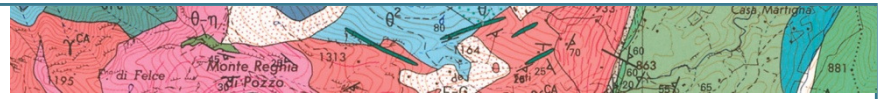


Strong Motion Seismology

- Broadband Acceleration Time Histories-

Hideo Aochi

BRGM : Bureau de Recherches Géologiques et Minières
(French geological Survery)

Géosciences pour une Terre durable
brgm

Index

> **Introduction to Strong Motion Seismology**

> **Deterministic Simulations at Low Frequencies**

- ~~1999 Izmit, Turkey, earthquake (Mw7.3)~~
- 2007 Chuetsu-oki, Japan, earthquake (Mw6.6)

> **Stochastic Simulation at High Frequencies**

- 2007 Chuetsu-oki, Japan, earthquake (Mw6.6)

> **Perspective – Conclusion**

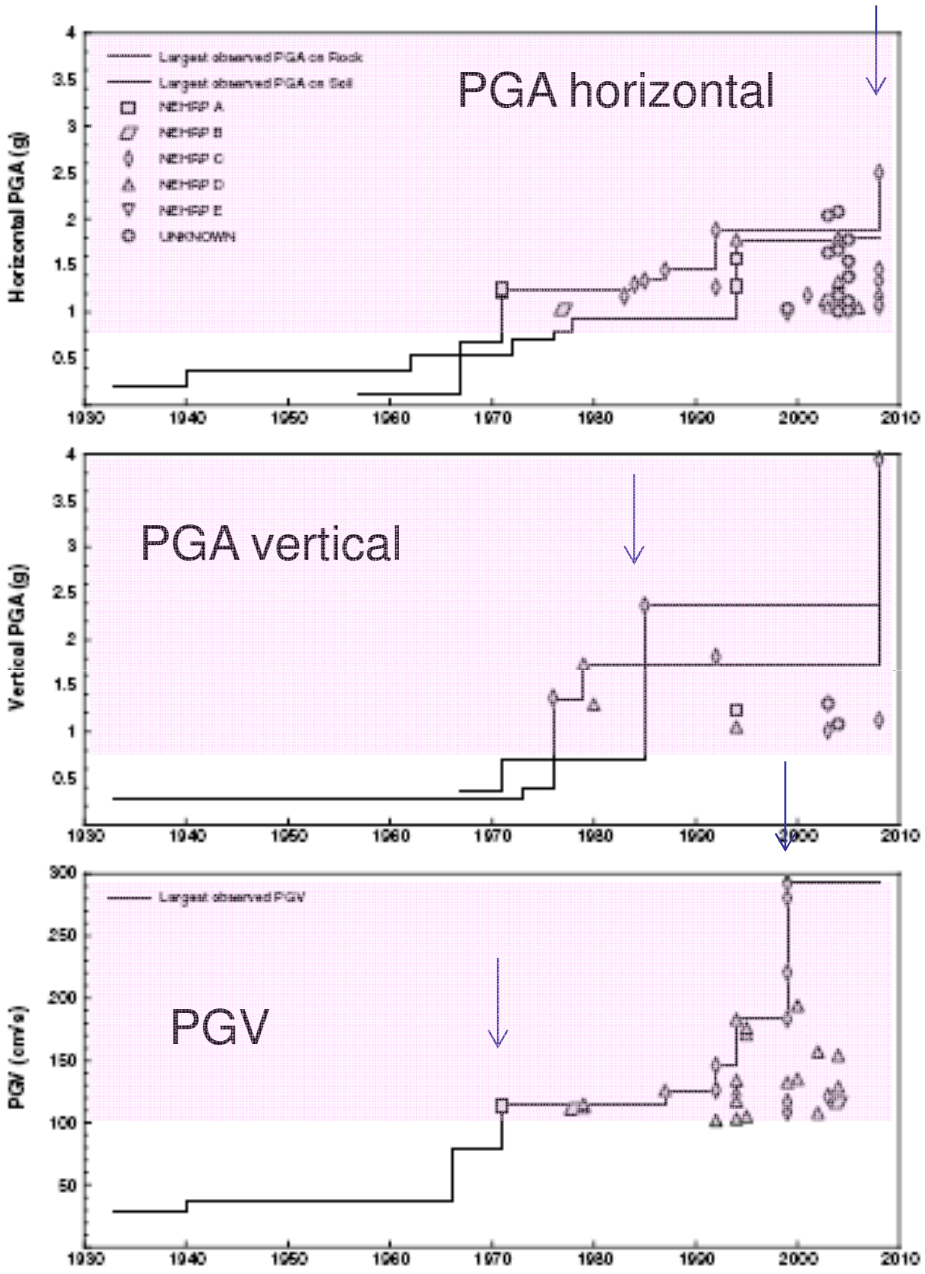
Géosciences pour une Terre durable
brgm

Observed strong motions

PGA = Peak Ground Acceleration (1g = 9.8 m/s/s)

PGV = Peak Ground Velocity (m/s)

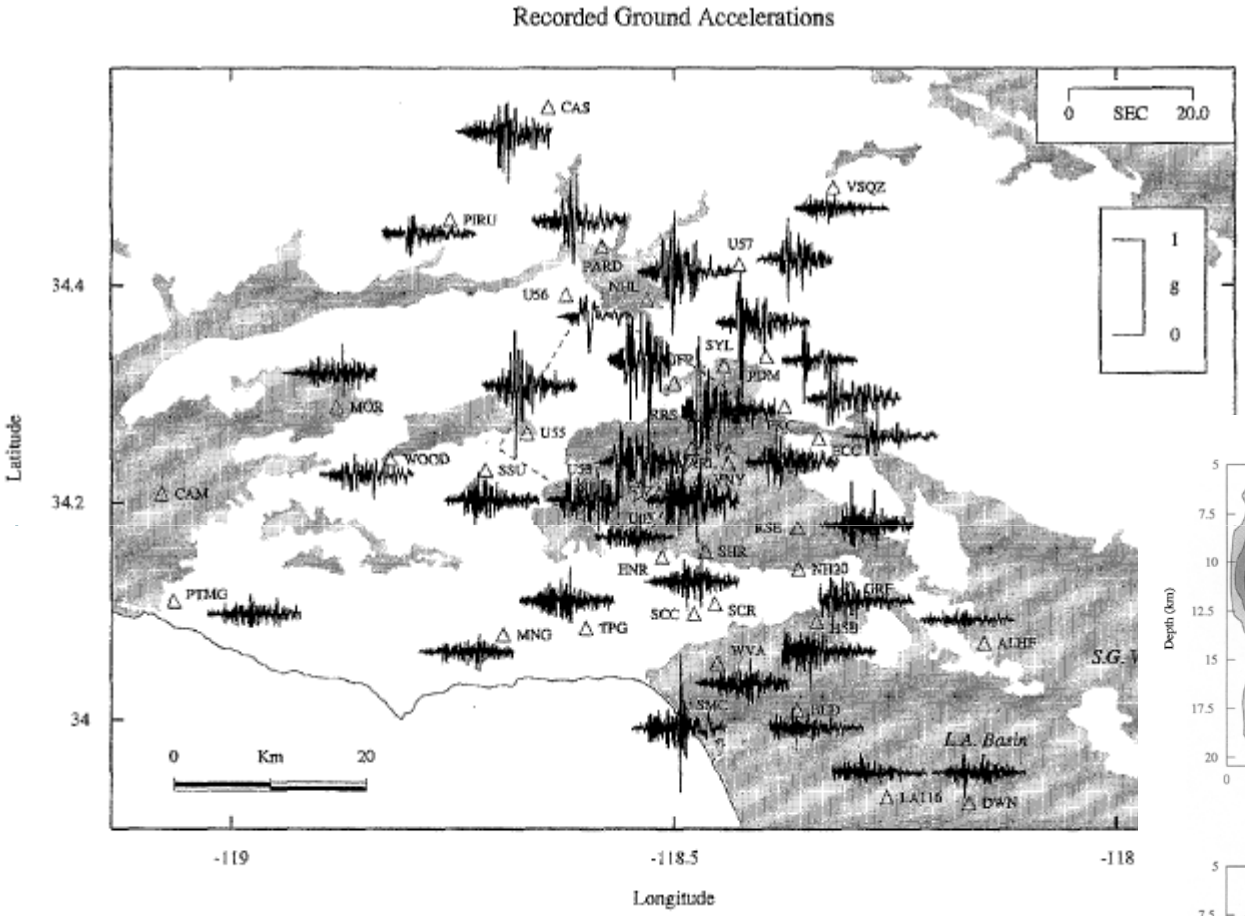
- 1971 San Fernando, CA (6.6)
- …
- 1985 Nahanni, Canada (6.8)
- …
- 1999 Chi-chi, Taiwan (7.6)
- …
- 2008 Iwate-Miyagi Nairiku, Japan (6.8)

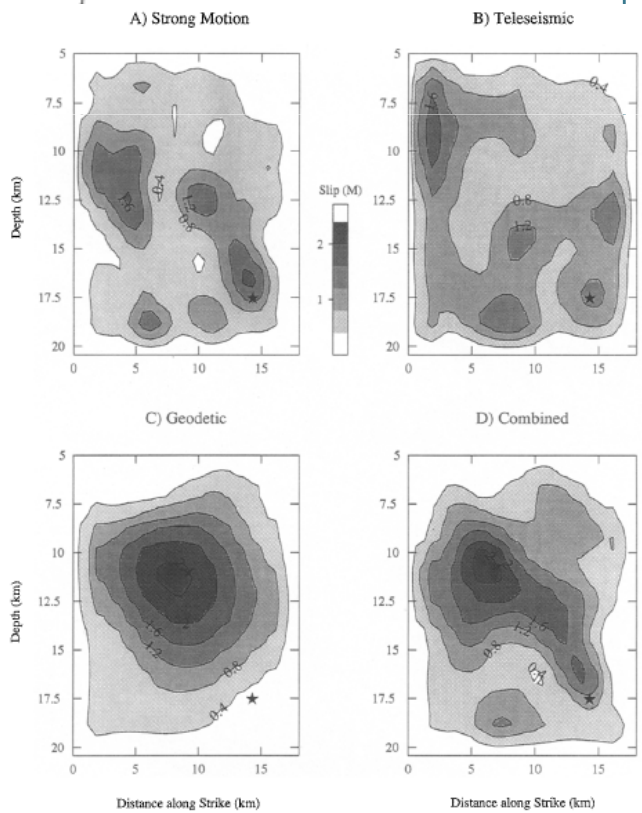


Strasser and Bommer (2009), Strong ground motions – Have we seen the worst?

1994 M6.7 Northledge earthquake

1994 M6.7 Northledge earthquake

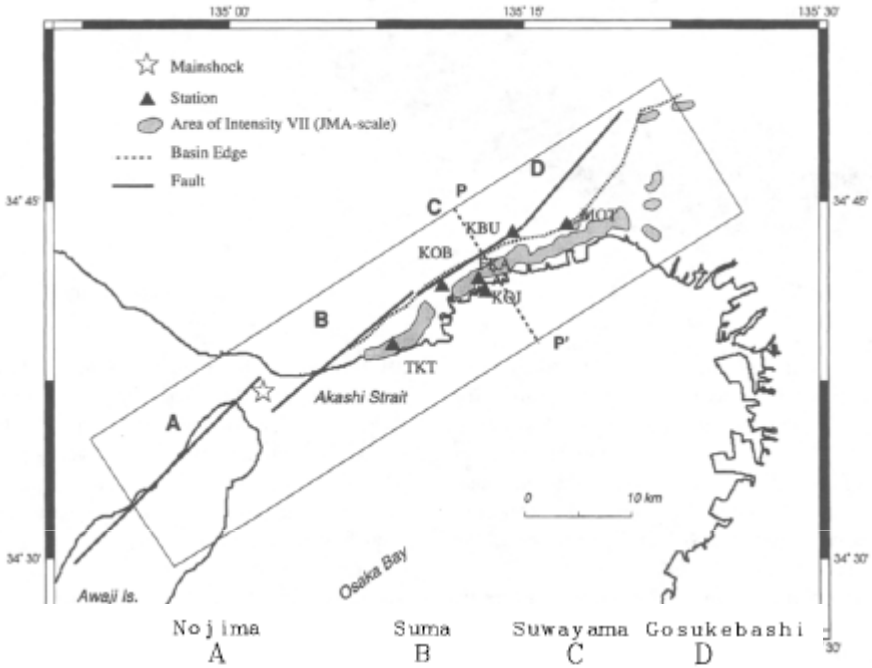


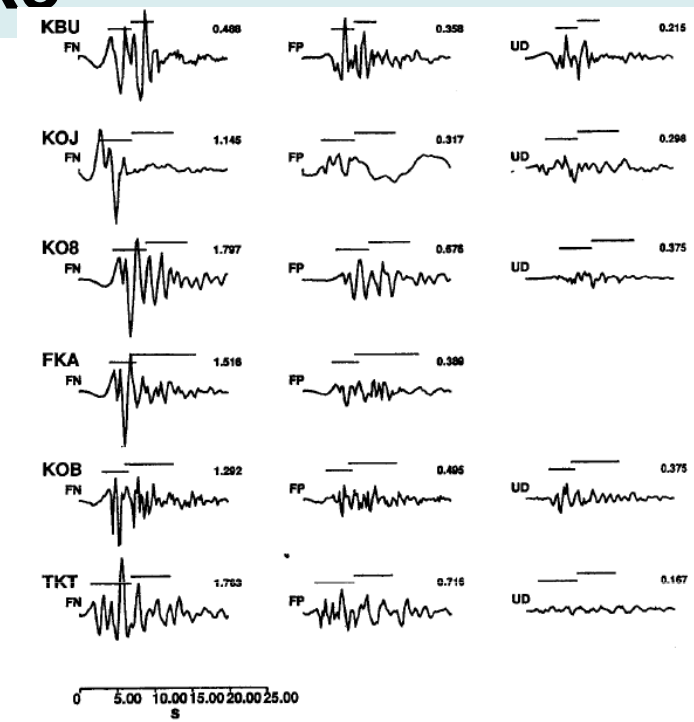


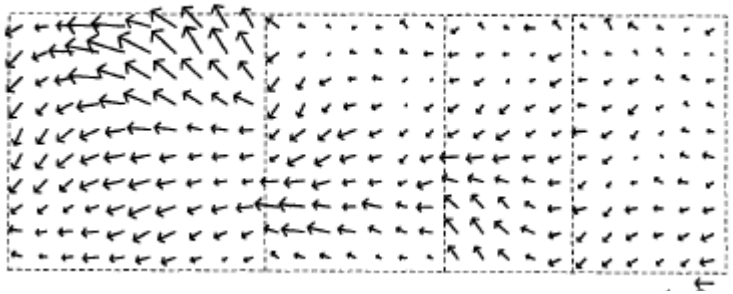
Wald and Heaton (1994): The slip history of the 1994 Northridge, California, earthquake determined from strong-motion, teleseismic, GPS, and leveling data.

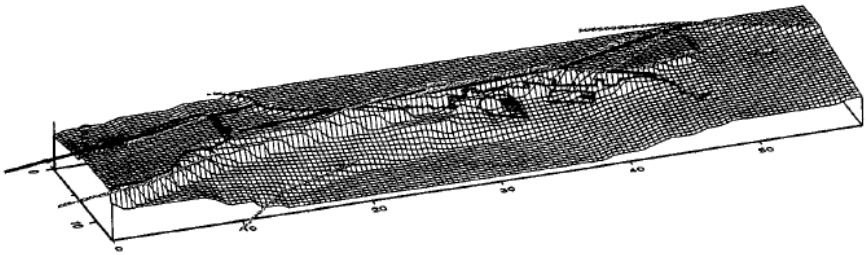
1995 M6.8 Kobe earthquake

1995 M6.8 Kobe earthquake









Irikura et al. (1997), Lesson from the 1995 Hyogo-ken Nanbu earthquake: Why were such destructive motions generated to buildings?
Pitarka et al. (1998), Three-dimensional simulation of the near-fault ground motion for the 1995 Hyogo-ken Nanbu (Kobe), Japan, earthquake.

What is « Strong Motion Seismology »?

> Study on « strong ground motion data »

> = Near-field ground motion of large earthquake

> = towards Quantitative Seismic Hazard Analysis (QSHA)

> = Source effect (wave radiation) + path effect (« attenuation ») + site effect (non-linearity)

> = Seismology + engineering seismology

Géosciences pour une Terre durable
brgm

Ground Motion Prediction Equations (GMPE)

> Empirical attenuation laws (Y = PGA, PGV, PSAs)

$$\ln Y = F_M(M) + F_D(R_{JB}, M) + F_S(V_{S30}, R_{JB}, M) + \varepsilon\sigma_T$$

Boore & Atkinson (2008)

$$F_M(M) = \begin{cases} e_1 U + e_2 SS + e_3 NS + e_4 RS + e_5(M - M_h) + e_6(M - M_h)^2; & M \le M_h \\ e_1 U + e_2 SS + e_3 NS + e_4 RS + e_7(M - M_h); & M > M_h \end{cases}$$

$$F_D(R_{JB}, M) = (c_1 + c_2(M - M_{ref}))\ln(R / R_{ref}) + c_3(R - R_{ref}); \quad R = \sqrt{R_{JB}^{\ 2} + h^2}$$

$$F_S(V_{S30}, R_{JB}, M) = F_{LIN} + F_{NL}$$

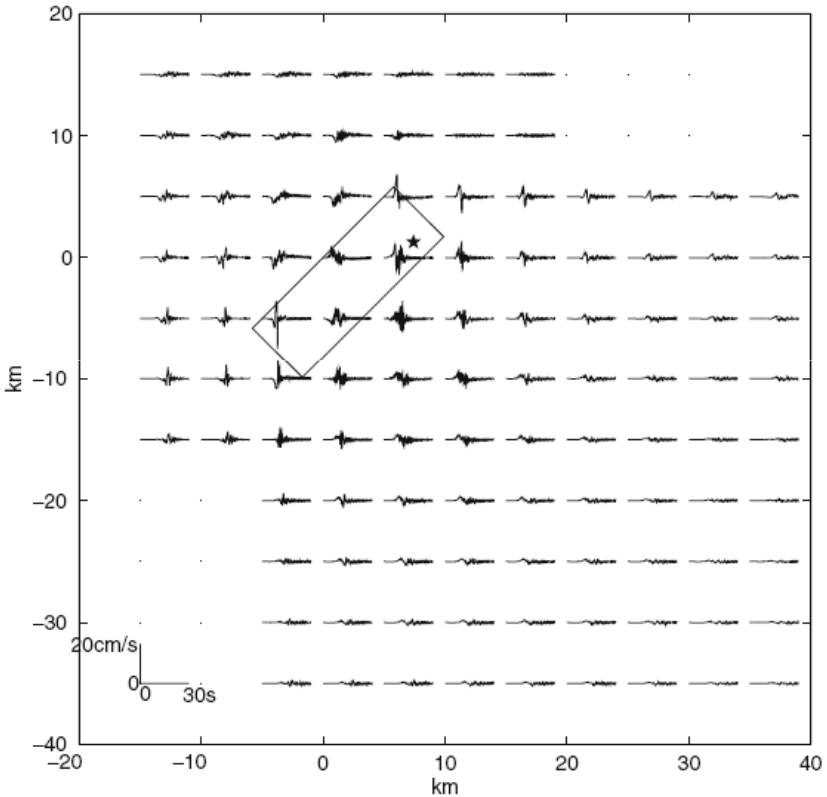
$$F_{LIN} = b_{lin}\ln(V_{S30} / V_{ref}); \quad V_{ref} = 760 \text{ m/s}$$

$$F_{NL} = \begin{cases} b_{nl}\ln(pga\_low / 0.1); & pga4nl \le a_1 (= 0.03g) \\ b_{nl}\ln(pga\_low / 0.1) + c(\ln(pga4nl / a_1))^2 + d(\ln(pga4nl / a_1))^3; & a_1 < pga4nl \le a_2 \\ b_{nl}\ln(pga4nl / 0.1); & a_2 (= 0.09g) < pga4nl \end{cases}$$

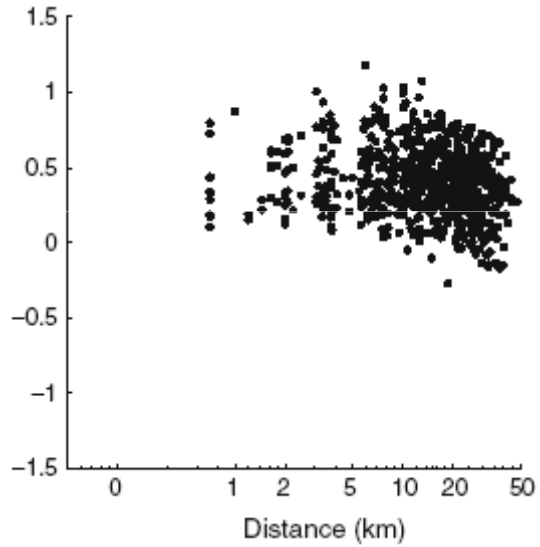
M = 5-8, R_{JB}<200 km, Vs=180-1300 m/s

Near Field Ground Motion

> Have we understood near field ground motion?



residual = log10(PGV_{emp}/PGV_{syn})



Aochi & Douglas (2006), Testing the validity of simulated strong ground motion from the dynamic rupture of a finite fault, by using empirical equations

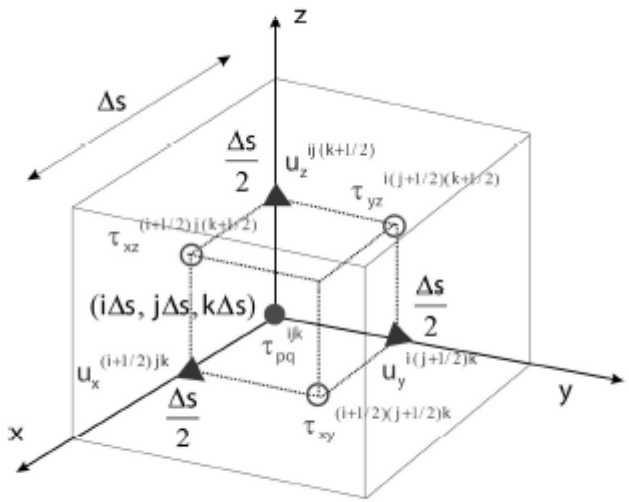
Finite Difference for Wave Propagation

> Stress-velocity formulation

$$\rho \frac{\partial^2 u_i}{\partial t^2} = \frac{\partial \sigma_{ij}}{\partial x_j} + f_i$$

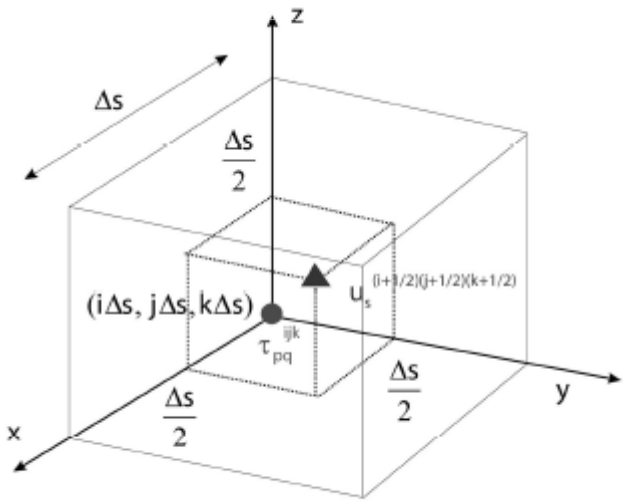
$$\rho \frac{\partial}{\partial t} v_x = \frac{\partial}{\partial x} \tau_{xx} + \frac{\partial}{\partial y} \tau_{xy} + \frac{\partial}{\partial z} \tau_{xz} + F_x \text{ and two other equations.}$$

$$\frac{\partial}{\partial t} \tau_{xx} = \lambda \left(\frac{\partial}{\partial x} v_x + \frac{\partial}{\partial y} v_y + \frac{\partial}{\partial z} v_z \right) + 2\mu \frac{\partial}{\partial x} v_x \text{ and five other equations.}$$



UNIT STAGGERED-GRID

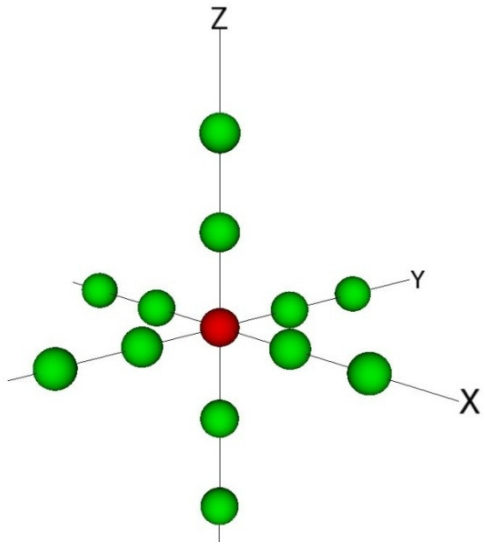
Virieux & Madariaga (1982)



PARTIALLY-STAGGERED-GRID

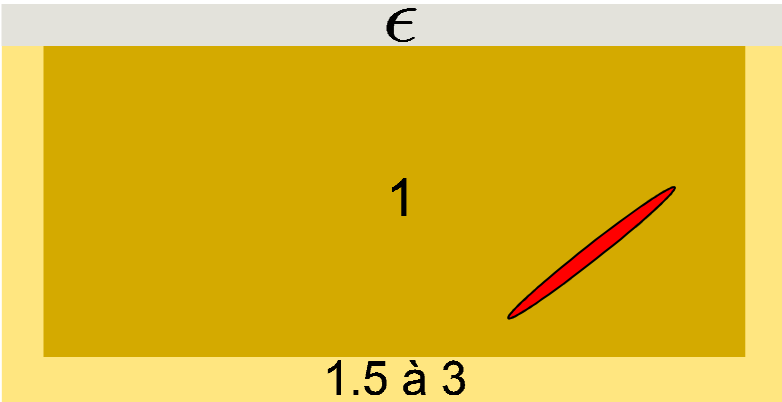
Saenger et al. (2000)

Finite difference scheme



- In most case, structural grid = easy domain decomposition.
- 4th order in space = good cost performance.

$$\frac{\partial}{\partial x} f(x) = \frac{1}{h}\left(\frac{9}{8}\left\{f(x+\frac{h}{2}) - f(x-\frac{h}{2})\right\} - \frac{1}{24}\left\{f(x+\frac{3}{2}h) + f(x-\frac{3}{2}h)\right\}\right)$$



Free surface (traction = 0)

Absorbing boundary condition
(No reflection. No inward wave)

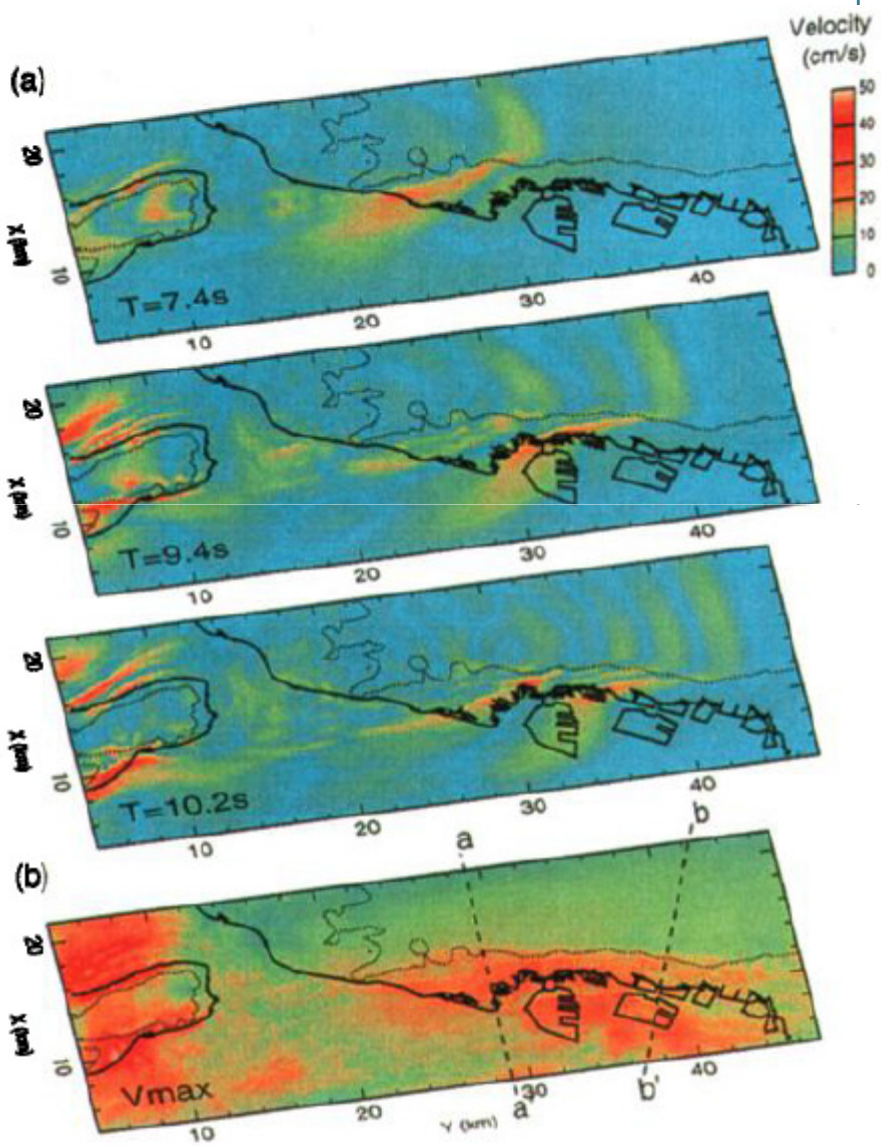
Earthquake source (pre-described or simultaneously to be calculated) … factor varies

Finite difference simulation 15 years ago

> Kinematic source on finite fault segments

> 51.2x25.6x25.6 km3 (0.2 km) = 256 x 128 x 128 grids

> A duration of 25s = 55 hours on 8 procs CRAY CS6400.



Furumura & Koketsu (1998)

Simulation Strategy from Source to Site

1. Initial Condition

   Fault Geometry, Tectonic Stress
   Rupture Criterion

2. Dynamic Rupture Propagation

   Boundary Integral Equation Method

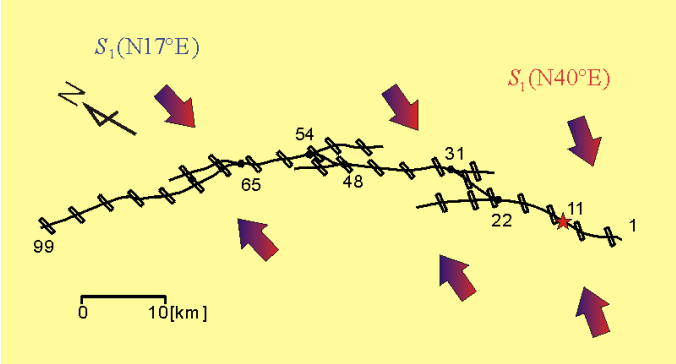
3. Seismic Wave Propagation

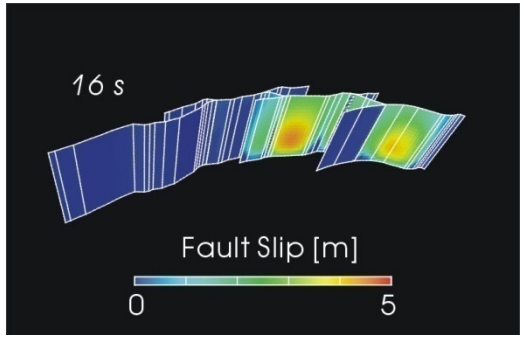
   FDM

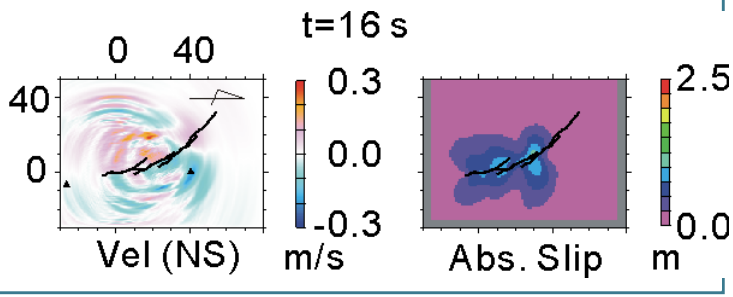
4. (Non-linear) Soil Behavior

   Finite Element Method

The 1992 Landers, CA (M7.3)

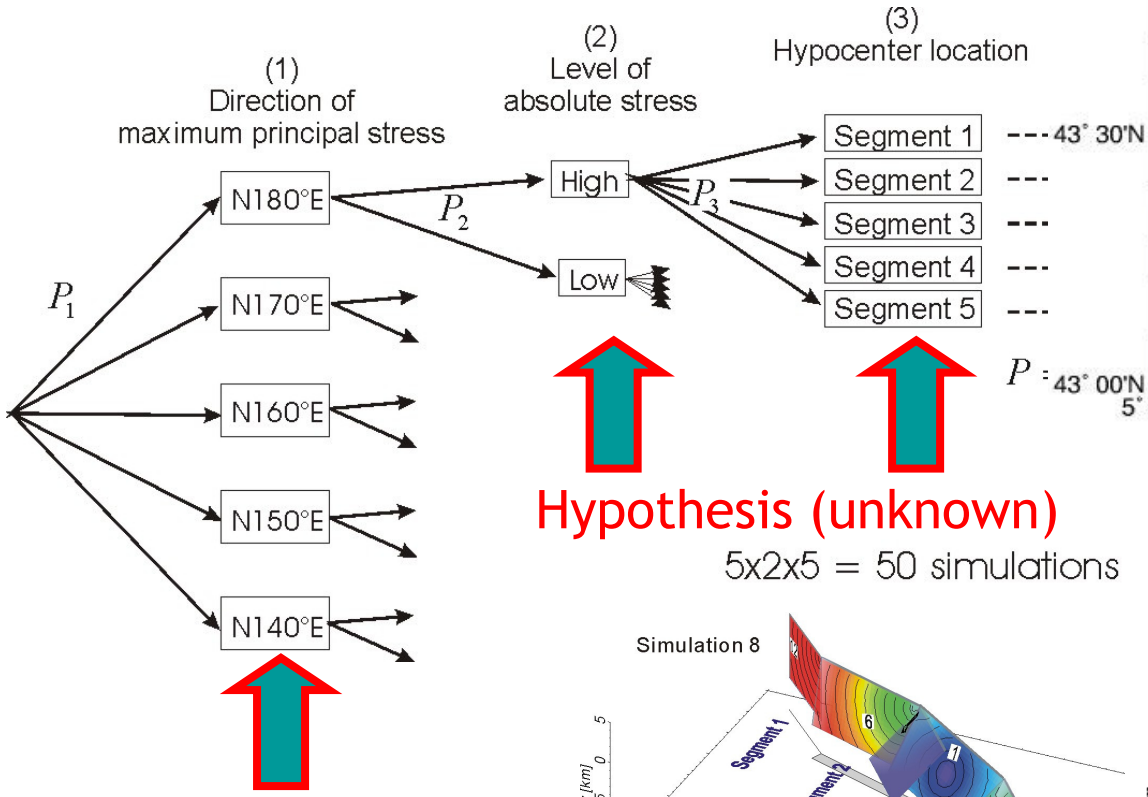


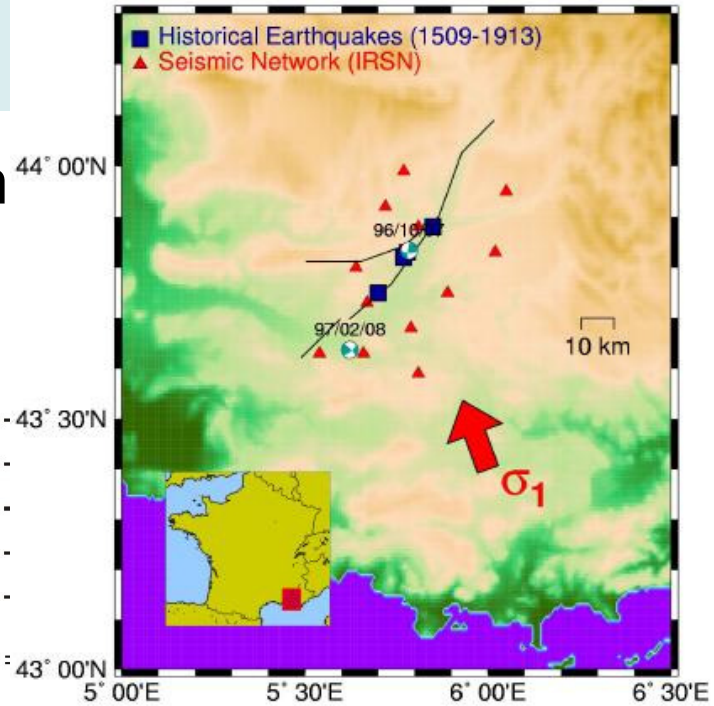




Moyenne Durance

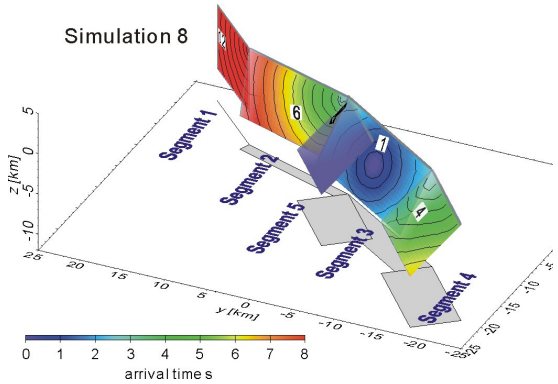
5 Segments with different mechanism

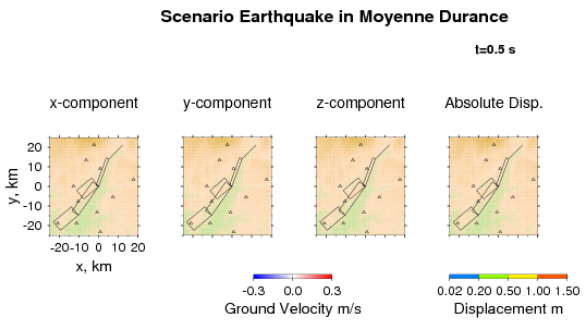




Hypothesis (unknown)

5x2x5 = 50 simulations



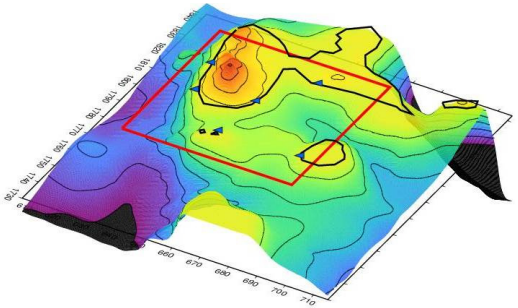


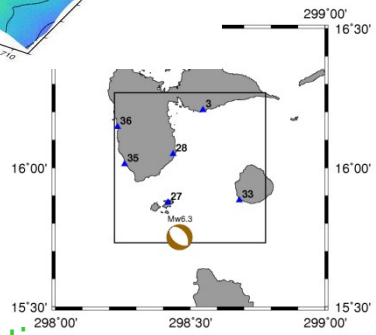
Tectonic Stress (uni-axi)

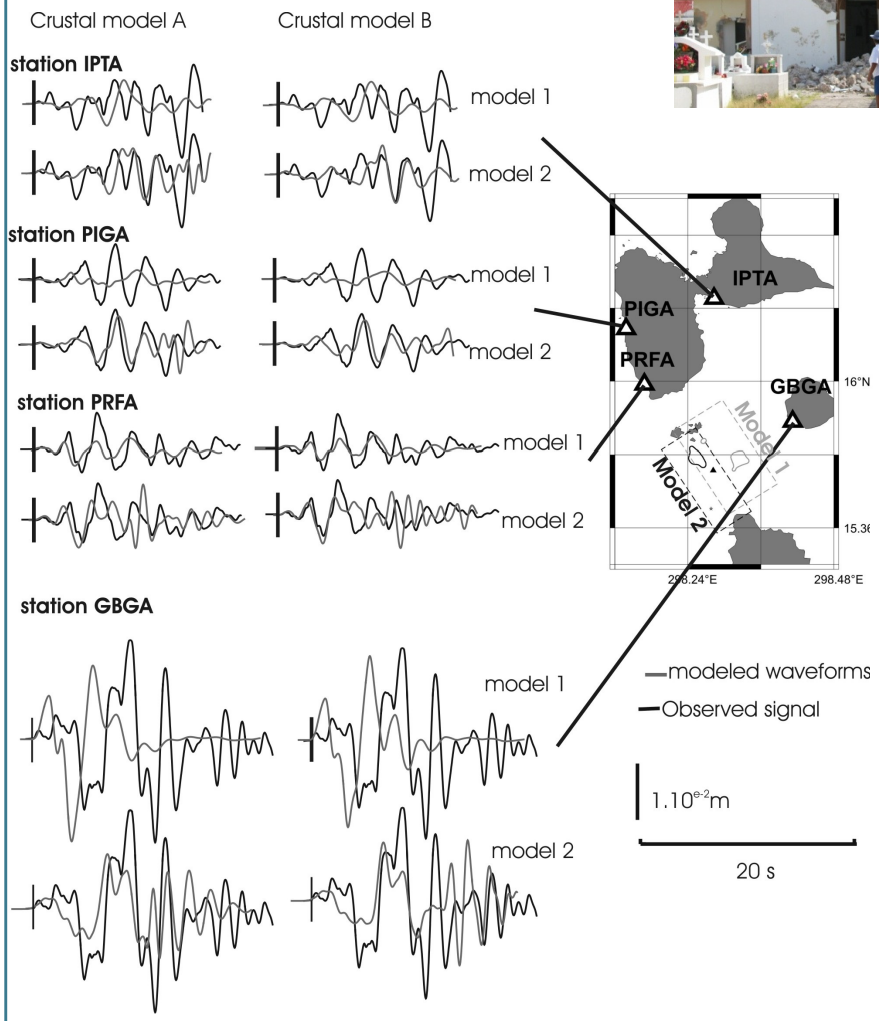
σ_1 = N160° E $\pm \alpha$

Aochi et al. (GJI, 2006)

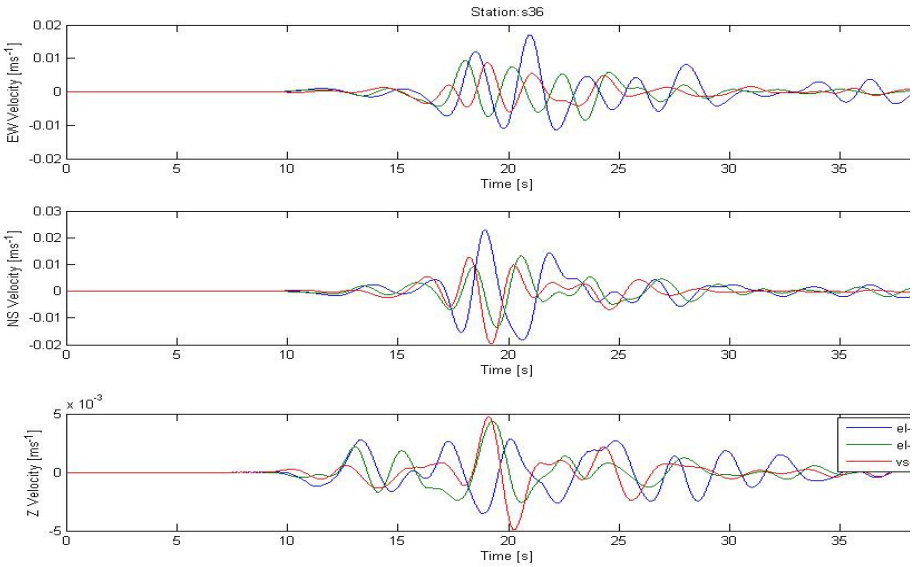
2004 Les Saintes







-Flat topography and elastic
-GEBCO topography and elastic
-GEBCO topography and viscoelastic



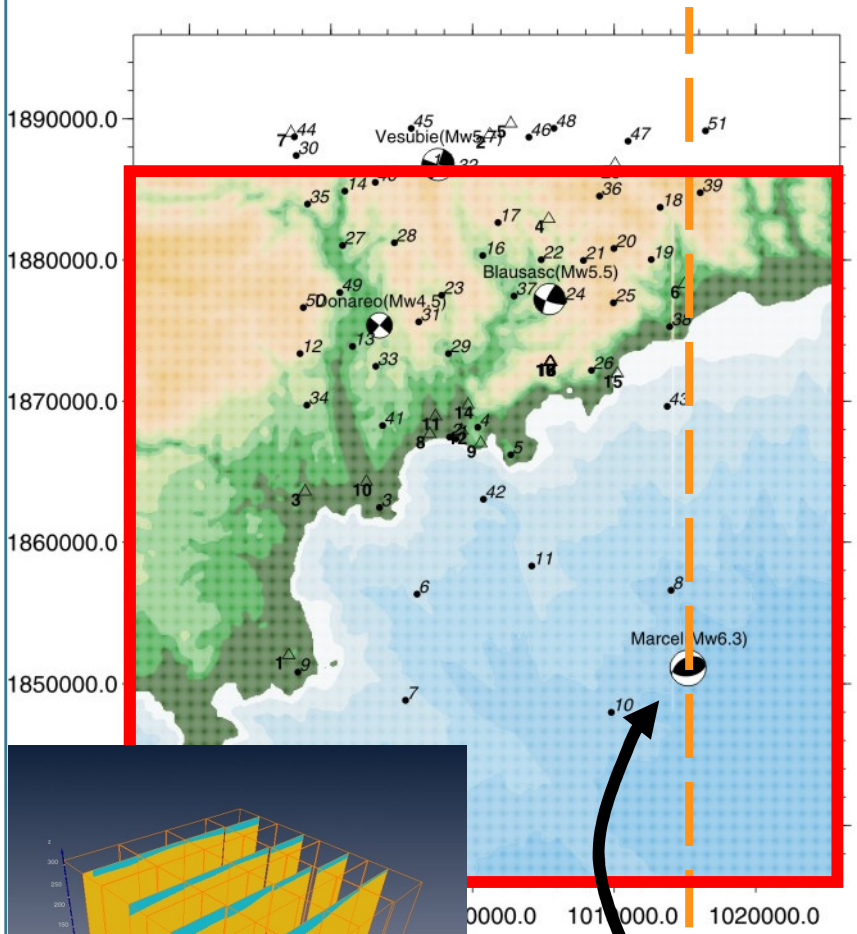
Salichon et al. (2009)

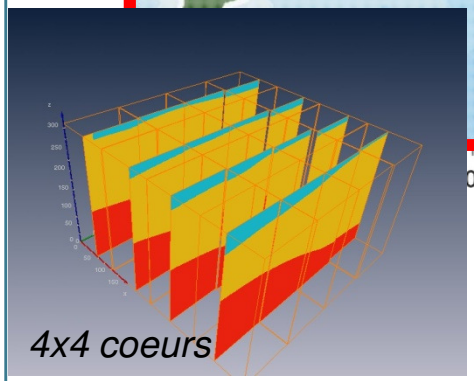
Jousset & Aochi (2006)

Nice region

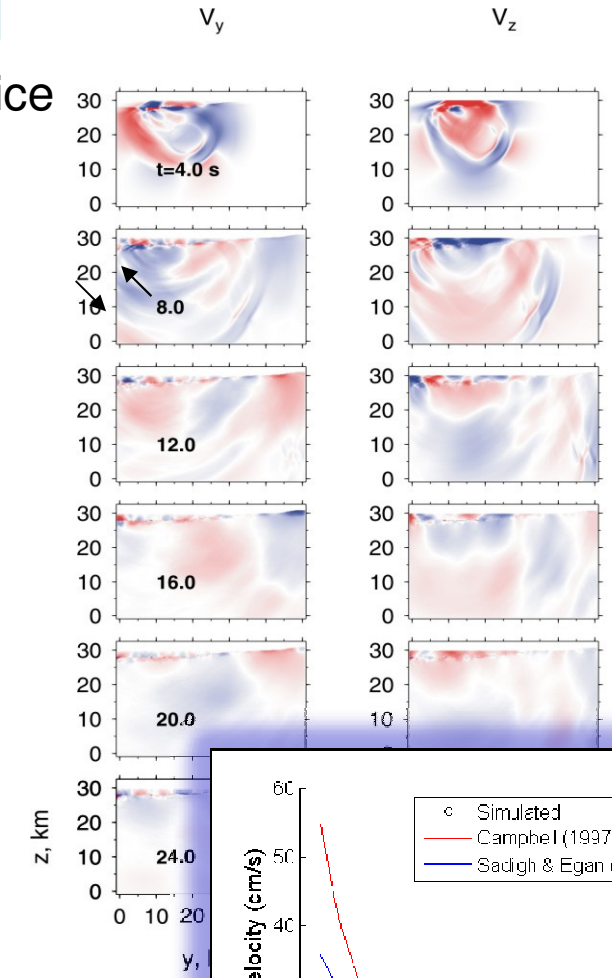
ANR QSHA (2006-2008)

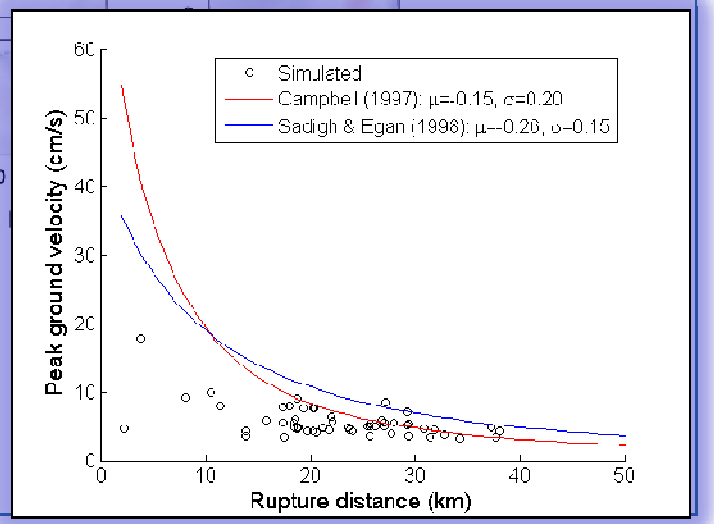
Modèle 50 x 50 x 30 km^3 autour de Nice





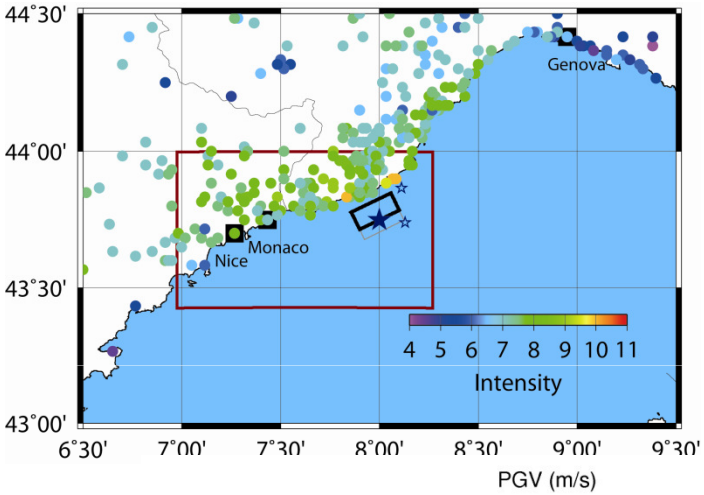
Faille étendu (18x9km) cinématique

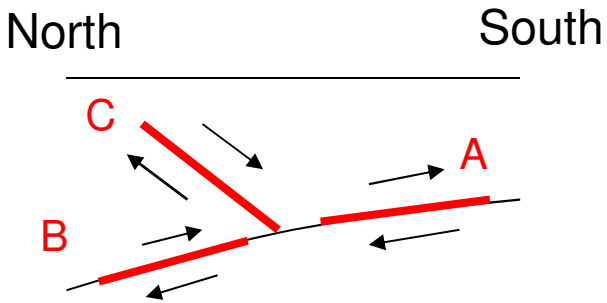




Interpretation of tectonics of 1887 Ligure earthquake

Macroseismic Intensity Date from SisFrance
(http://www.sisfrance.net)

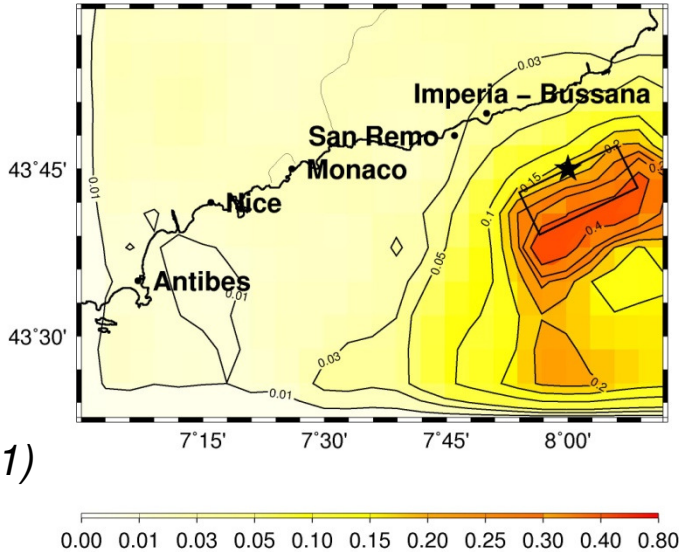


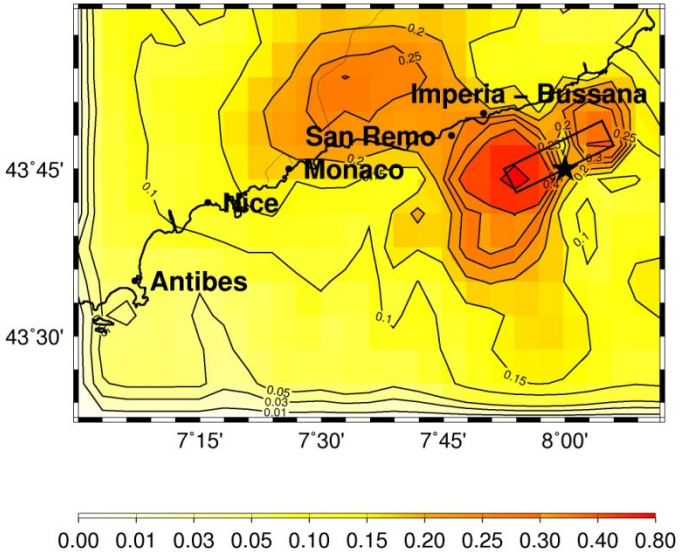


> **Reverse or normal faulting ?**

> **Different position / depth**

PGV (1 Hz)

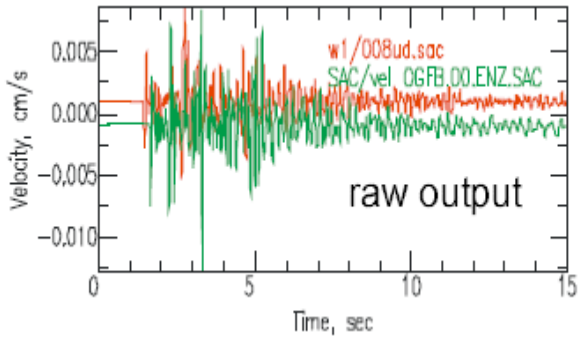


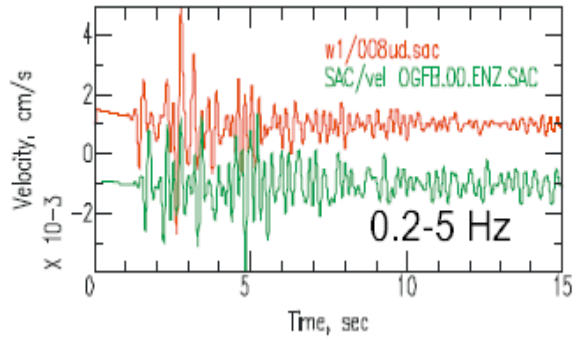


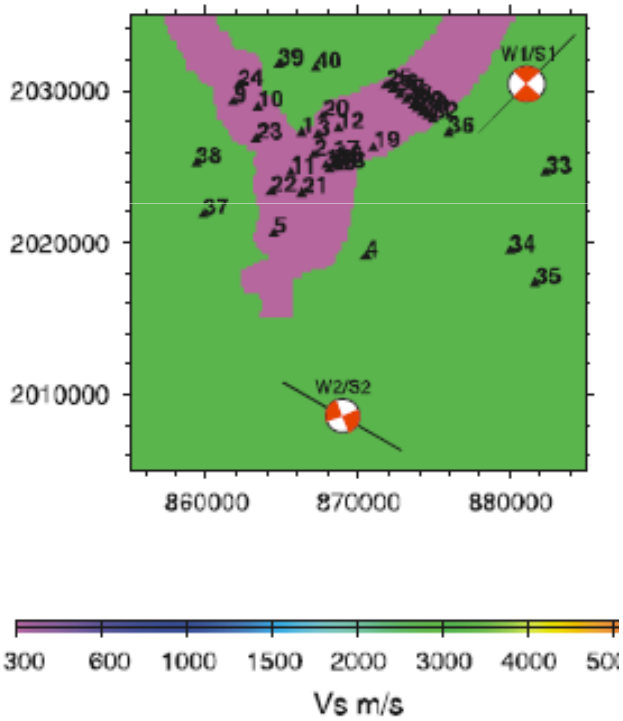
Aochi et al. (2011)

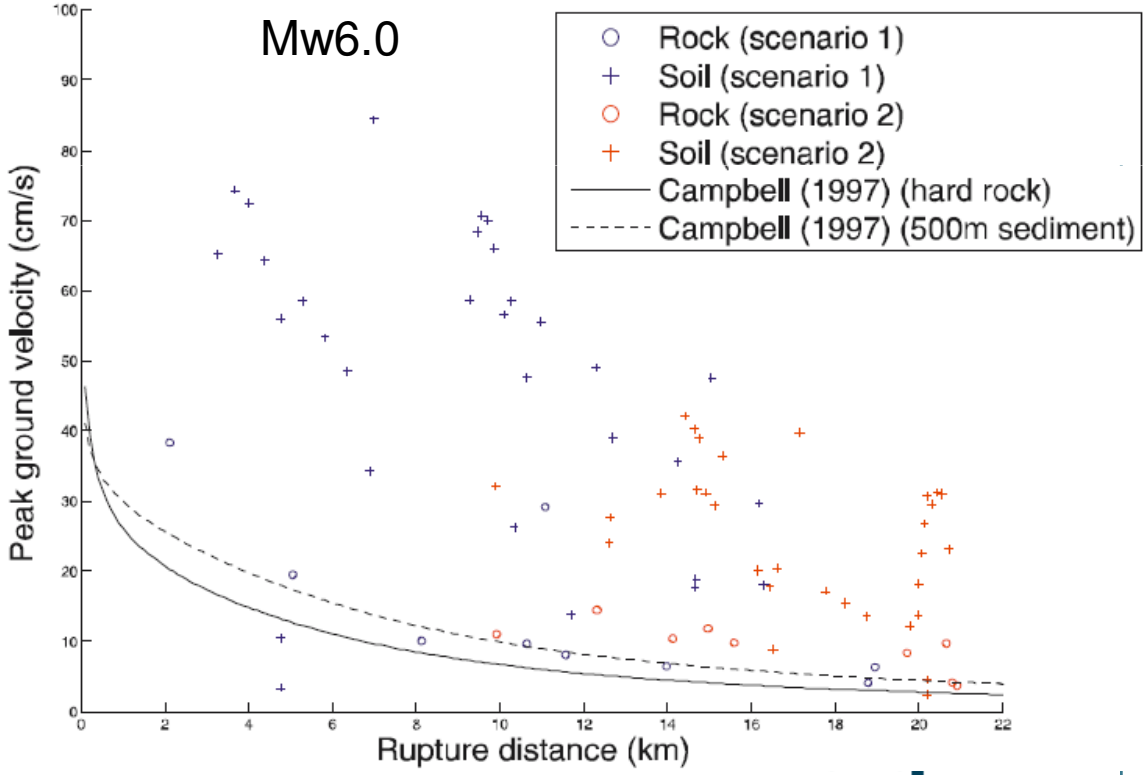
Grenoble basin

Mw2.8





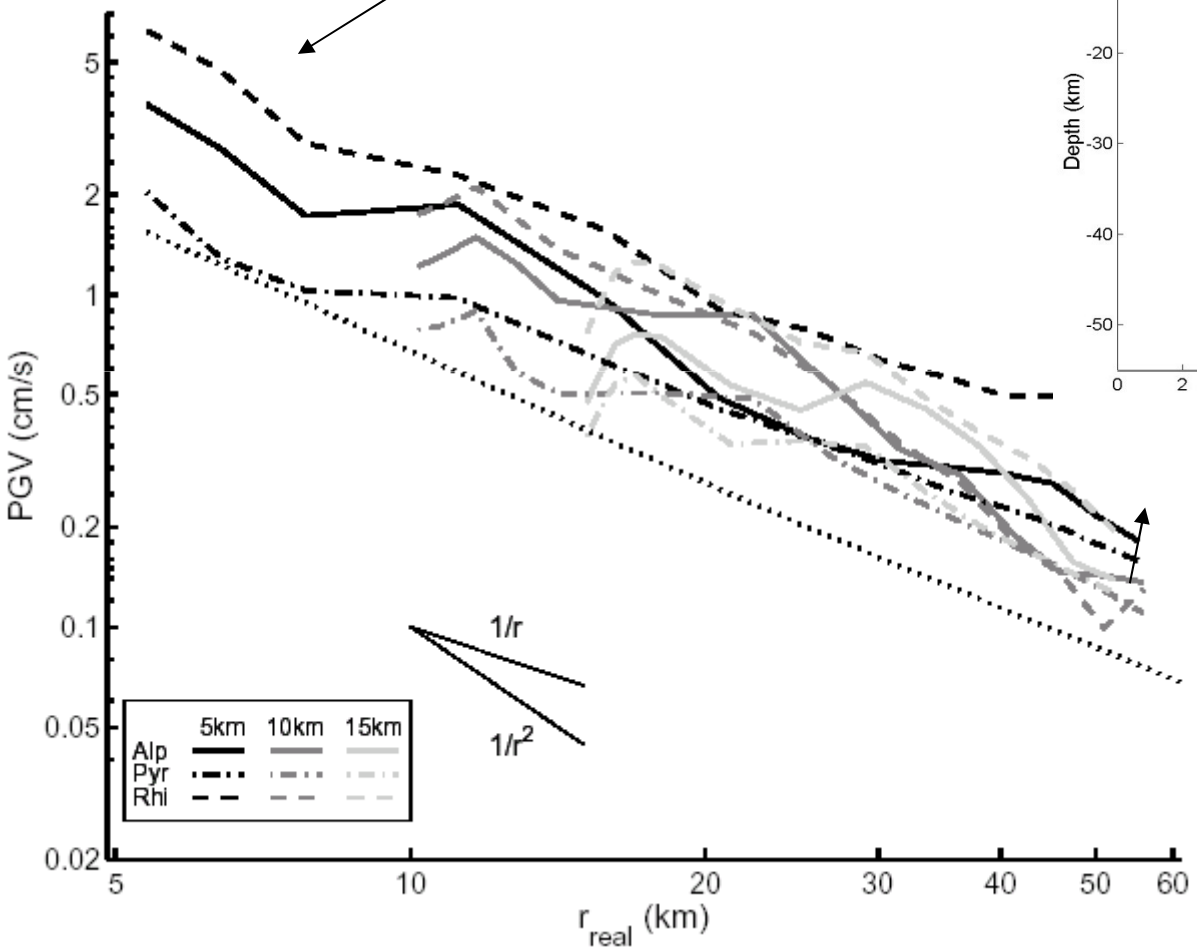


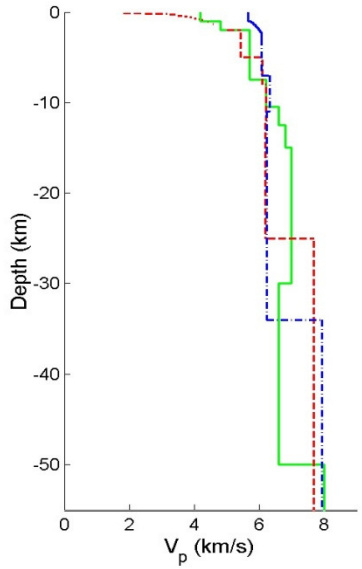


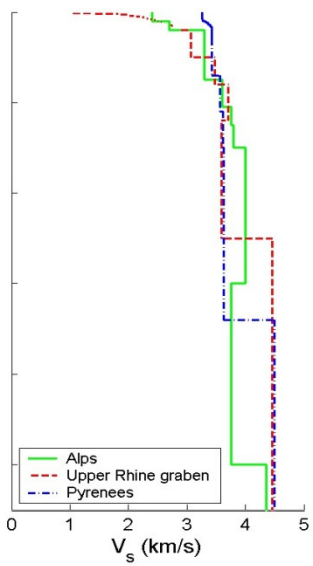
Aochi et al. (2006)

Variation and uncertainty in strong ground motion

Rhine (with soft layer, shallow earthquake)



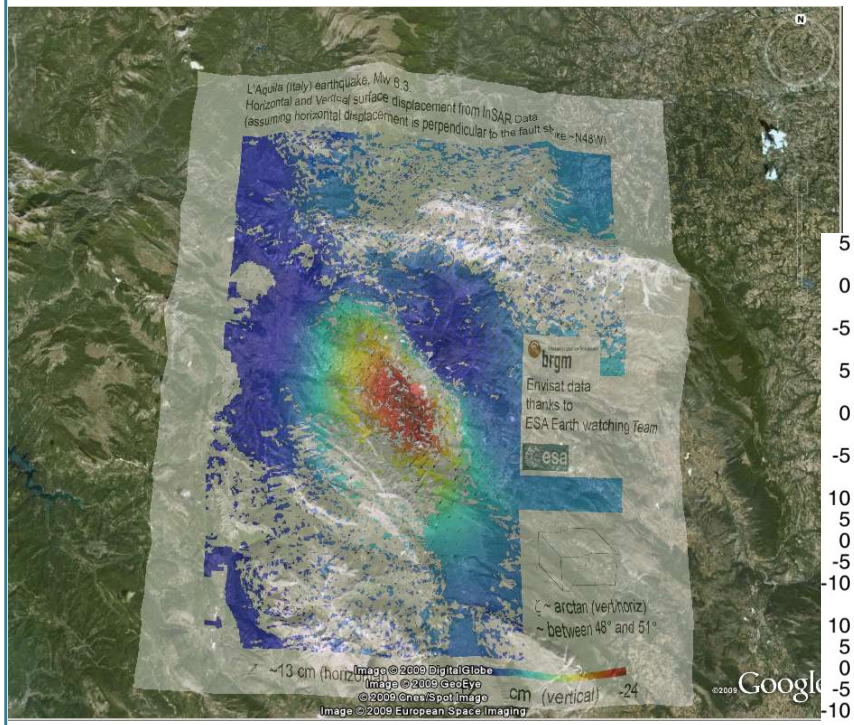


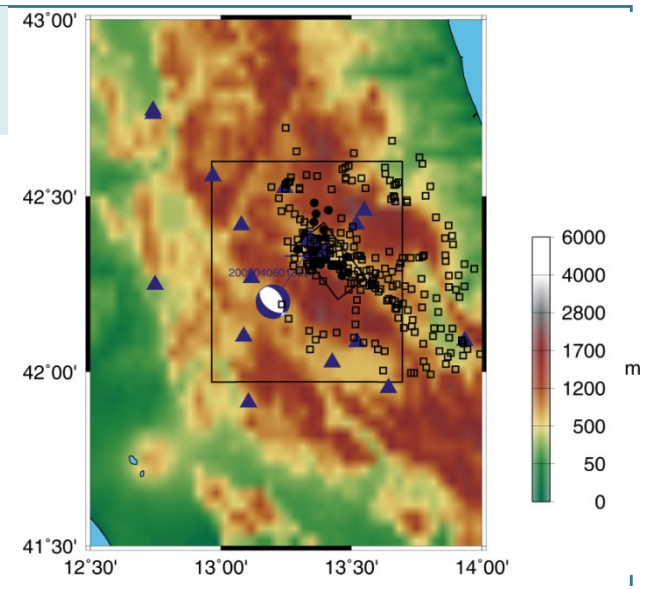


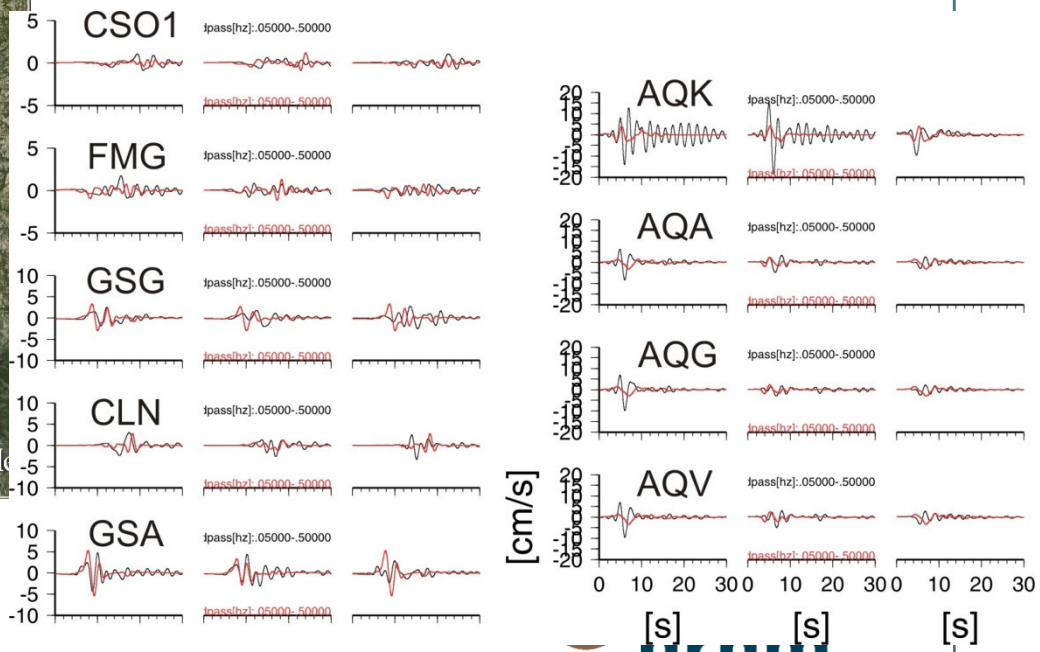
Campbell (1997)

Douglas et al. (2007)

2009 l'Aquila, Italy



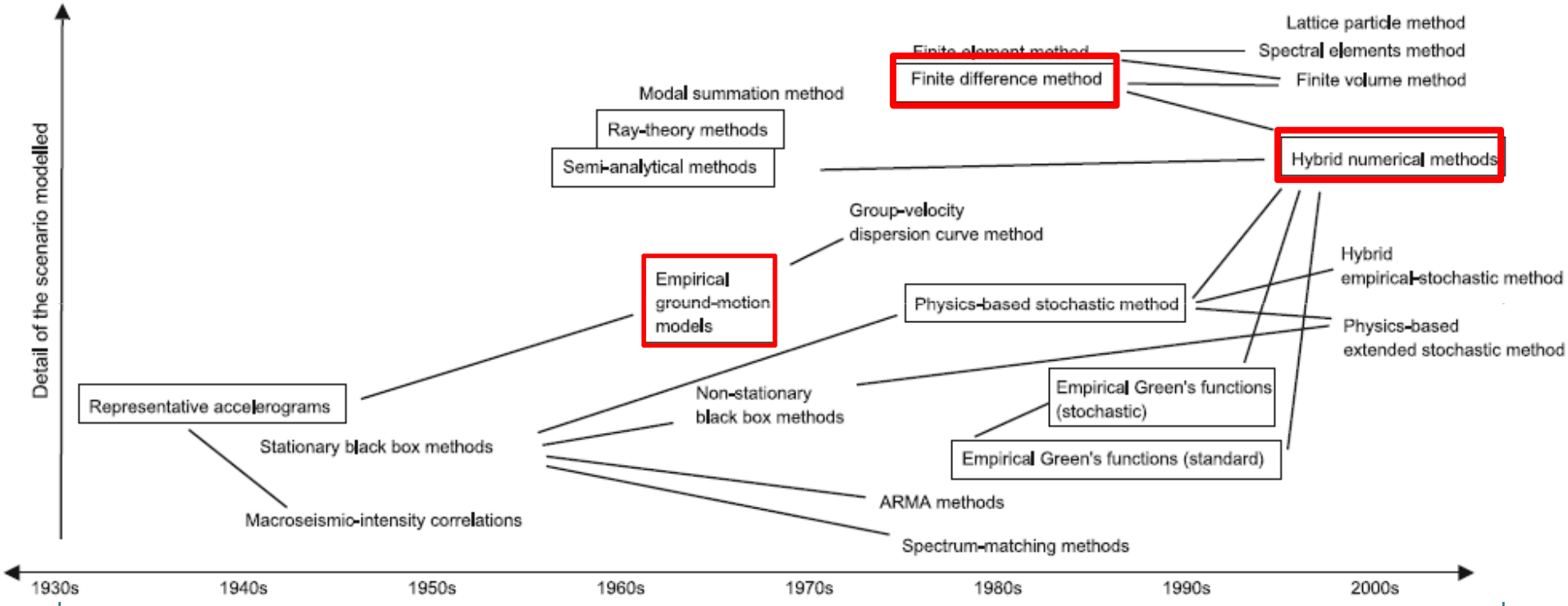




Unpublished works

History of ground-motion prediction

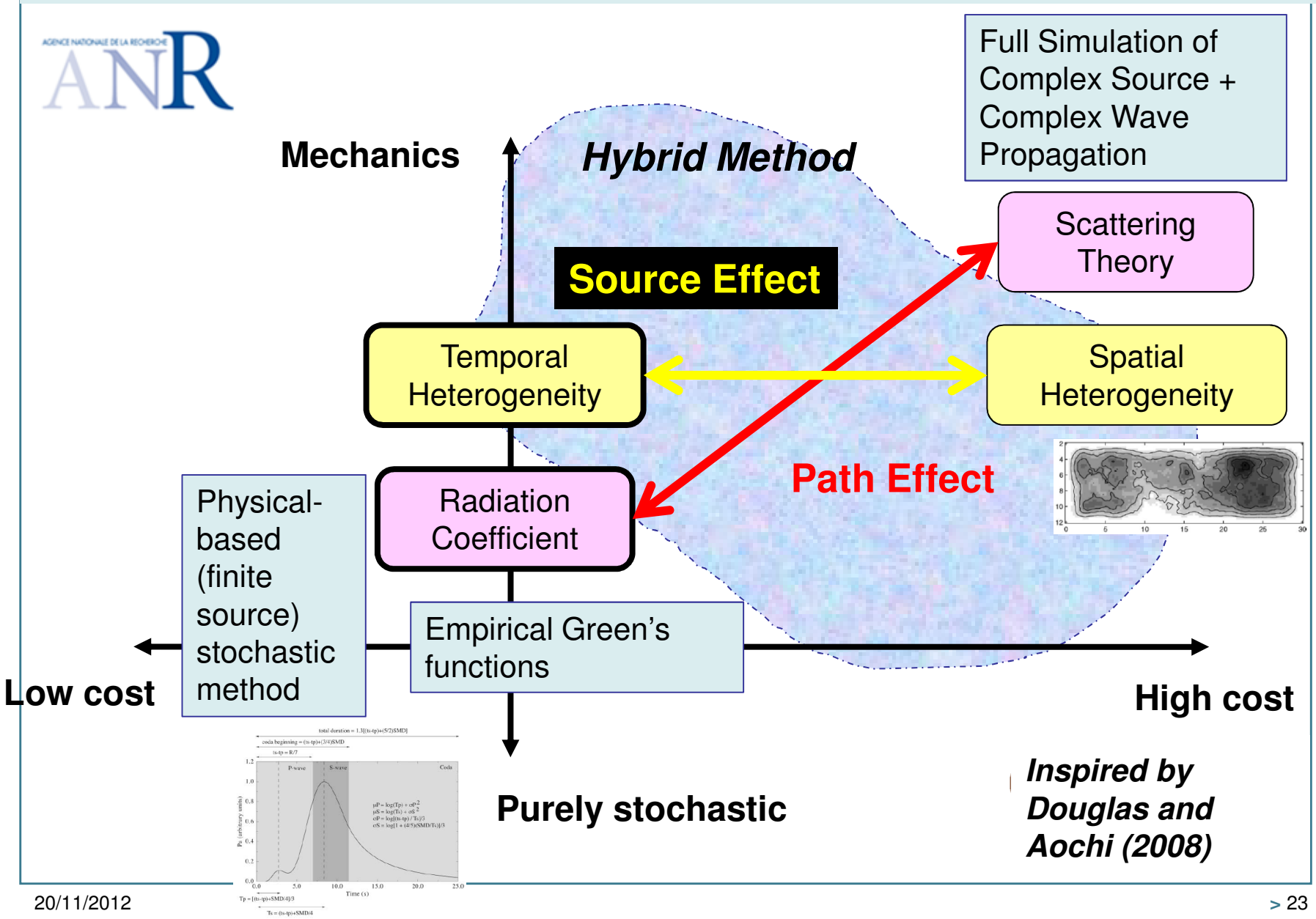
Douglas & Aochi (2008)



Boxes indicate those methods often used in research and/or practice

Géosciences pour une Terre durable
brgm

DEvelopment of Broadband Time histories for Engineers



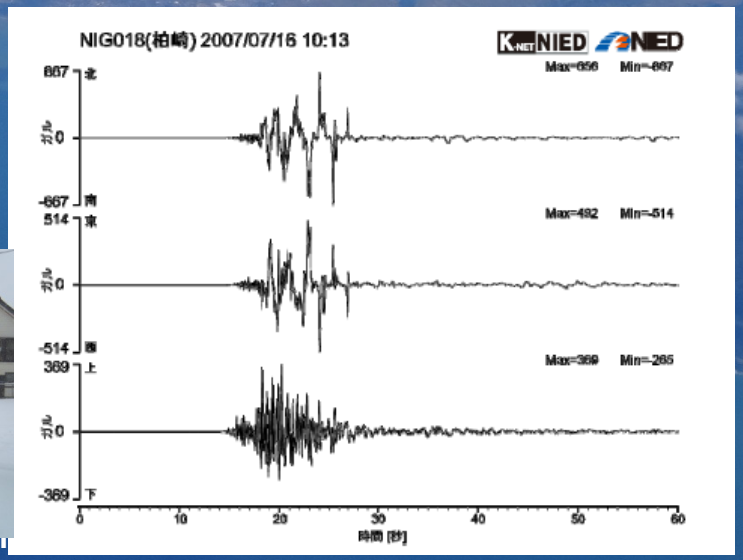
Inspired by Douglas and Aochi (2008)

2007 Mw6.6 Chuetsu-oki earthquake

Kashiwazaki town

Kashiwazaki – Kariwa NPP

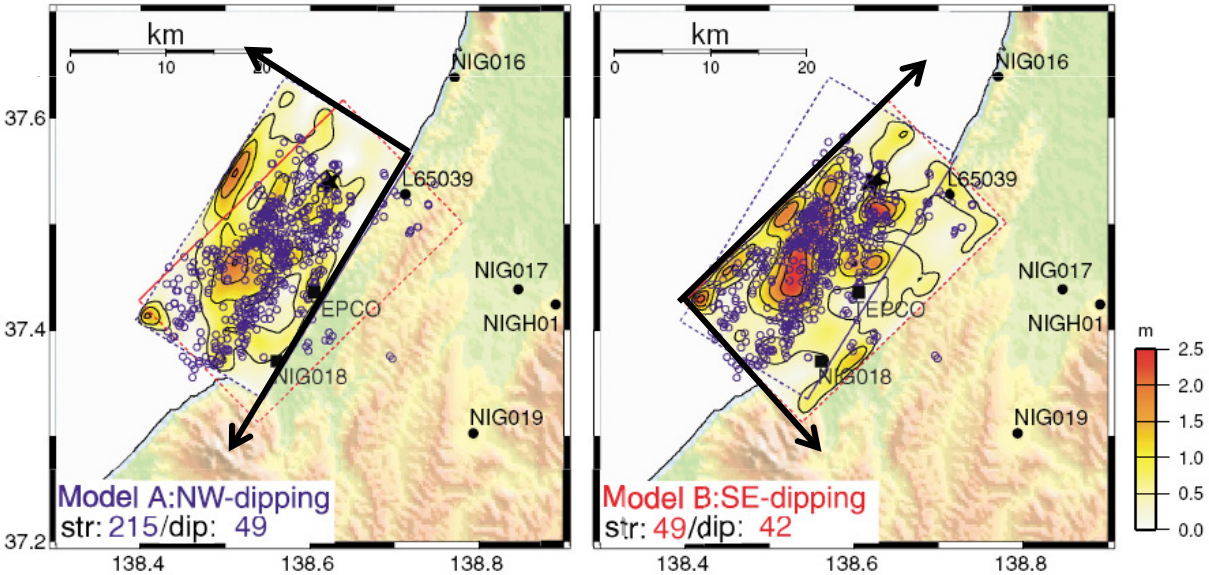
Japan Sea

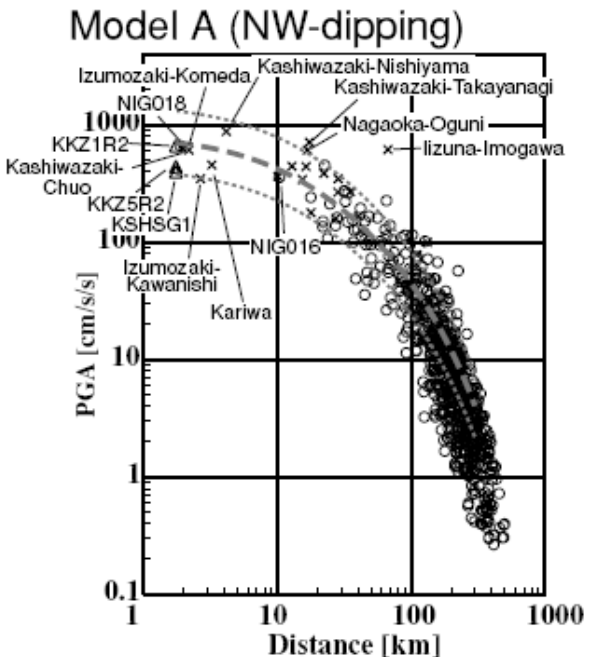


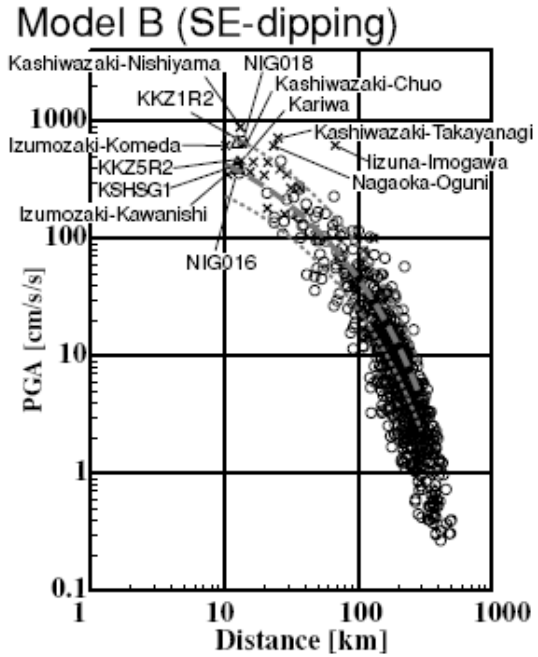
Near-field Ground Motion and Fault Model

> Seismological Inersion

- Adequate solutions are found for both fault orientations.

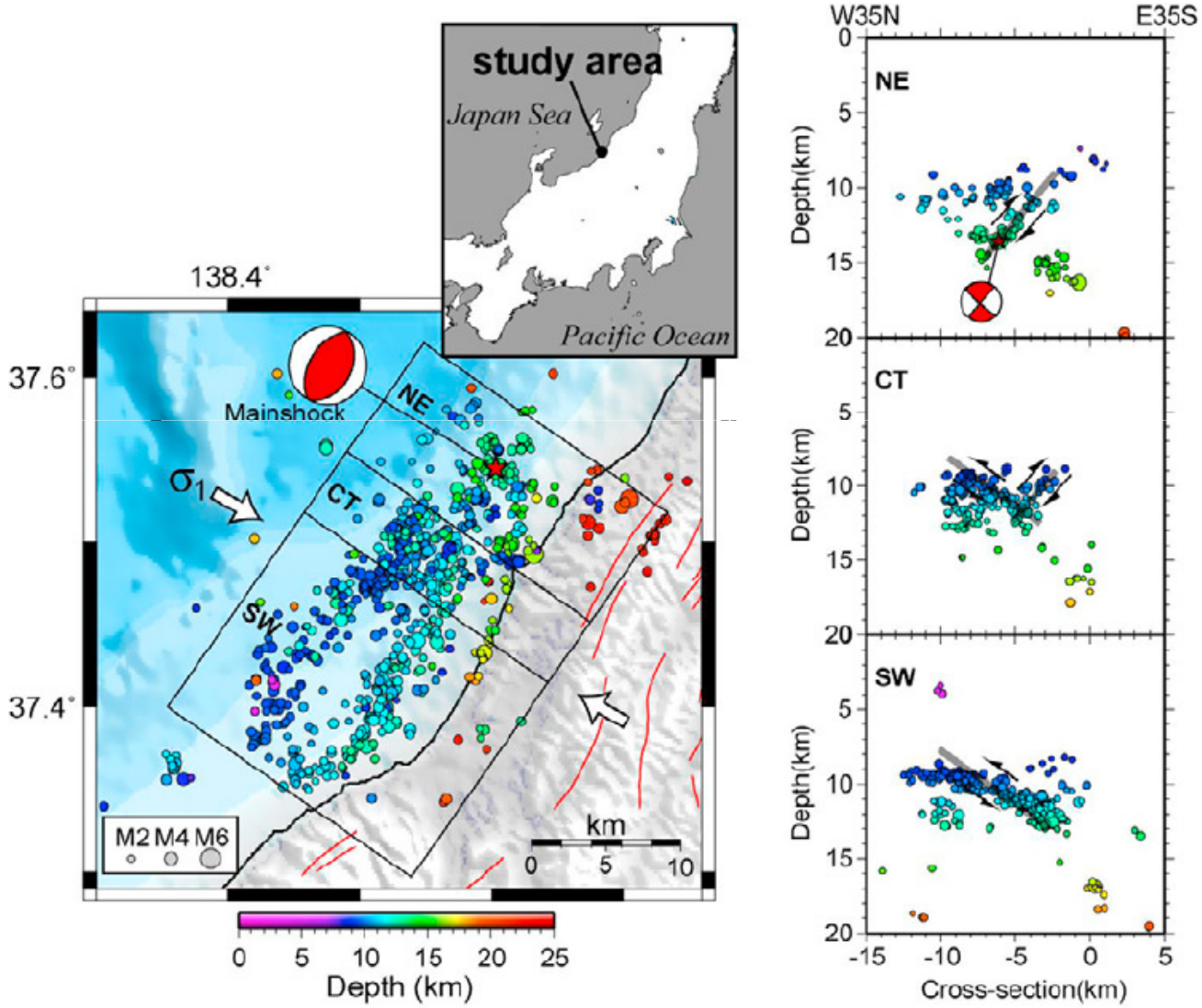






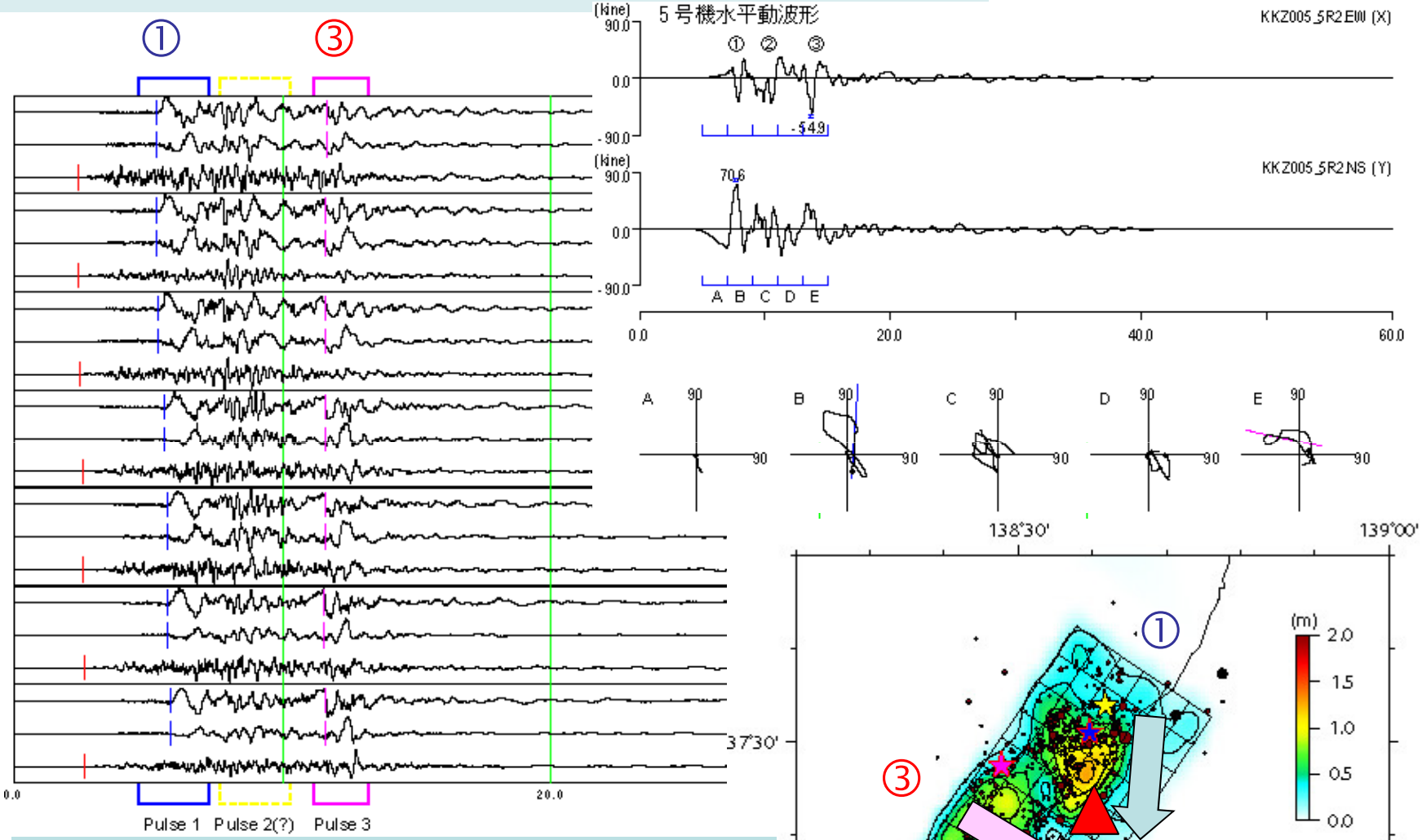
Aoi et al. (2008)

Near-field Ground Motion and Fault Model



Courtecy of Dr. A. Kato (ERI)(2008)

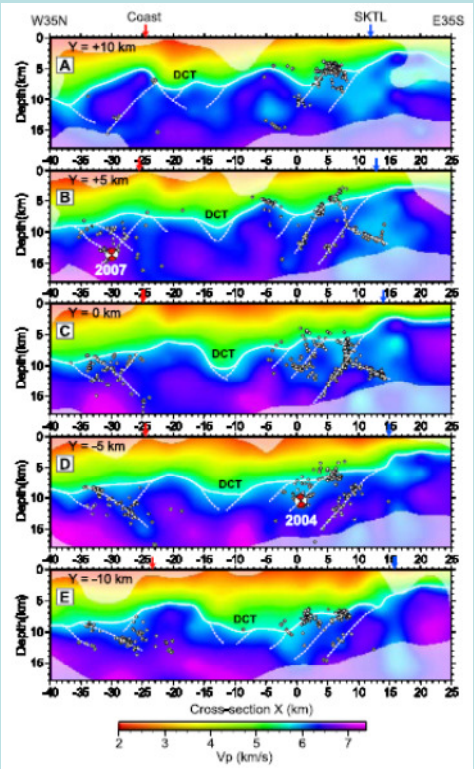
Asperity and fault geometry



Hikima and Koketsu (2008)

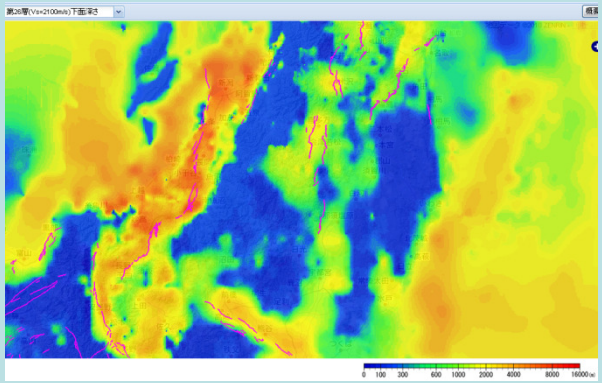
Station nucléaire Kashiwazaki-Kariwa a subi des accélérations (680 gal) dépassant le critère (450 gal)

ERI



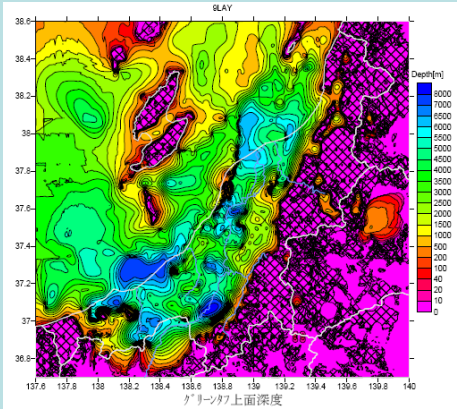
NIED

Vs=2700 m/s upper boundary

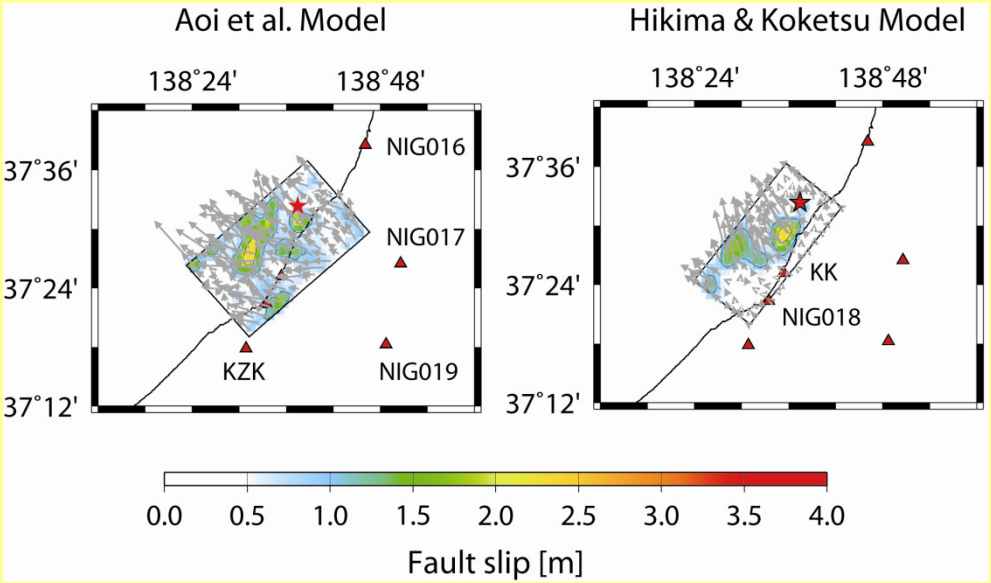


GSJ

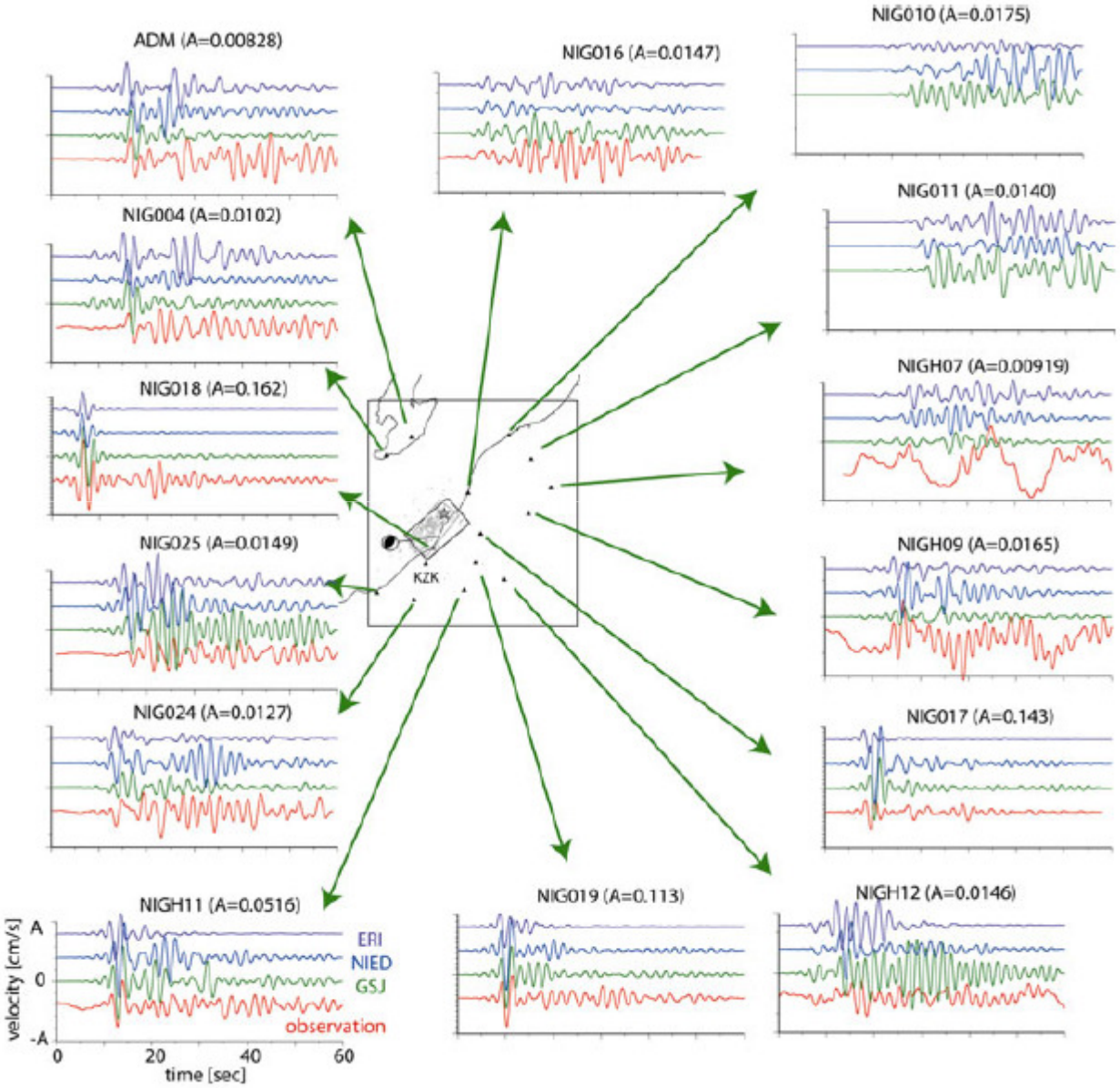
Vs = 2878 m/s



3D Structure Model x Finite Source Model



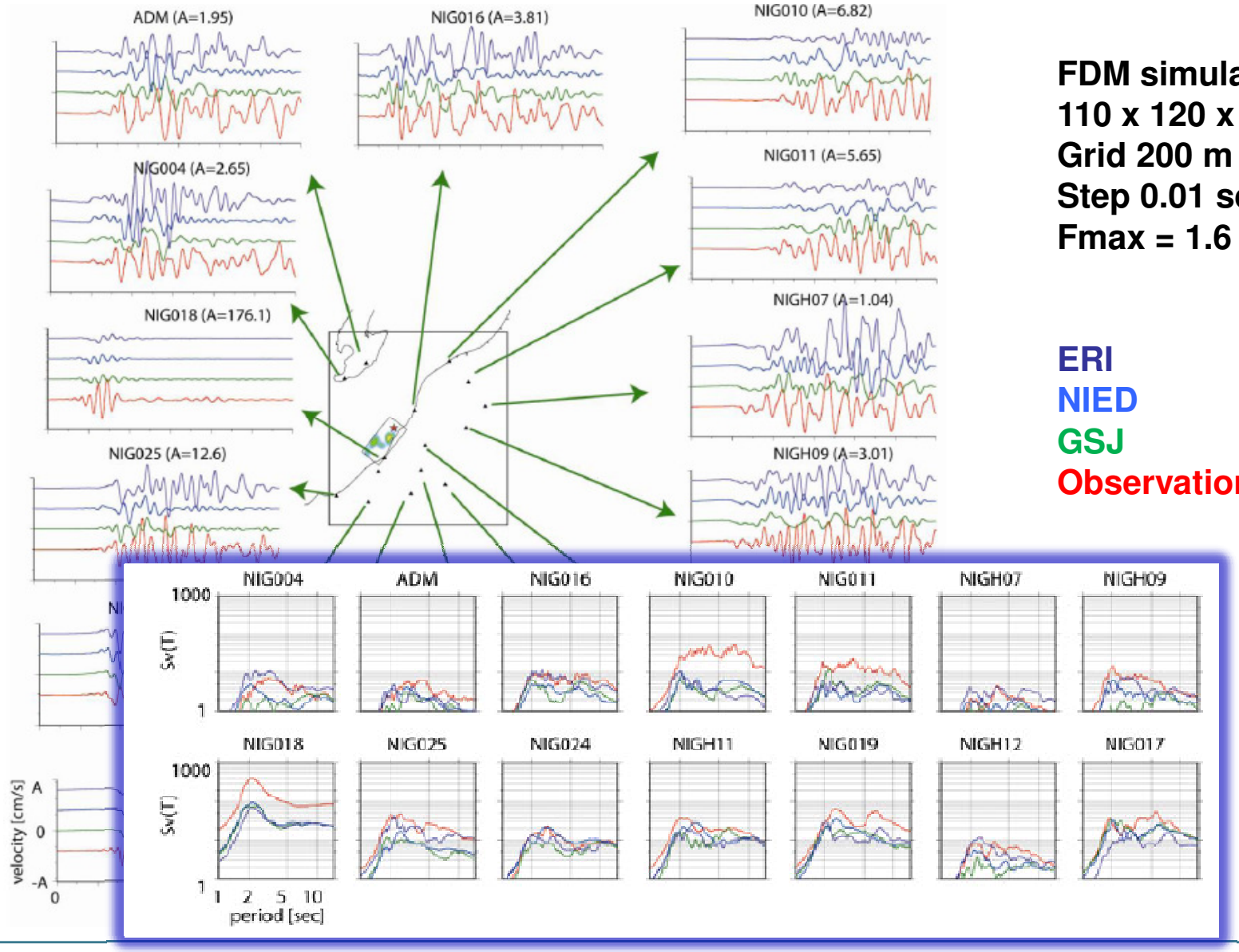
Aftershock simulation (Mw4.5)



FDM simulation
110 x 120 x 70 km
Grid 200 m
Step 0.01 sec
Fmax = 1.6 Hz

ERI
NIED
GSJ
Observation

Main shock simulation (Model Hikima & Koketsu)

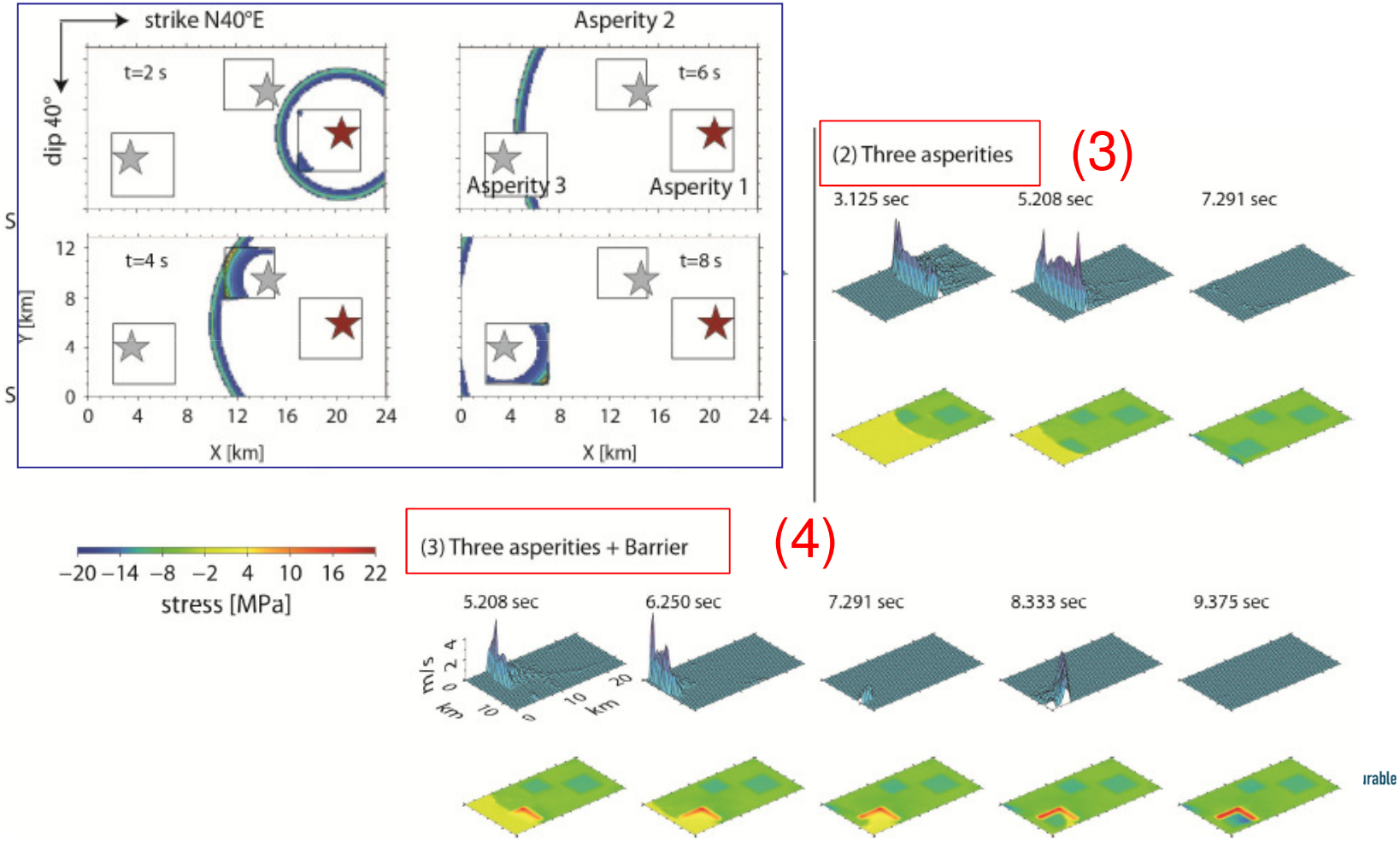


FDM simulation
110 x 120 x 70 km
Grid 200 m
Step 0.01 sec
Fmax = 1.6 Hz

ERI
NIED
GSJ
Observation

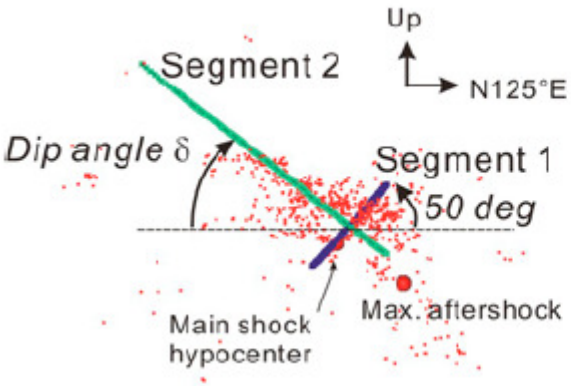
SMGA (Strong Motion Generation Area) models

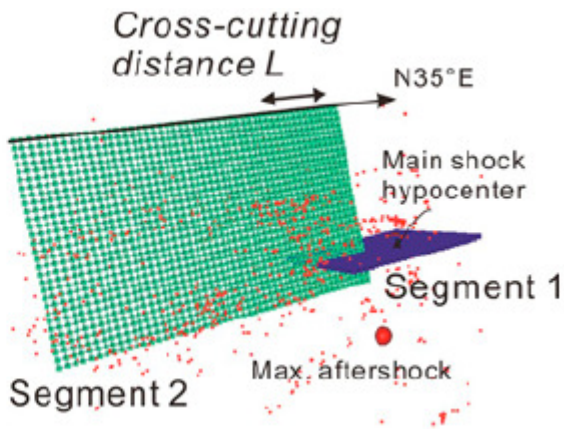
> Three SMGAs are identified (Irikura et al.)

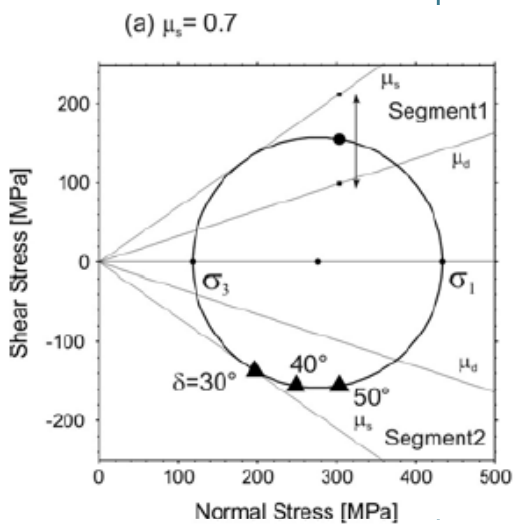


Aochi and Dupros (2011)

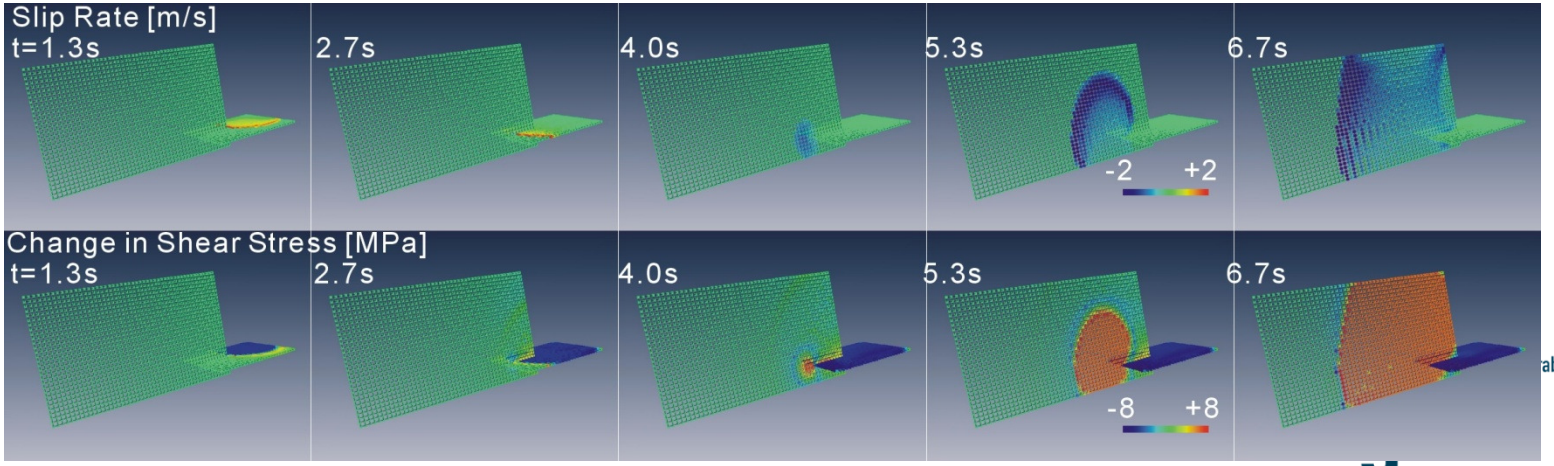
Dynamic cross-cutting fault model





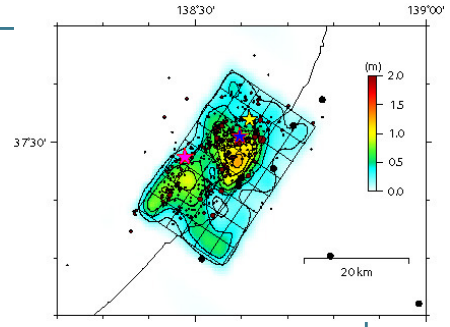


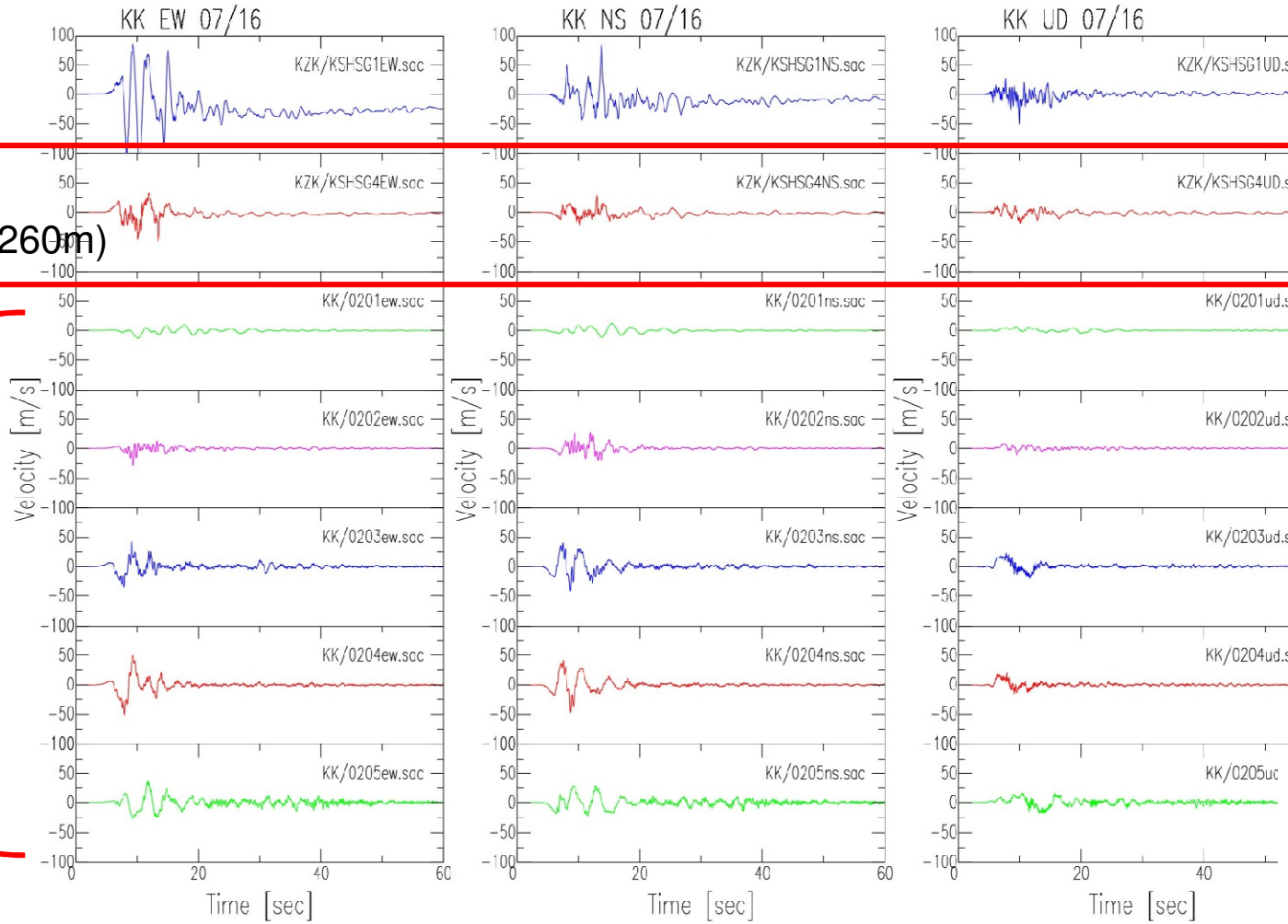
(5)



Kashiwazaki-Kariwa NPP

> Dynamic source models are not calibrated though, …





Borehole receiver (260m)

5 models

Kinematic 1

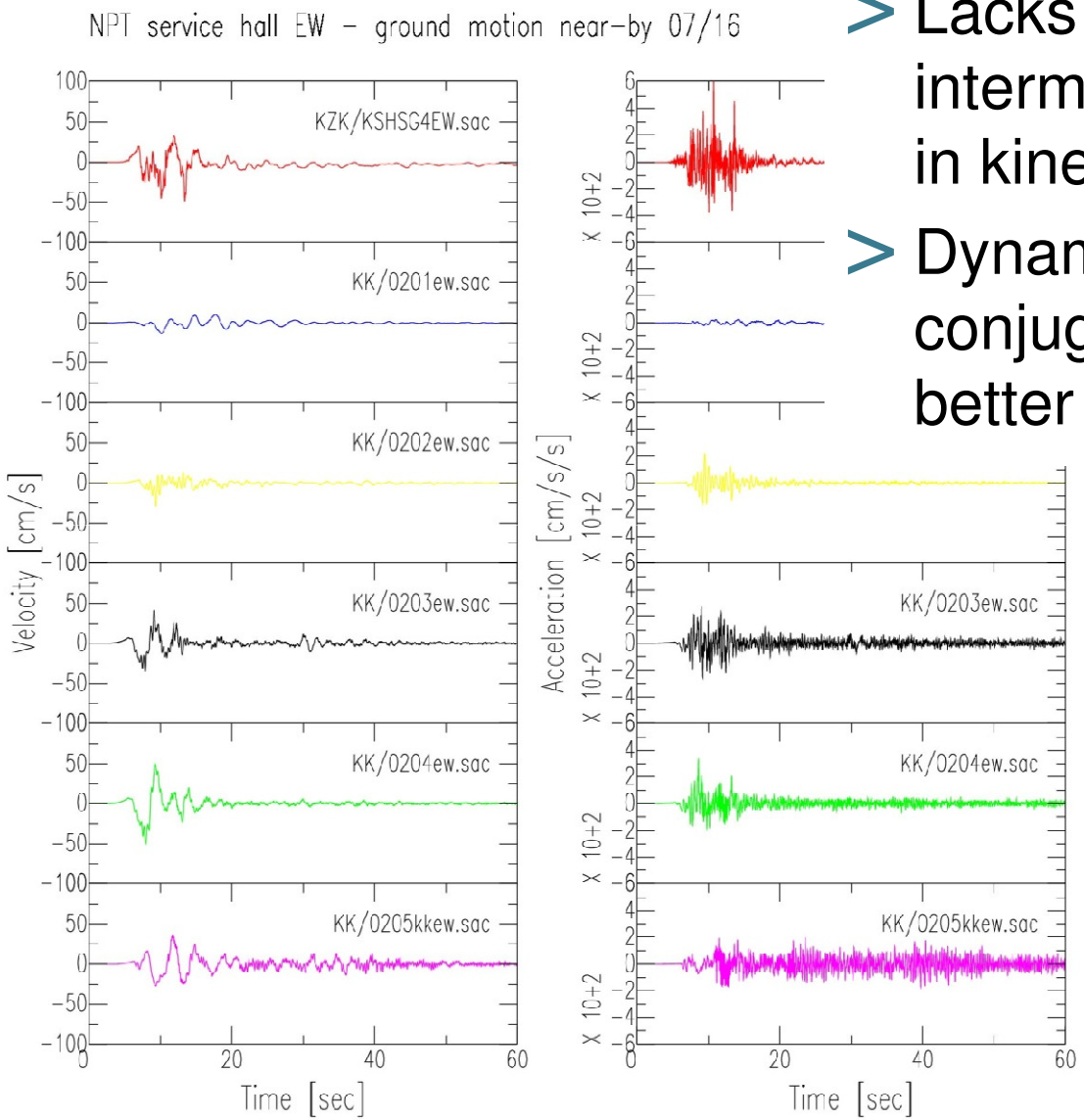
Kinematic 2

SMGA 1

SMGA 2

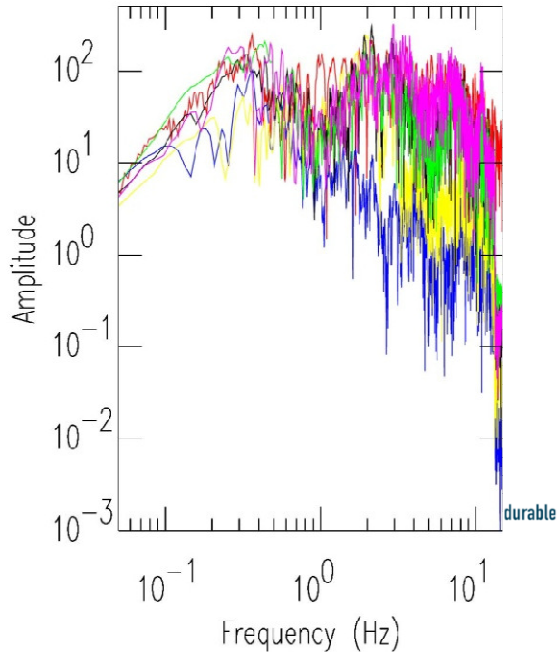
Dynamic conjugate faults

NPP borehole record



> Lacks of power at intermediate frequencies in kinematic models

> Dynamic model on conjugate faults provides better result??



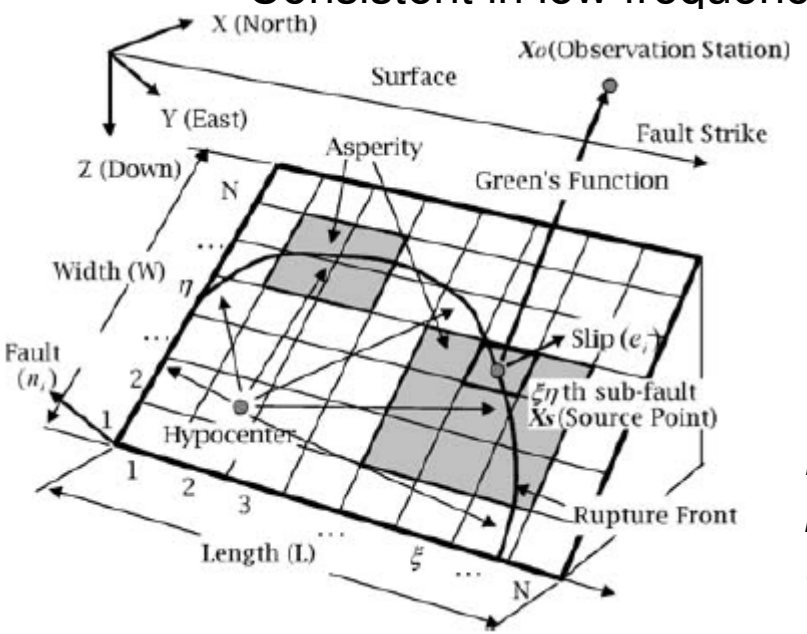
Stochastic High Frequency Generation

> Mechanical-base Hypothesis

- High freq. generation area = Low freq. generation area
- All fluctuations at source (not in propagation)
- Extention of low frequency deterministic description

> Advantage

- La finiteness of source taken into account
- Coarse sub-faut division + temporal fluctuation
- Consistent in low frequency (velocity, displacement)

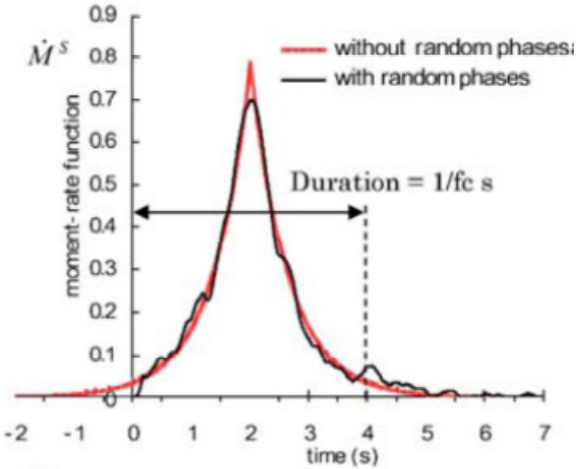


Hisada (2008), Broadband strong motion in layered half-space using stochastic Green's function technique

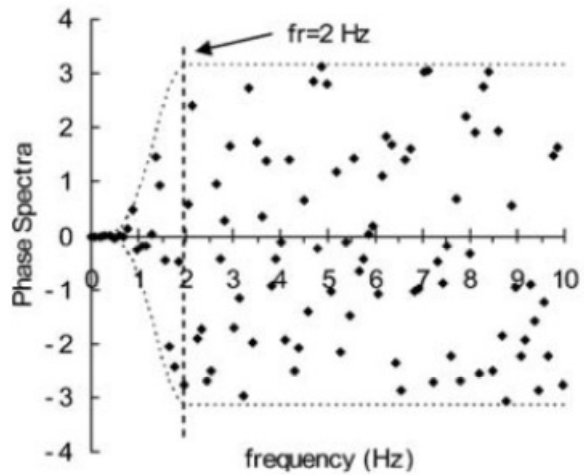
High frequency generation – Basic idea

> **We adopt Hisada (2008)'s method so that the stochastic description is consistent with the deterministic one at low frequencies**

Source time function in time domain



Phase - frequency



Coherent phase in low frequency
Random phase for high frequency

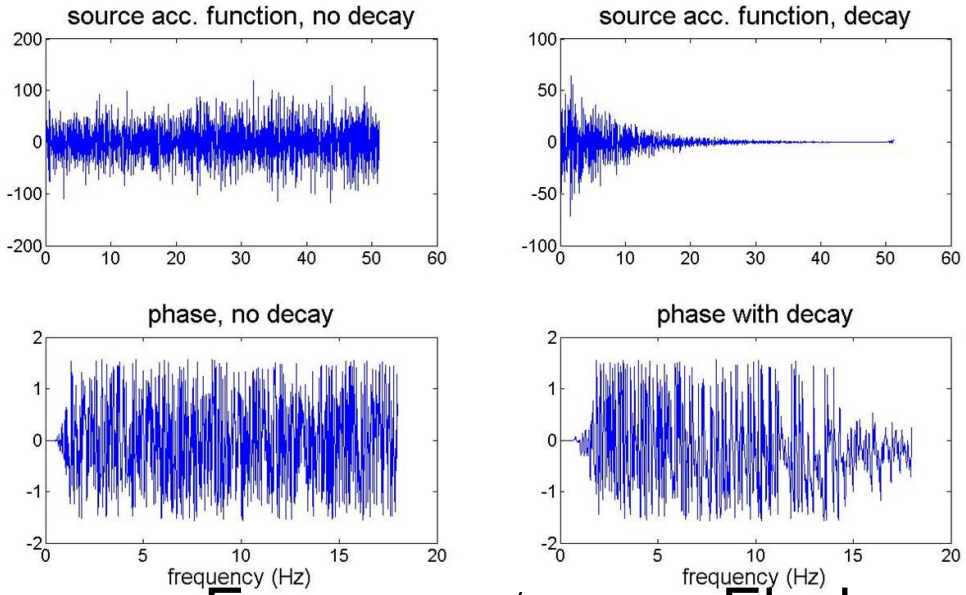
Hisada (2008)

Géosciences pour une Terre durable

Note: Green function based on reflectivity (scattering not included).

Localisation of high-frequency sources

Process : Apply a function exponentially decreasing on the original function, so as to the energy of high-frequency sources are localised at the begining of the waveform. (e.g. attenuation factor calibrated on the observation from Jin and Aki, 2005).



Ea ≠ Eb !

We ajust the initial amplitude so that the total energy is conserved.

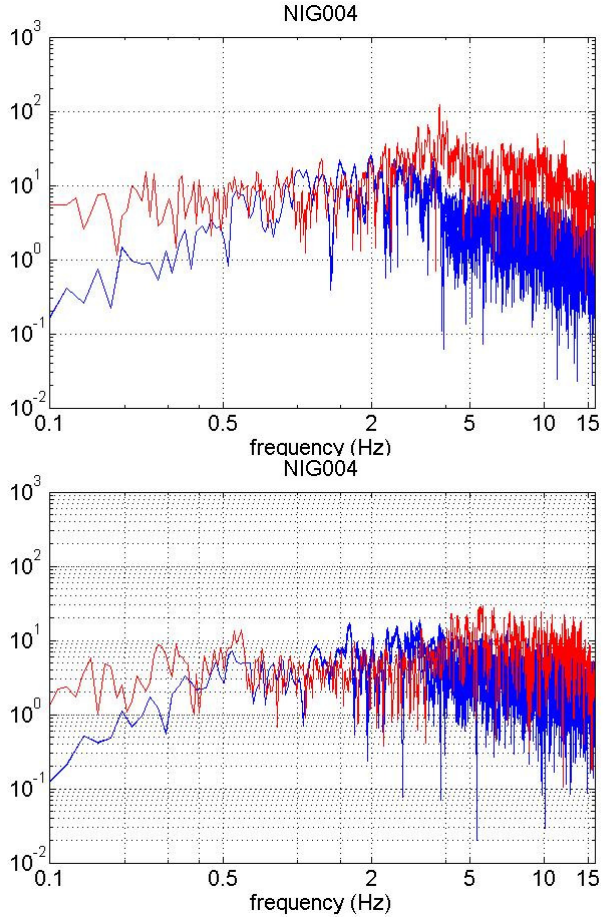
Correction of energy

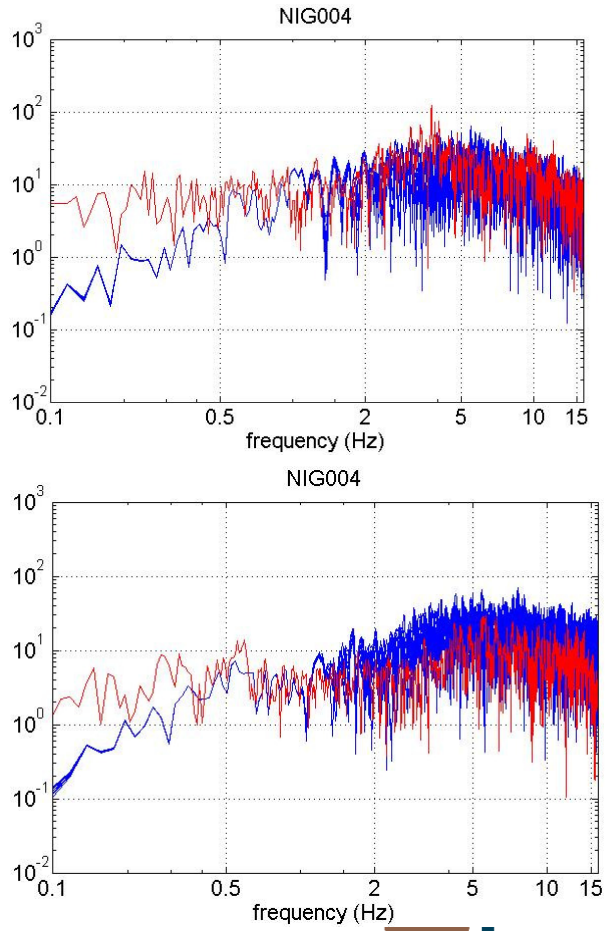
Original Hisada ‘s method

Applying a decay function

NS

UD

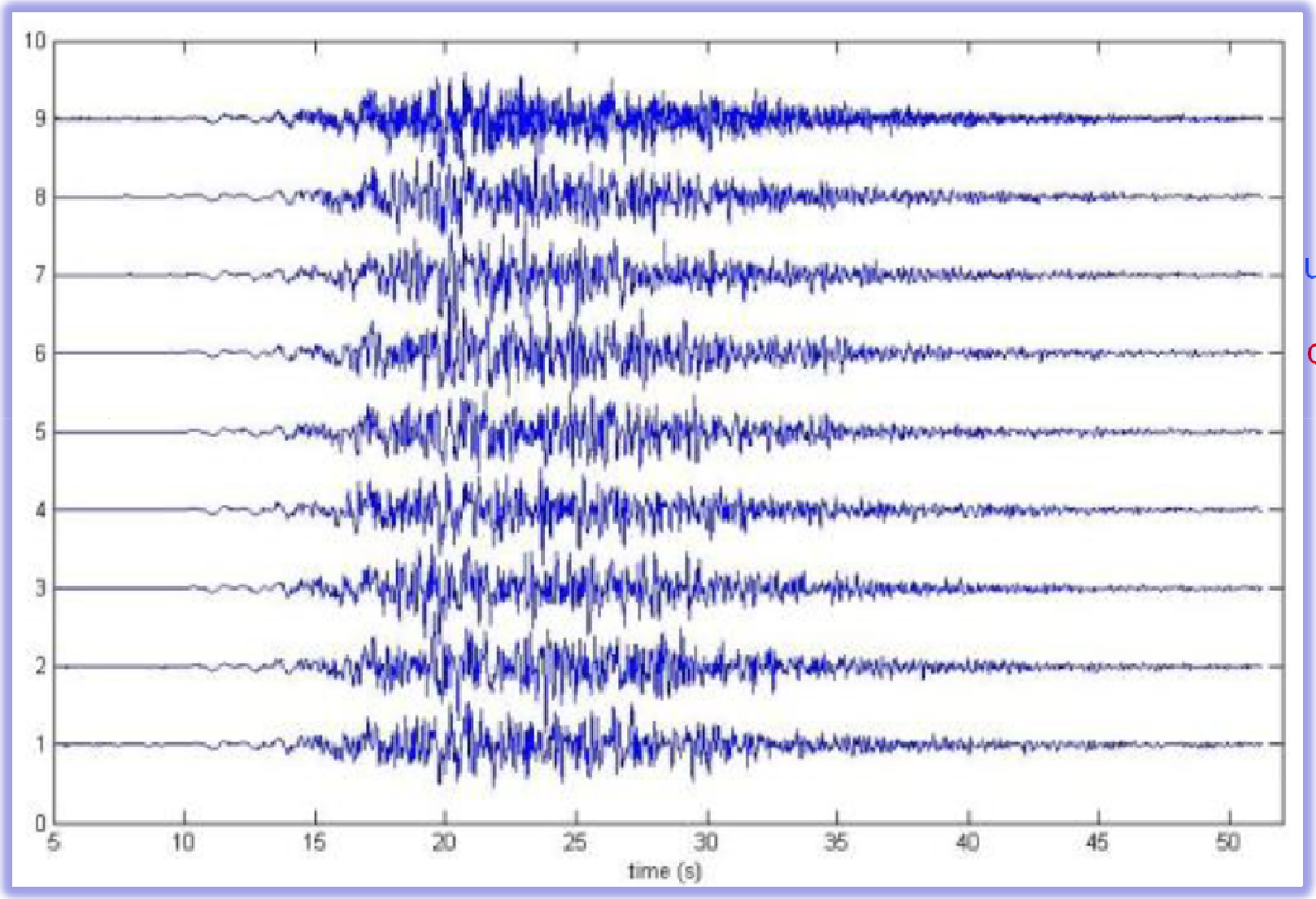




e Terre durable

brgm

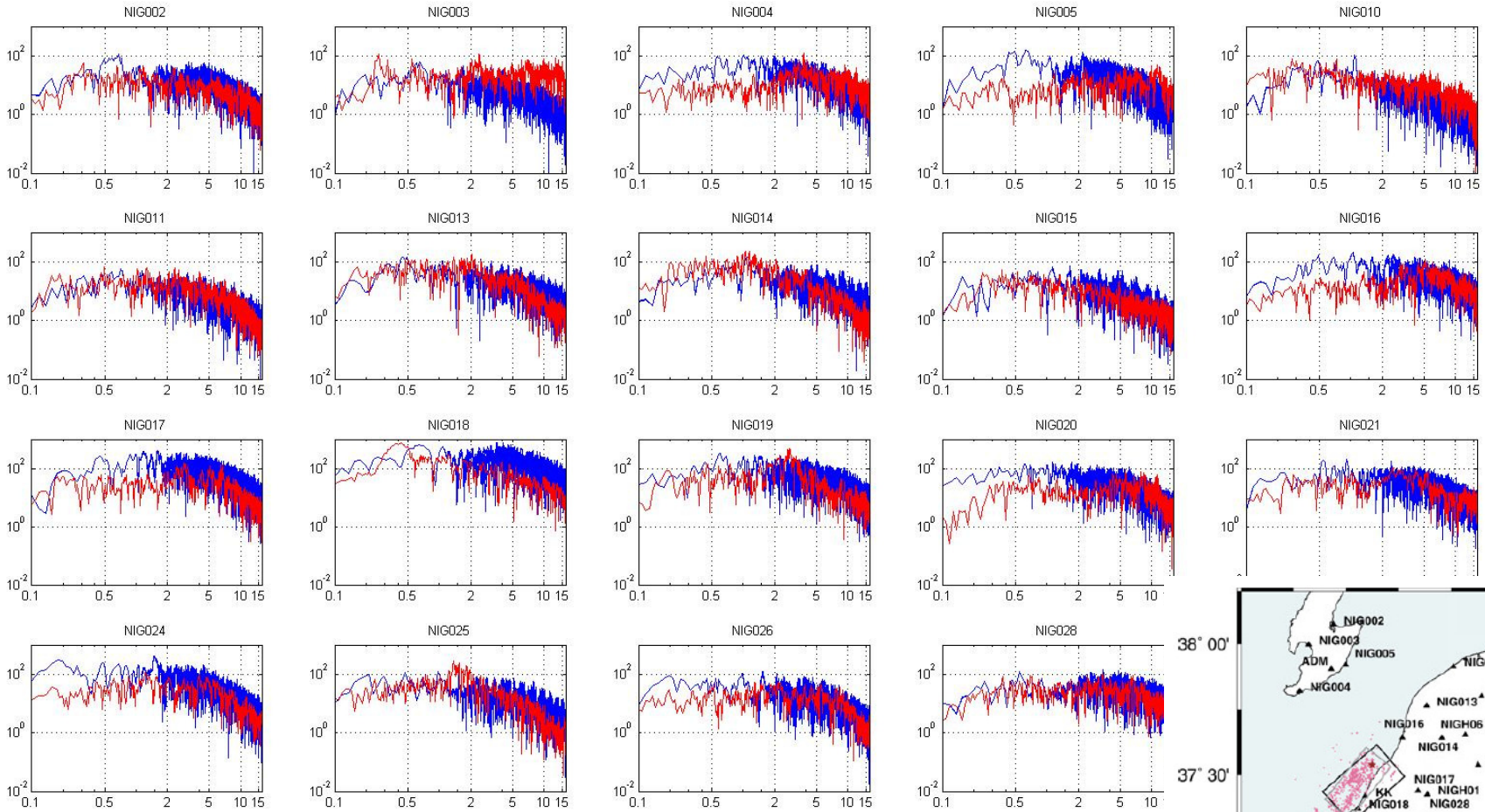
An example at station NIG004



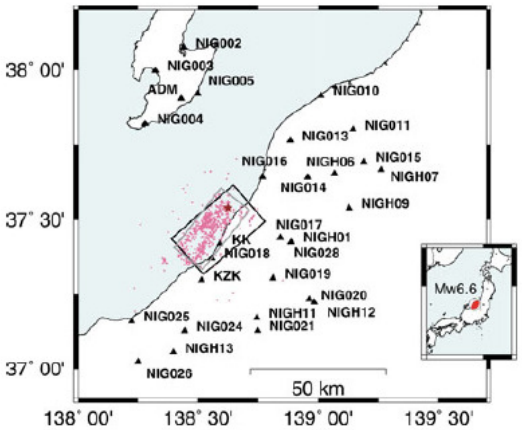
ue

on

Stochastic simulation of the 2007 Chuetsu-oki earthquake



Observation
Synthetic



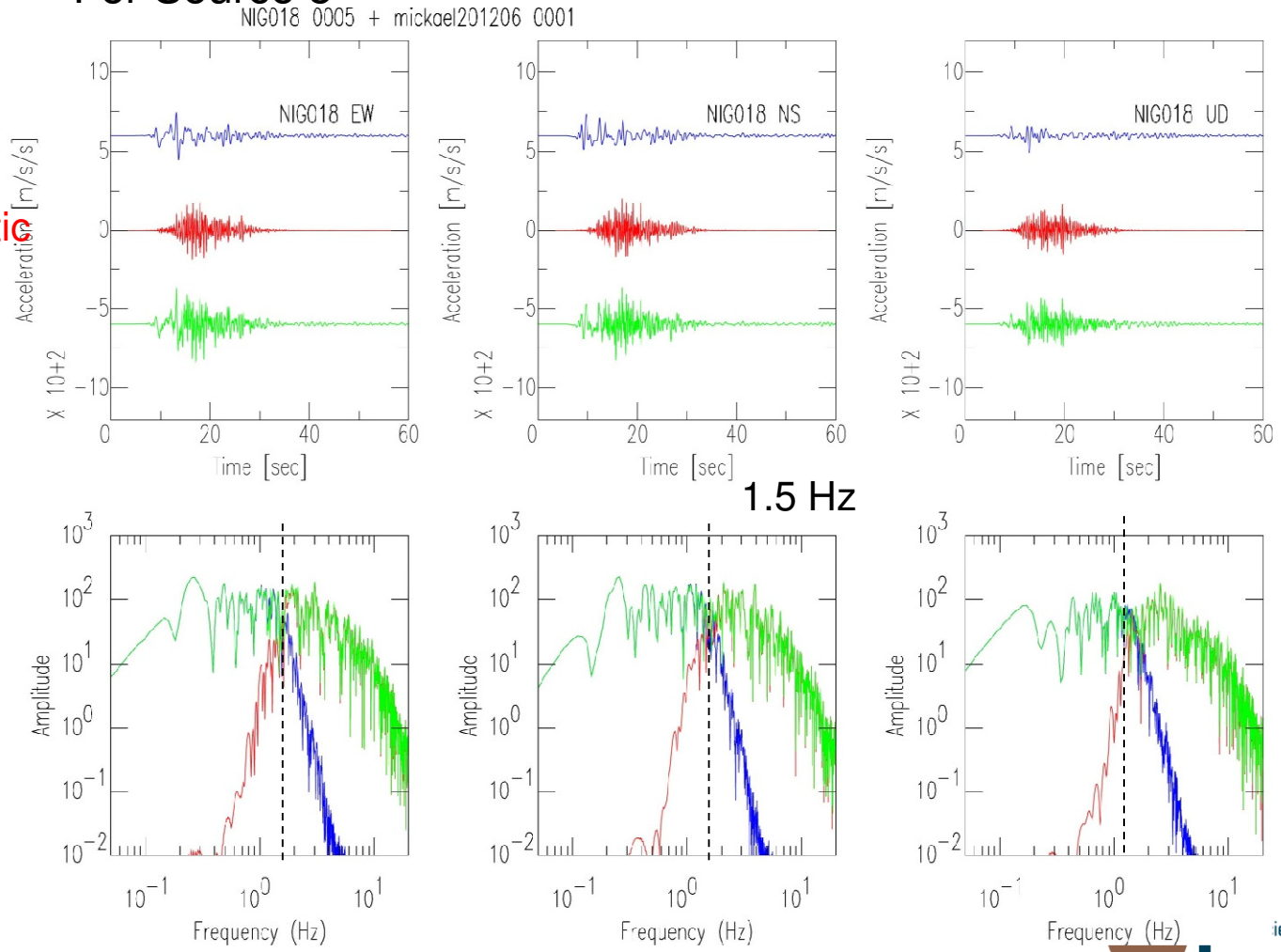
Hybrid ground motion generation for NIG018

For Source 5

FDM

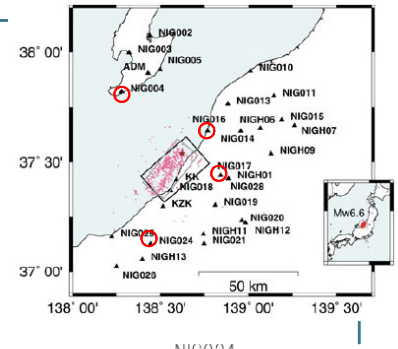
Stochastic

Hybrid

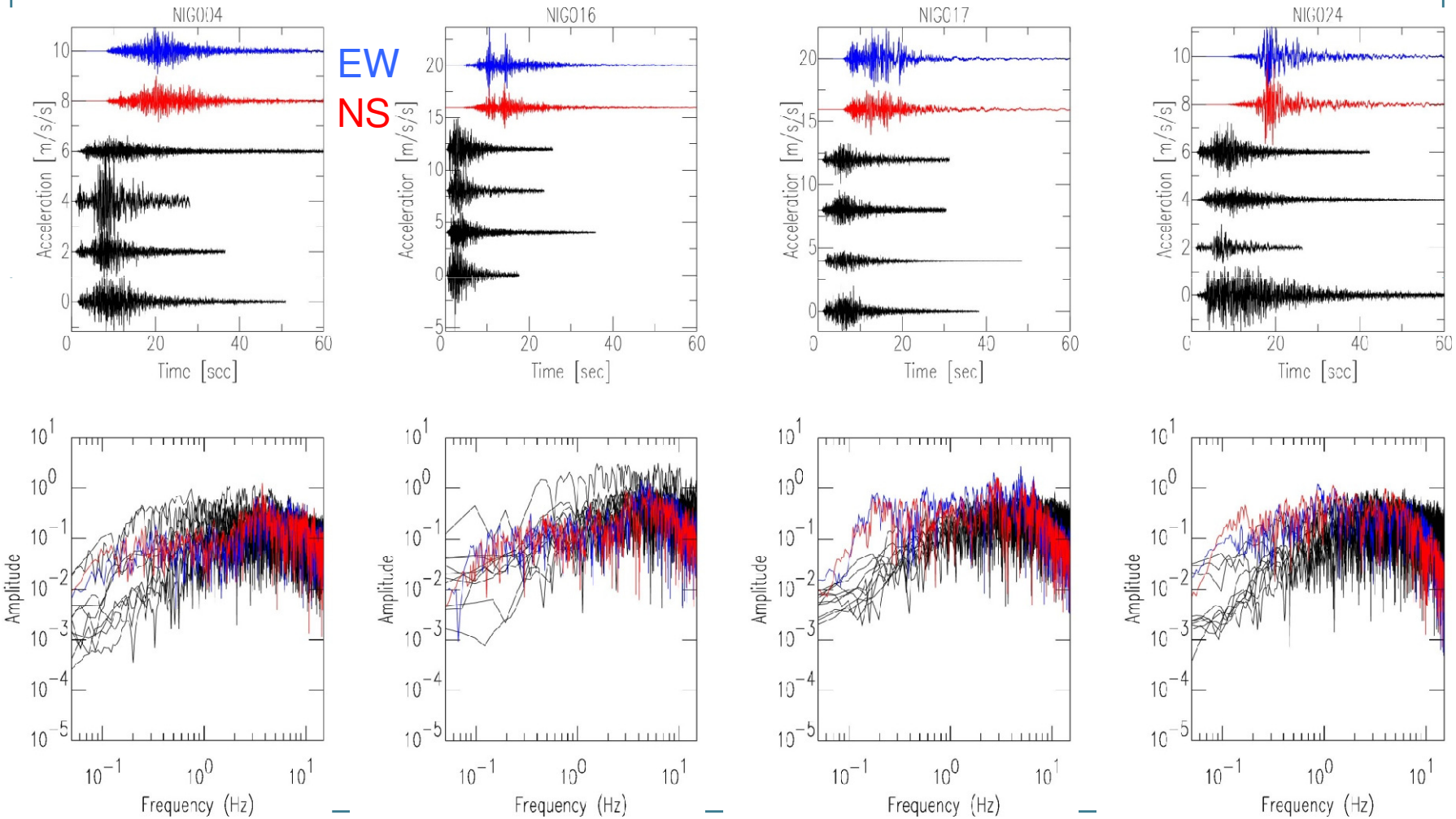


> **Coherent in low frequency, 3-components.**

Stochastic simulation of the 2007 Chuetsu-oki Earthquqake



Courtecy of Dr. F. Bonilla (Ifsttar) by DEBATE project



Conclusion/Perspective

> **Strong Motion Seismology = Comprehension of mixed effect of source x structure (x site effect).**

> **Quantitative prediction of ground motion is essential for seismic hazard analysis. = It is important to show how well the past earthquake can be modelled.**

> **Mechanical-based deterministic/stochastic simulations are applicable in the near field of finite source, completing kinematic approach and GMPEs.**

> **It remains unsolved:**

- Large amplitude de ground motion (extreme ground motion) should be physicaly constrained.
- Incoherent wave propagation (stochastic Green function) could be better.

Géosciences pour une Terre durable
brgm

Thank you for your attention.

Seeking an 1-year-postdoc for ANR S4 (Subduction Standard & Slow Seismology).

Call for papers: 3rd International Workshop on Advances in High-Performance Computational Earth Sciences: Applications and Frameworks – 13th ICCS, 5-7 June 2013, Barcelona, Spain.

Call for abstracts: "S201 Earthquake scenarios" in « strong ground motion » - IASPEI 2013, 22-26 July 2013, Gothenburg, Sweden.

Géosciences pour une Terre durable
brgm