With MIC chip and GPU we can do more
- by building our own workstation
- For 8000 dollars
- Chinese student labor is cheap

Intel MIC / Nvidia GPU 开发工作站



协处理器：Intel Xeon Phi

- 57 Cores
- 1.1 Ghz
- 6GB GDDR5

机箱（8个串口硬盘槽）、电源：

- 1620W 电源
- 8个SATA硬盘槽

英伟达 Kepler GPU

- 2688 Cores
- 837 Mhz
- 6GB GDDR5

主板：

- 两个 Sandy Bridge CPU
- 48GB ECC 内存 1600Mhz

其他可选配件：

- QDR Infiniband HCA - $600
- 10Gb Ethernet - $600
- Extra Xeon Phi - $2,000
- Extra Nvidia GPU - $1,000

总计：

- 主板: $500
- 中央处理器: $800
- 48GB内存: $600
- Intel协处理器: $4,000
- 英伟达 GPU: $1,000
- 4TB SATA 硬盘: $200
- 机箱电源: $1,000
- 总计: $8,100

Advantages of having your workstation in office (bangoshi)

- You can examine parameter space more freely
- For large jobs, you can take the train to
- Beijing or Guangzhou to run this on larger
- computers.
- Important to use advanced algorithms to save computer time instead of using traditional numerical methods
- Applied mathematics is important for modelling

M=9.0 Tohoku Earthquake and Tsunami: A new interpretation

SHIGE MARUYAMA

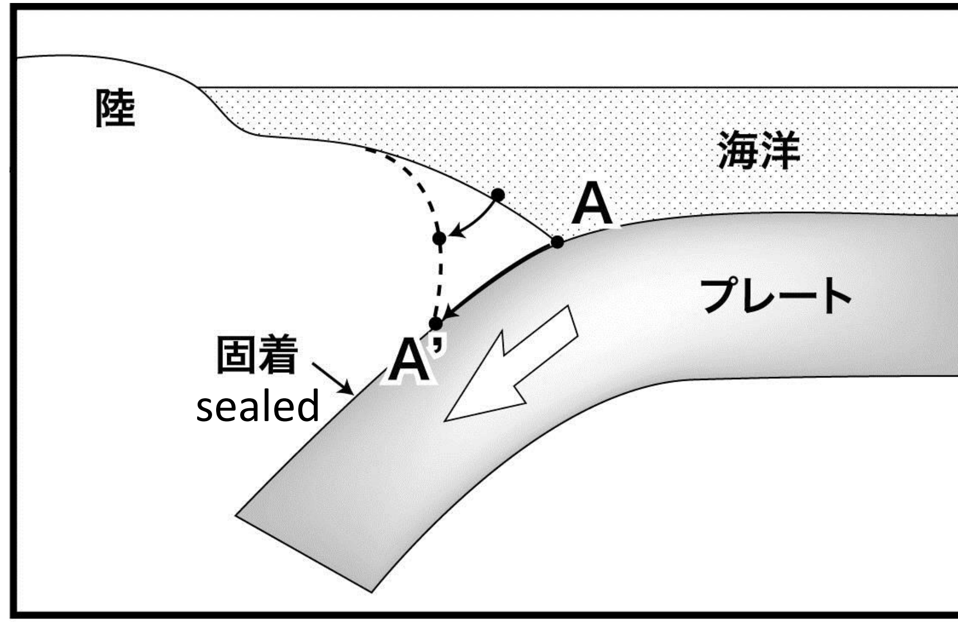
also appeared first in AOGS, 2011 Taipei, Taiwan
and Jeju Island , Korea conference 2012.

Introduction

- 1 M=9.0 Tohoku earthquake, origin and process
- 2 Associated tsunami by slab rebound?
- 3 Episodic submarine landslide, why?
- 4 In the case of SW Japan
- 5 Conclusions

General interpretation

Above: Descending slab being contact with hanging wall from A to A’.
Below: Sudden rebound upward (=earthquake causes tsunami)



Tsunami

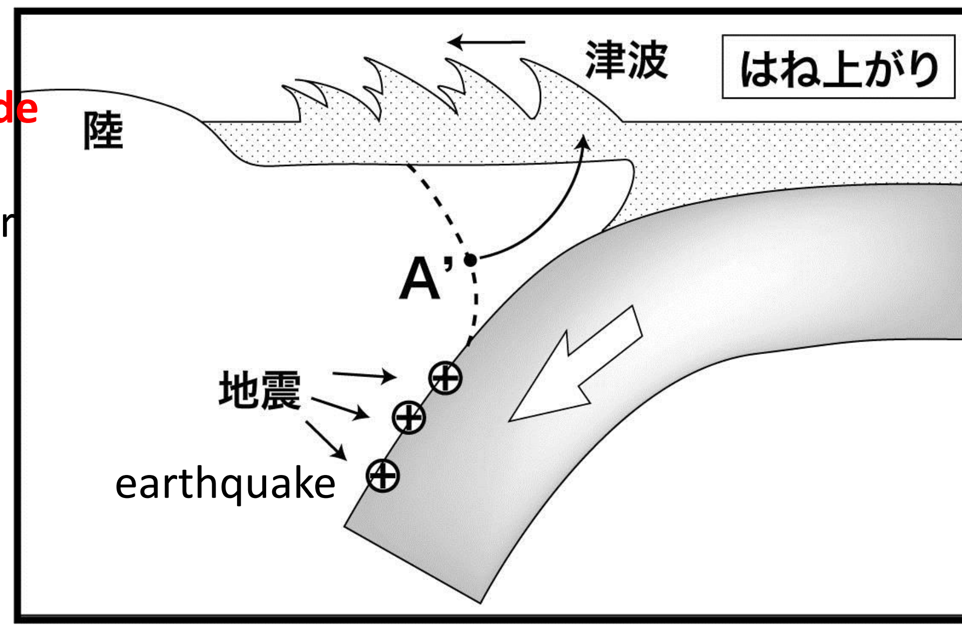
3．11，2011 **Tohoku Earthquake**

New Interpretation

●Origin of tsunami：**Huge submarine slide**

●Concept of asperity：**Opposite**

Gravitational energy release usually never trigger big earthquake, instead **silent earthquakes occur**, due to ubiquitous occurrence of dehydrated fluids; conversely big earthquake occurs along fluids-poor or absent region**. Spray fault**.



Ordinary interpretation: Benioff quake along A-B tsunami

Tectonic erosion-type earthquake

A-C: spray fault: active fault observed already
D: topographic high: eastern margin of sedimentary basin: **gravitationally unstable**

Submarine landslide

After-shock seismicity

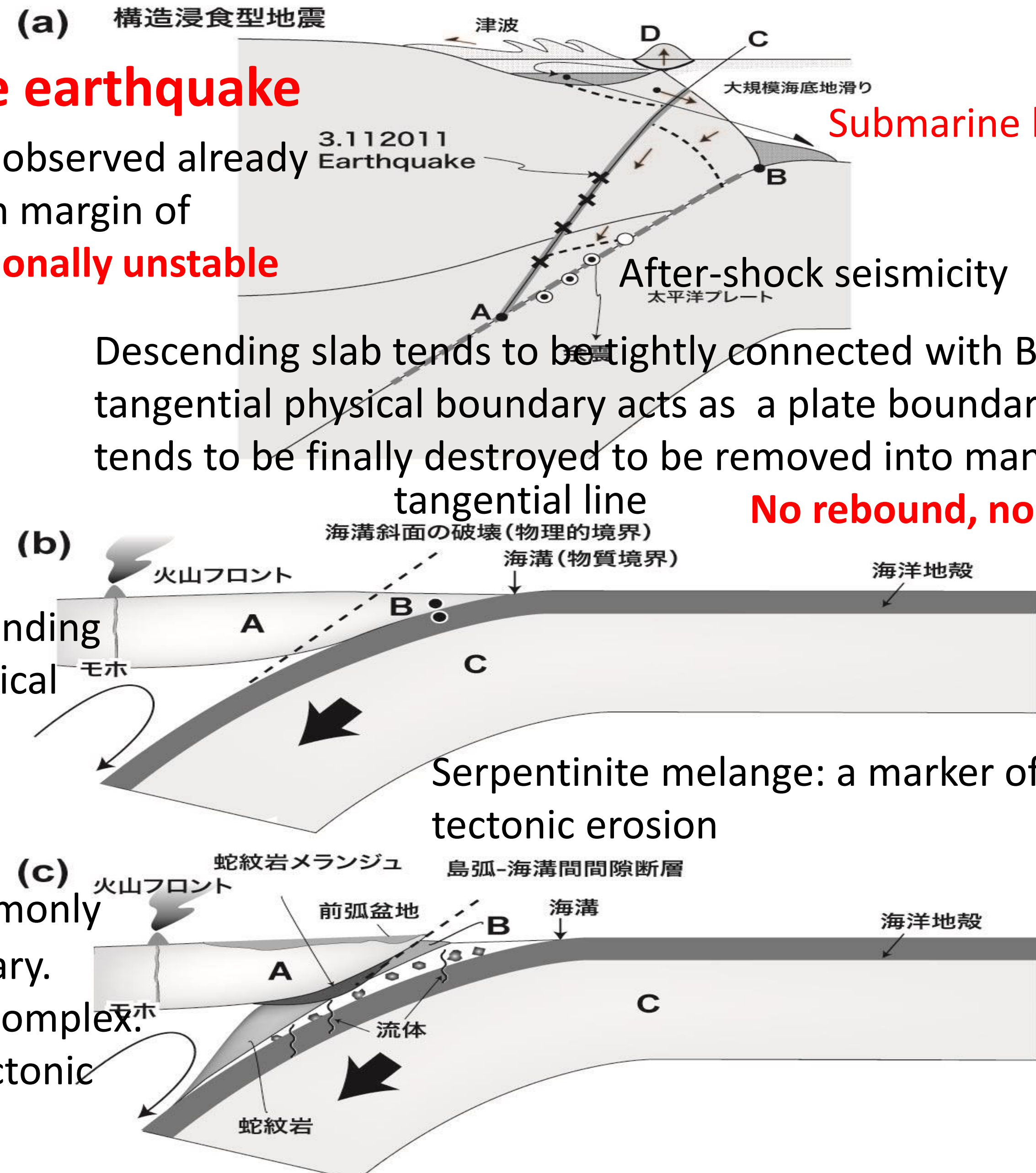


図2

Descending slab tends to be tightly connected with B; hence tangential physical boundary acts as a plate boundary. B tends to be finally destroyed to be removed into mantle.

tangential line

No rebound, no!

Mechanism

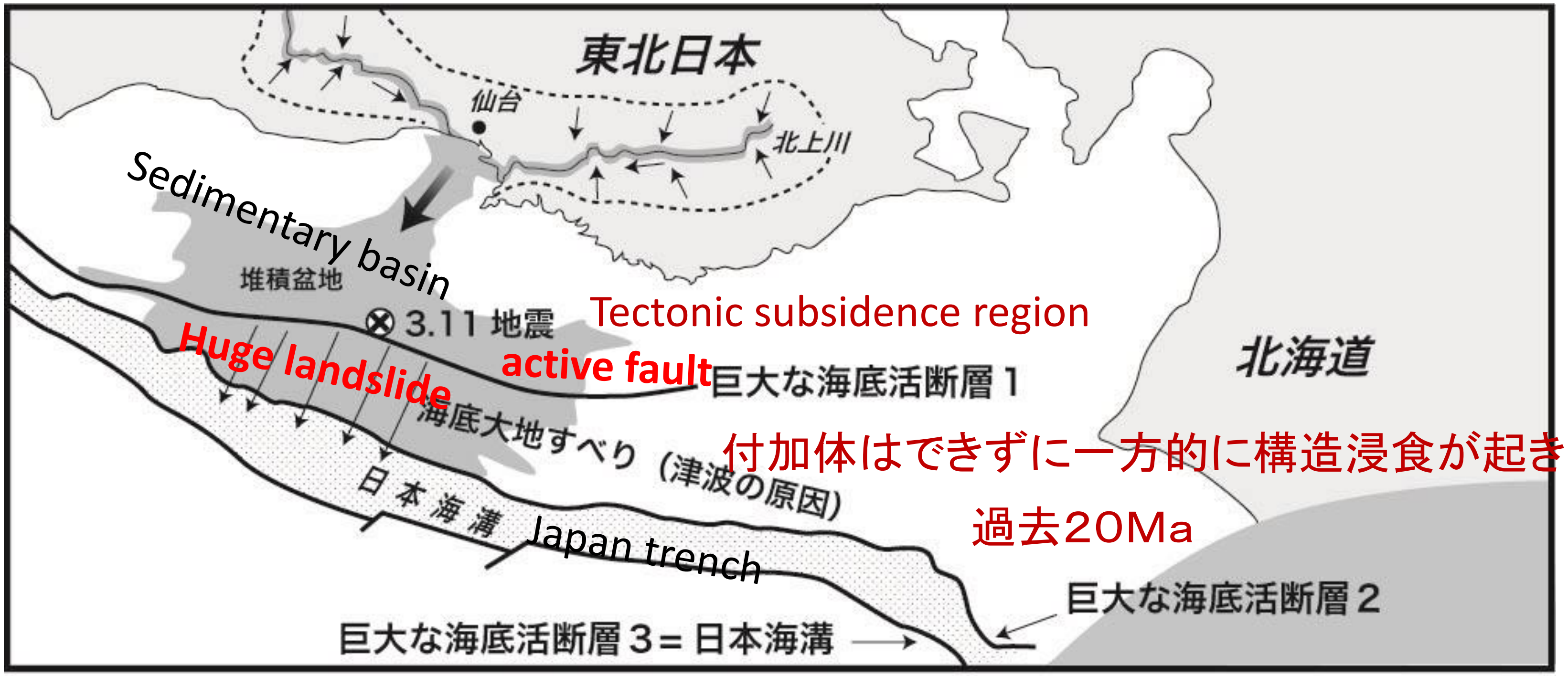
A: Hanging wall lithosphere
B: Small triangular region
C: Descending Pacific plate
B behaves as a part of descending Pacific slab, because of physical boundary(broken line)
Trench=material boundary

Serpentinite melange: a marker of past tectonic erosion

Tectonic erosion: commonly occurs at consuming boundary.
Nearly lack of accretionary complex.
Sediment subduction by tectonic erosion.

Origin of tsunami

Collapse of huge sedimentary basin. This is episodic controlled by (1) fullfill of sedimentary basin, every 1000 years, and episodic activity of spray fault triggers huge submarine landslide.



Why does a huge sedimentary basin develop between an arc and trench?

（1）Tectonic extrusion of materials along a spray fault to make a topographic barrier (**trench-slope break**). Right below the barrier, active thrust spray fault is present.

（2）Specific natural geography off NE Japan arc: all sediments are transported to off-Sendai into the huge sedimentary basin. **Hence, gravitational instability increases always to trigger a huge submarine slide that causes tsunami.**

Questions to doubt the current interpretation

- 1 No supports of theoretical and observational facts (to support the rebound theory by seismologists, Kanamori-san): lithosphere is rigid-brittle, and not rubber!
- 2 Overriding lithosphere is always destroyed, fragmented and transported into the depth by descending slab.
- 3 Marine geophysics found the common occurrence of **tectonic erosion**, instead of formation of Acs（Scholl and von Huene, 2007; Yamamoto、2011）
- 4 Ubiquitous occurrence of spray faults between arc and trench: earthquakes occurs along the spray fault in addition to Benioff plane.

Examination

- １　Let us examine the above scenario by the observed facts.
- ●Did the 3.11 Earthquake occur along Benioff plane or along spray fault? Difficult to determine.
- ●Did the Tsunami begin along a N-S trending 400km long line or spot (right above a submarine landslide): **Spot origin ?**
- ●Did we observe a huge submarine landslide deposited on Japan trench? Yes! Need more works

Landslides at Tohoku Earthquake

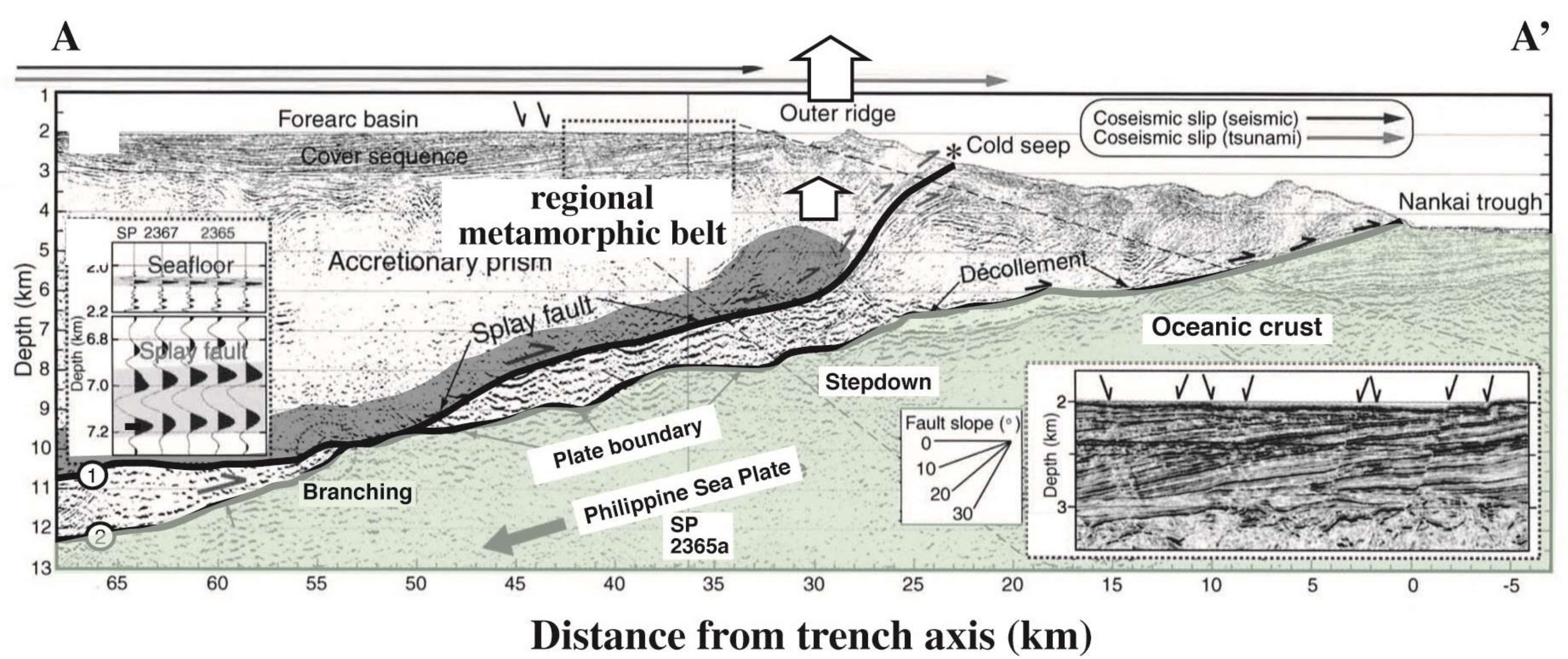
- More than 500 localities have been recorded onland in NE Japan Arc. This suggests that submarine landslides were also present, although not yet found by poor research and viewpoints except some spot localities by JAMSTEC submergible vessel right after 3.11 Quakes.

If so now we can control Tsunami disaster- An example of SW Japan

- 1 Structure of arc-trench gap in SW Japan arc
- 2 Degree of development of sedimentary basin in fore-arc region
- 3 Tsunami disaster can be controlled by removing the gravitationally unstable sedimentary cumulates in the sedimentary basins.
- 4 If this hypothesis is correct, we can escape from tsunami hazards, e.g., Indonesia and other regions.
-

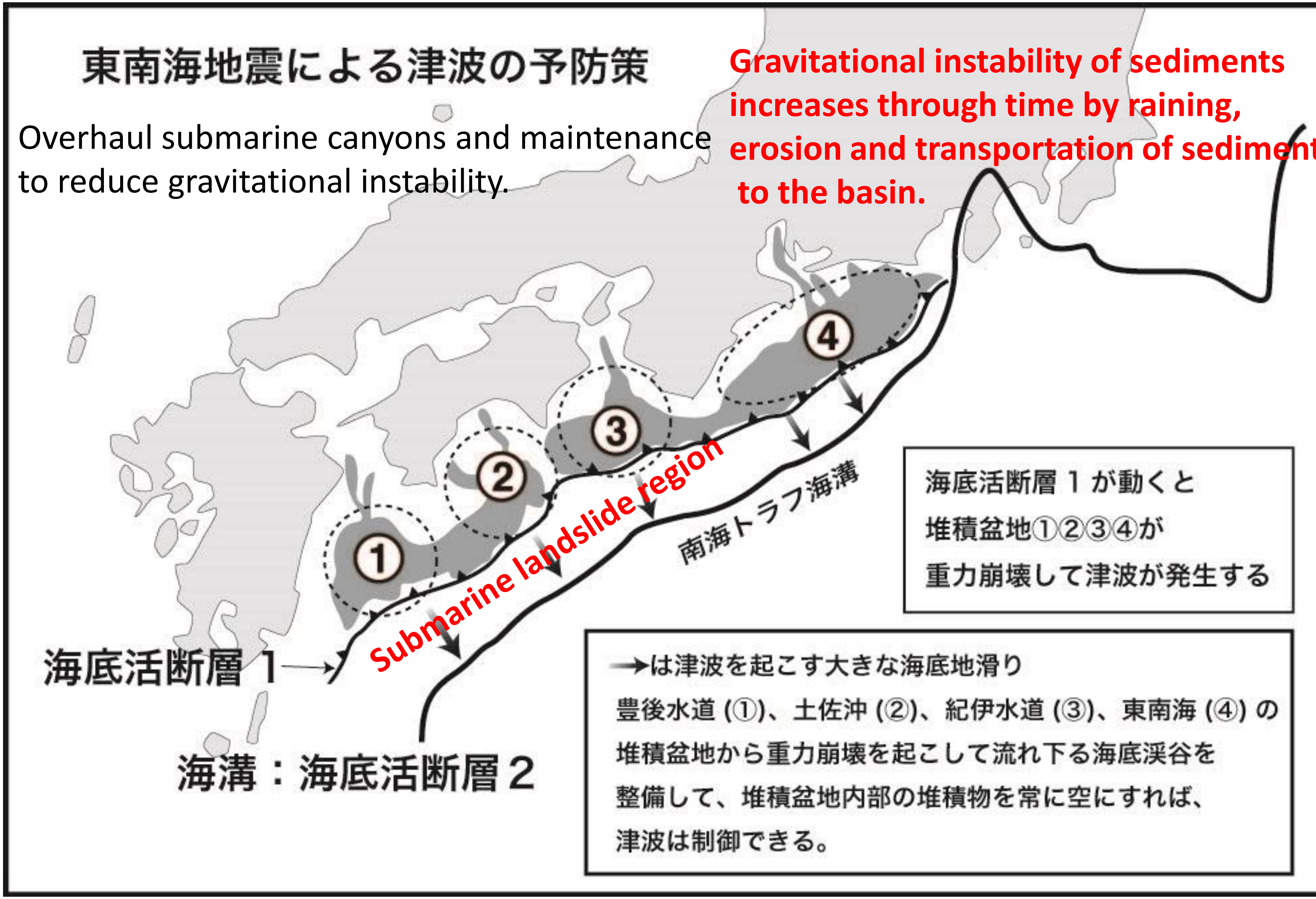
Spray faults and earthquakes

Fore-arc basin above Nankai trough, off Kii Peninsula, would finally collapse to flow-down sediments into trench, causing tsunami disaster, triggered by earthquakes along spray faults branching from 10 km depth from decollemant zone (Benioff plane).



Modified after Park et al. (2002)

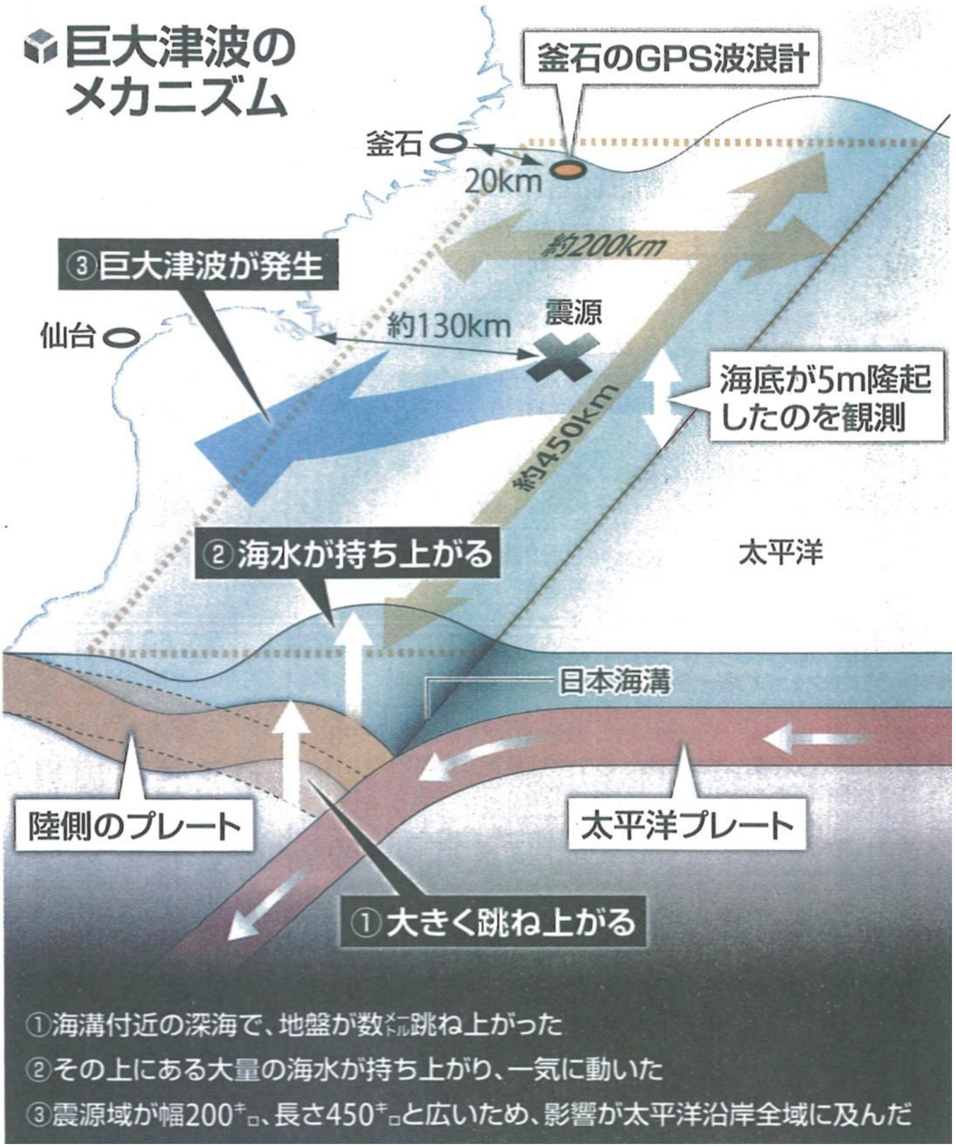
How to protect us from tsunami disaster

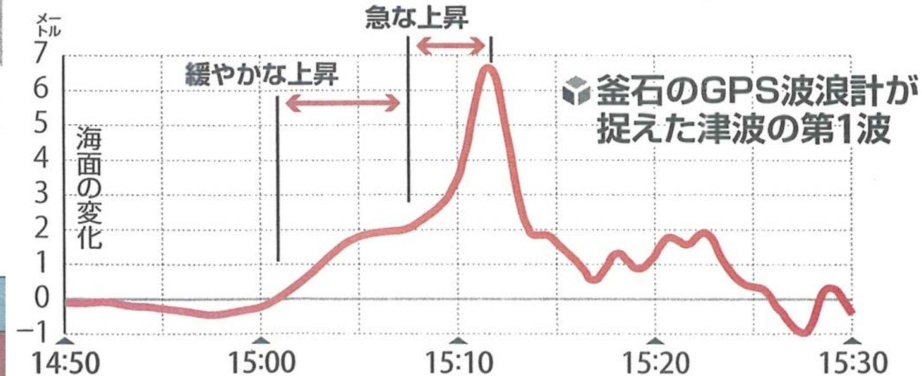


Conclusions

- 1 3.11, 2011 Tohoku Earthquake occurred along the spray fault, as a typical type of tectonic erosion-type earthquake.
- 2 Related tsunami was triggered by a collapse of gravitationally unstable fore-arc basin, and submarine landslide caused tsunami wave (spot-source, not by line source).
- 3 Tsunami hazard, hence can be controlled by
- overhaul submarine canyons and reduction of gravitational instability.

巨大地震のメカニズム


巨大津波のメカニズム
釜石のGPS波浪計
釜石
20km
約200km
③巨大津波が発生
震源
仙台
約130km
海底が5m隆起したのを観測
約450km
②海水が持ち上がる
太平洋
日本海溝
陸側のプレート
太平洋プレート
①大きく跳ね上がる
①海溝付近の深海で、地盤が数メートル跳ね上がった
②その上にある大量の海水が持ち上がり、一気に動いた
③震源域が幅200キロ、長さ450キロと広いため、影響が太平洋沿岸全域に及んだ


釜石のGPS波浪計が捉えた津波の第1波
メートル
7
6
5
4
3
2
1
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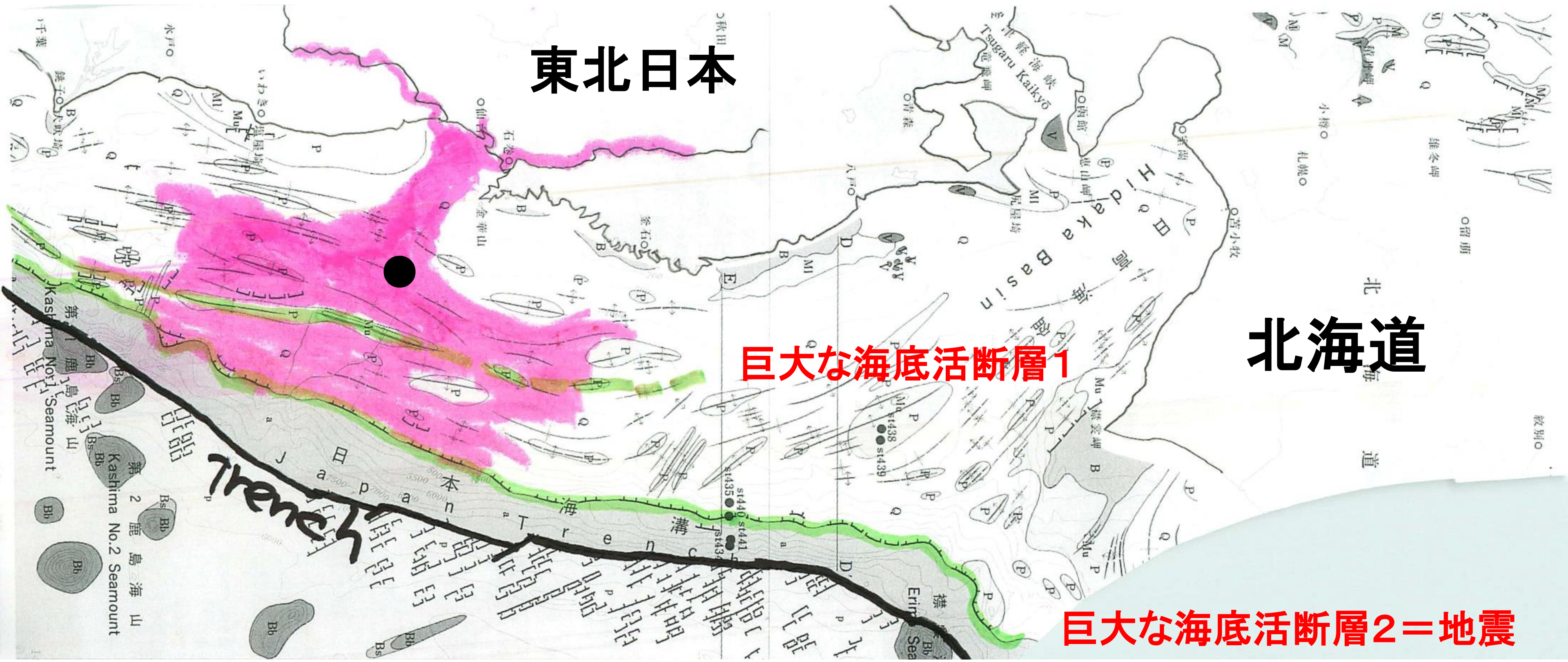
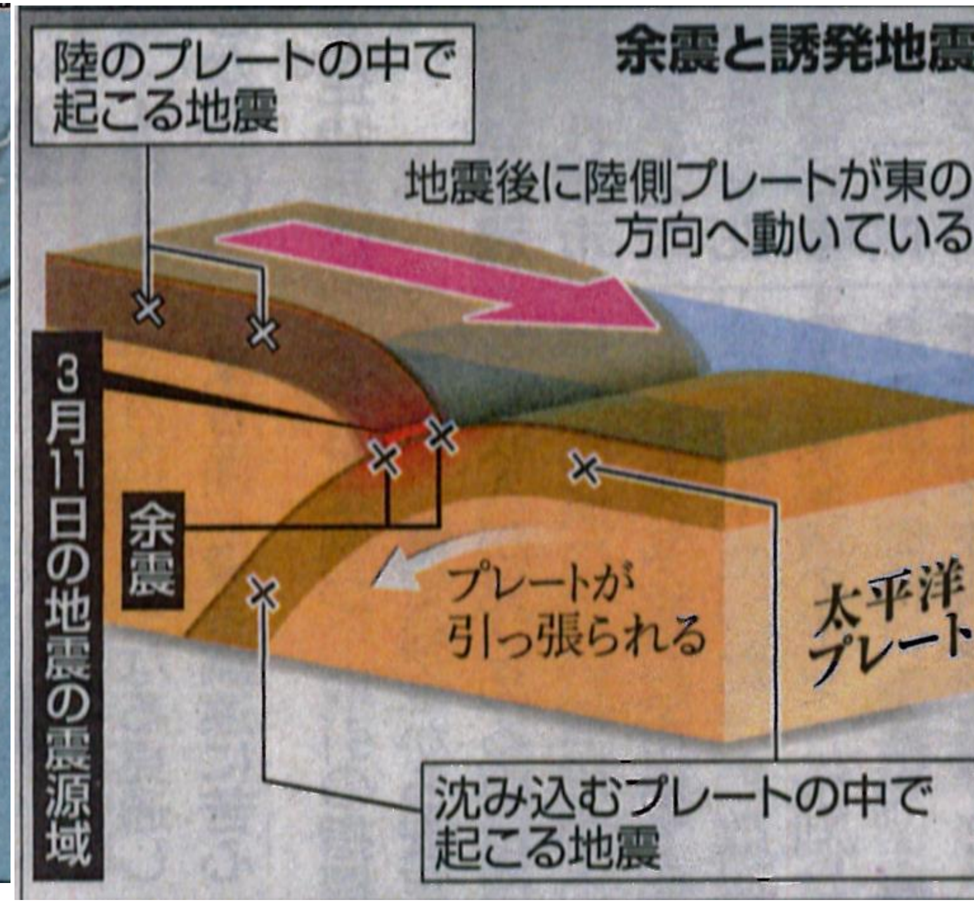
海面の変化
緩やかな上昇
急な上昇
14:50
15:00
15:10
15:20
15:30

海溝内壁の力学境界断層で地震は起きた



巨大な海底活断層3＝日本海溝

3月11日の地震の震源域



出典:4．17　朝日新聞