Workshop on Numerical Modeling of Earthquake Source Dynamics, Smolenice Castle, Slovak Republic

Broadband Strong Motion Simulation Based on a Dynamic Fault Rupture Model: Application to the 2000 Tottori, Japan earthquake

by

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Objectives and Motivations

- To study the HF generation process of the 2000 Tottori, Japan, earthquake by using a dynamic model of fault rupture.
- To explore possible ways to calculate accurate HF ground motion propagation characteristics.
- To develop a strong motion simulation methodology in a broad frequency band by incorporating a spontaneous fault rupture dynamic model, and test it with earthquake recordings.
- To explore possible future directions for the estimation of ground motion for scenario earthquakes.

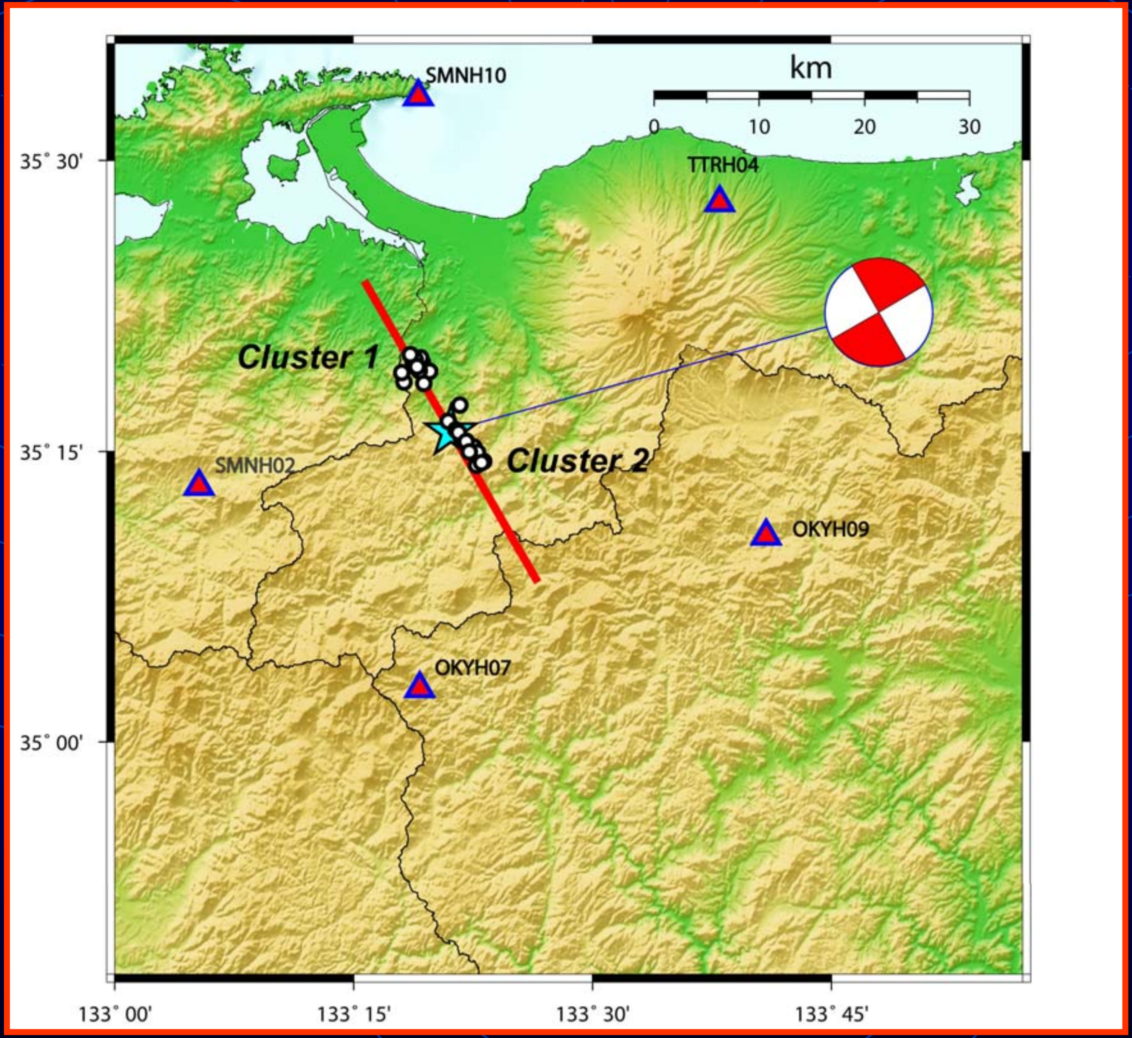
Generation mechanism of HF

- Some studies locate the HF radiation near boundaries of large slip region while in others both regions overlap (Zeng et. al. 1993, Kakehi et al. 1996, 1997, Nakahara 1999, 2002).

- Dynamic crack models have long before recognized the importance of large rupture velocity variations or stopping phases, for the generation of HF (Madariaga, 1977, 1983, Boatwright 1982).

- For large earthquakes not only stopping phases but also local de-celaration and acceleration of the rupture velocity may contribute to HF radiation (Achenbach and Harris 1978, Cocco and Boatwright 1993, Sato 1994).

Dynamic Model of the 2000 Tottori, Japan earthquake

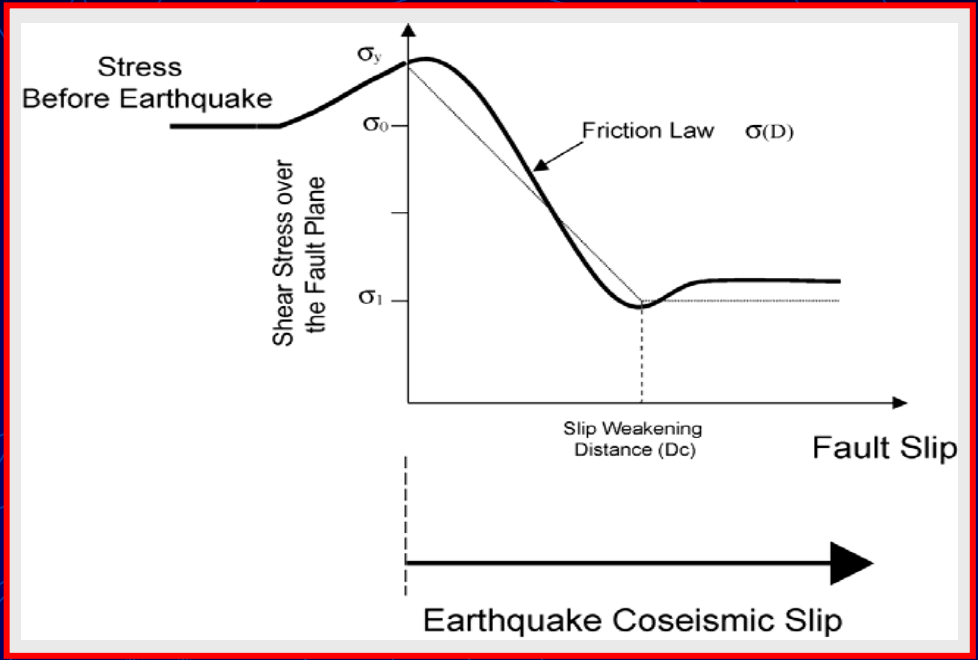


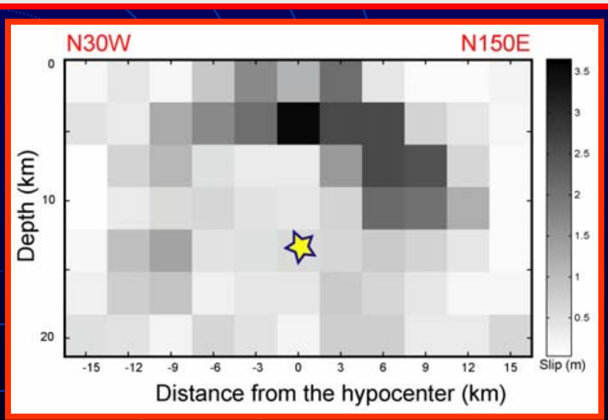
Dynamic rupture model of the 2000 Tottori earthquake using Staggered Grid Split Node FDM

• Slip weakening friction law.

•Friction law parameters (Bouchon et al. 1997, Ohnaka 2000, Pulido et al. 2000, Mikumo et al. 2003, Zhang et al. 2003, Tinti et. al. 2005).

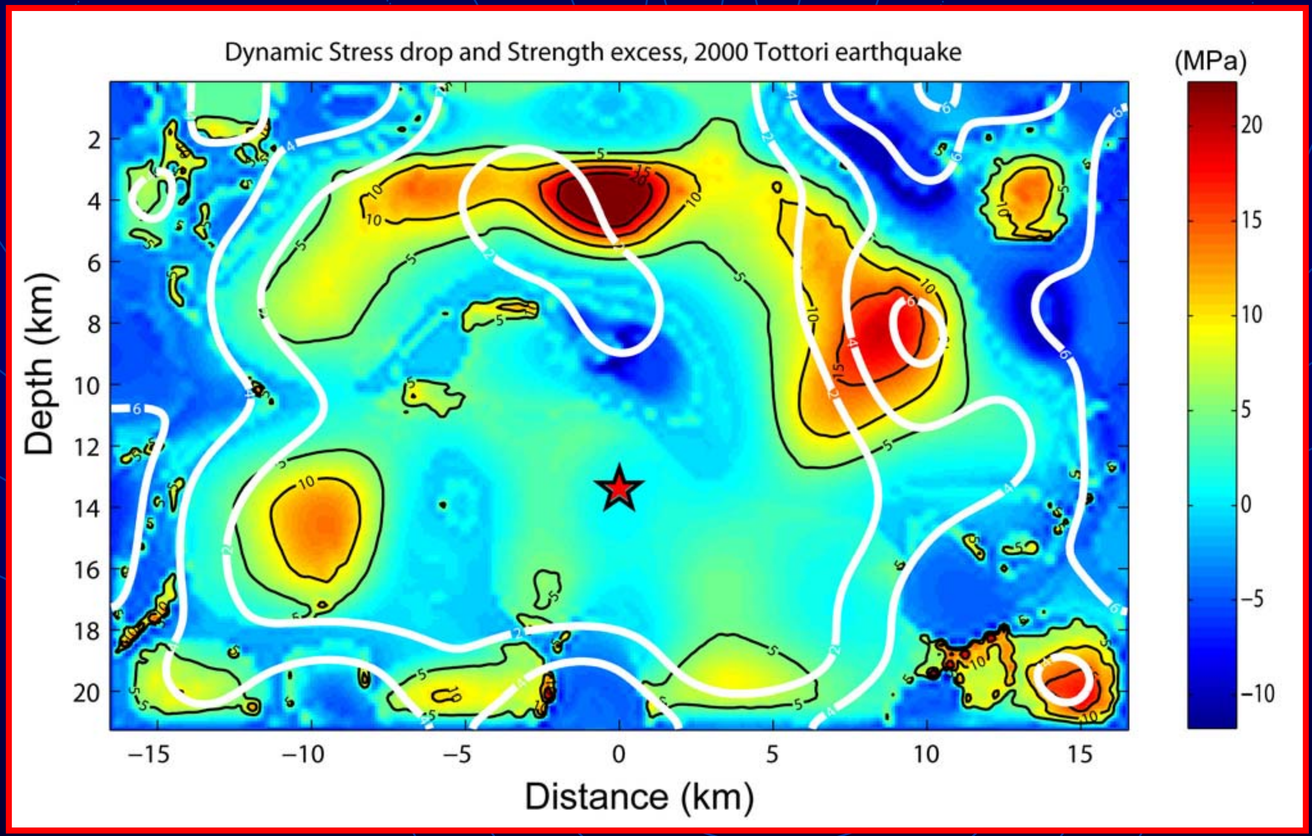
•4th order staggered grid FDM using Split Node Fault representation (Dalguer and Day 2006). Grid size 0.1km time step 0.0065s. Accuracy to about 3-5Hz.





Kinematic model Tottori eq. (Iwata et al 2000)

Dynamic Stress Drop (**asperities**) and Strength excess (**barriers**) Tottori earthquake

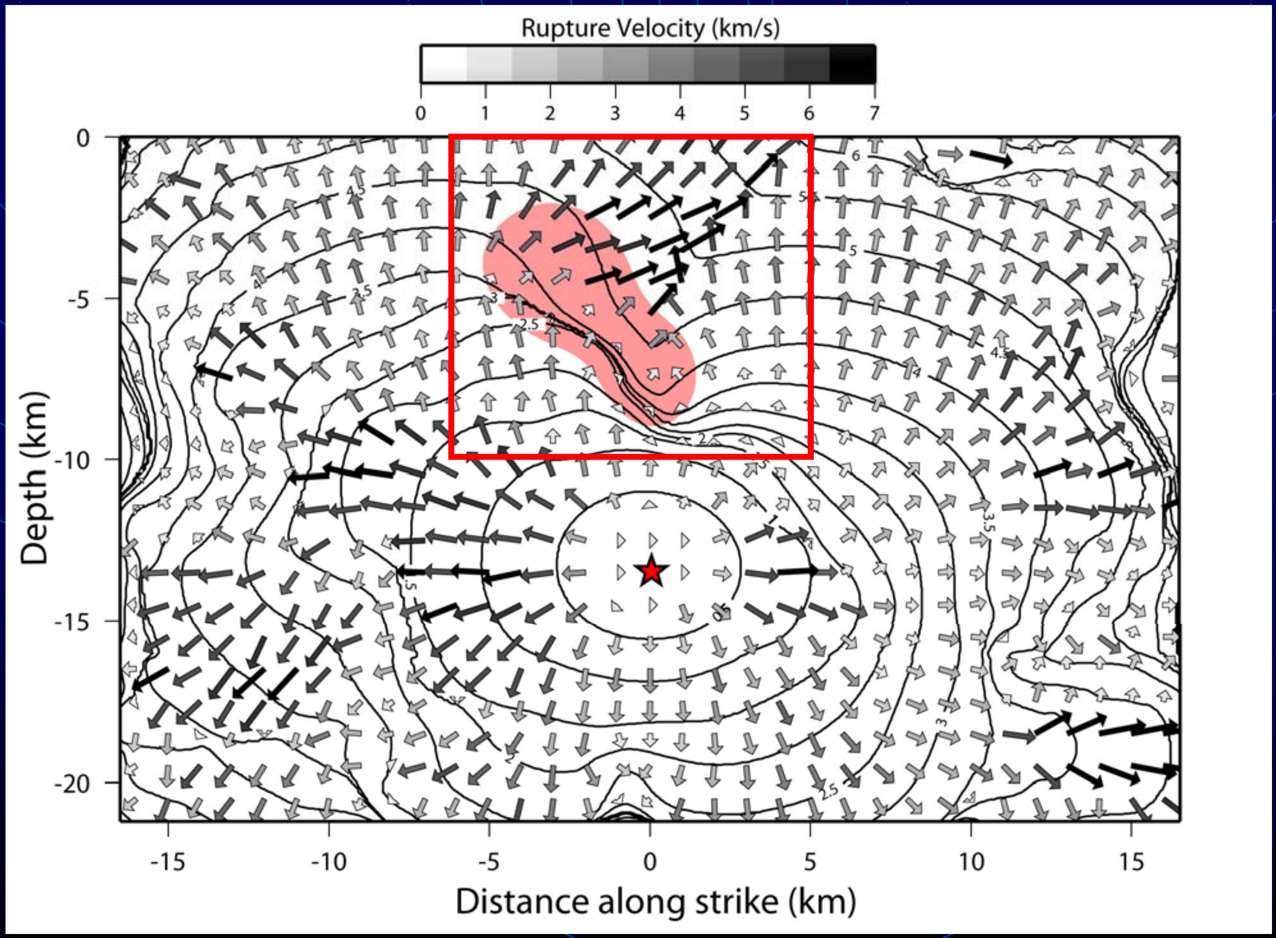


Asperities and Barriers defined as in Page et. al. (2005)

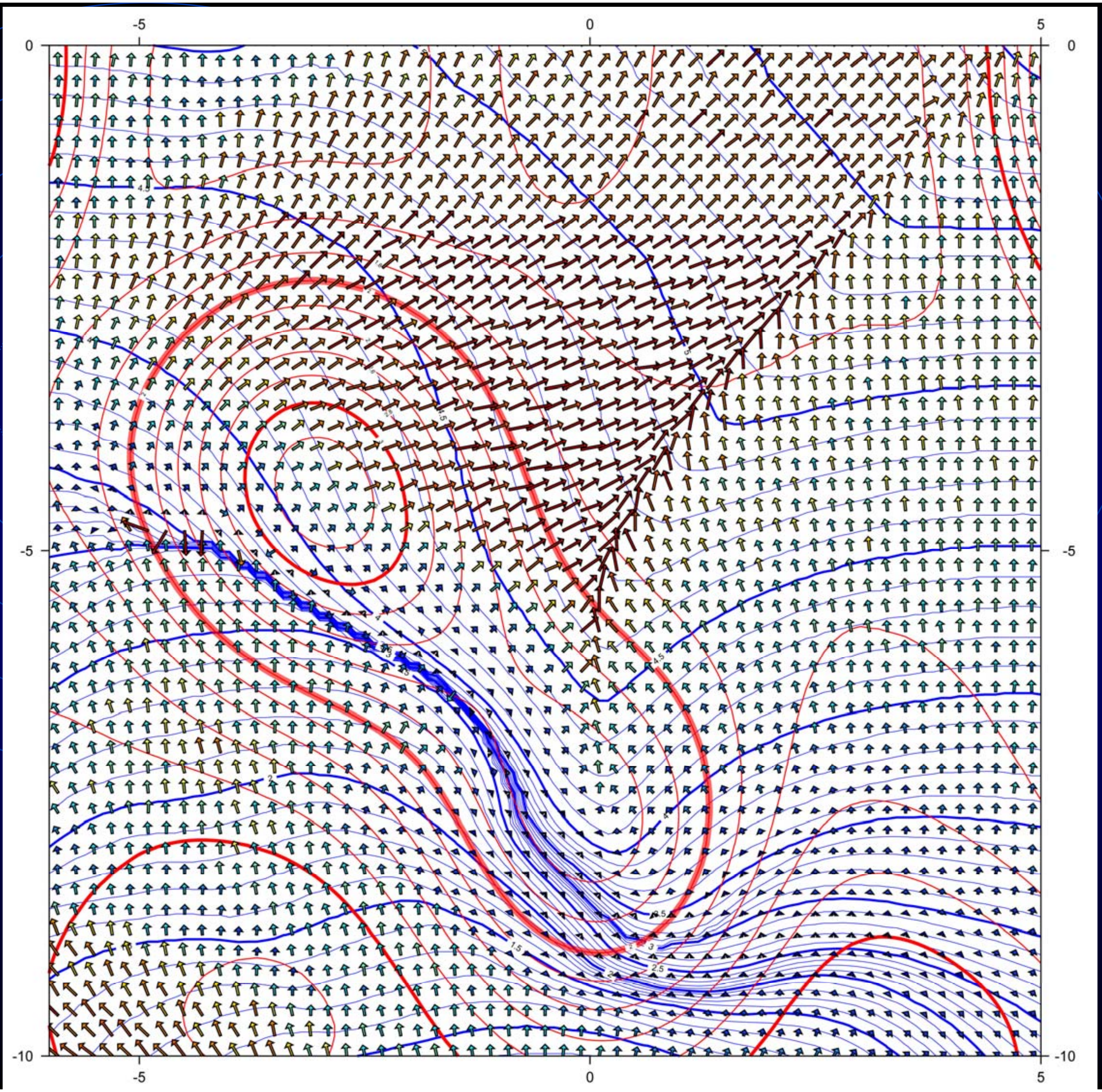
Rupture Velocity Vectors

$$u = \nabla t = \frac{\partial t}{\partial x}\hat{i} + \frac{\partial t}{\partial z}\hat{k}$$

$$\vec{V}_{r_{ij}} = \frac{\cos\varphi_{ij}}{|\nabla t|_{ij}}\hat{x} + \frac{\sin\varphi_{ij}}{|\nabla t|_{ij}}\hat{y}$$

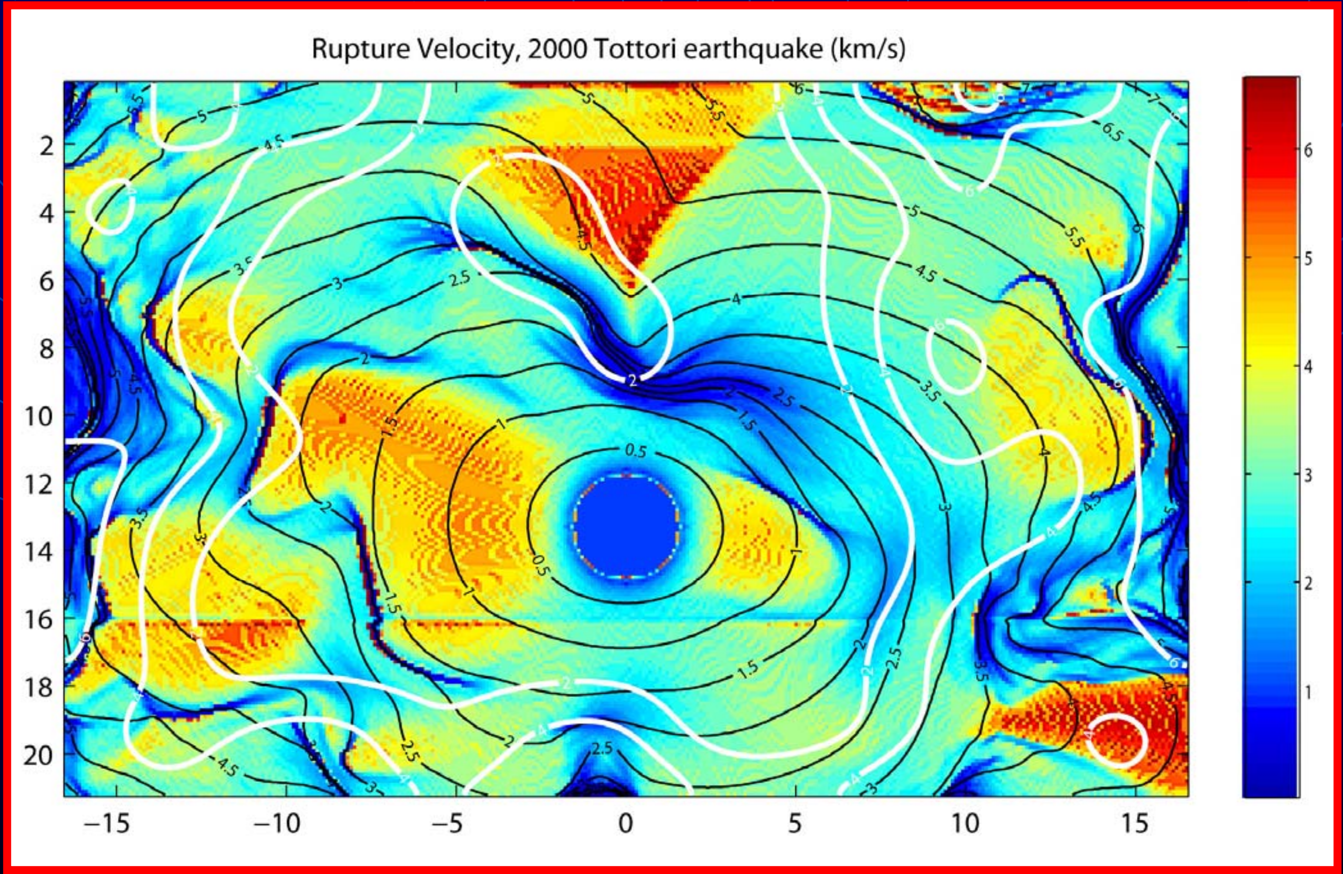


Rupture Velocity Vectors (Detail)



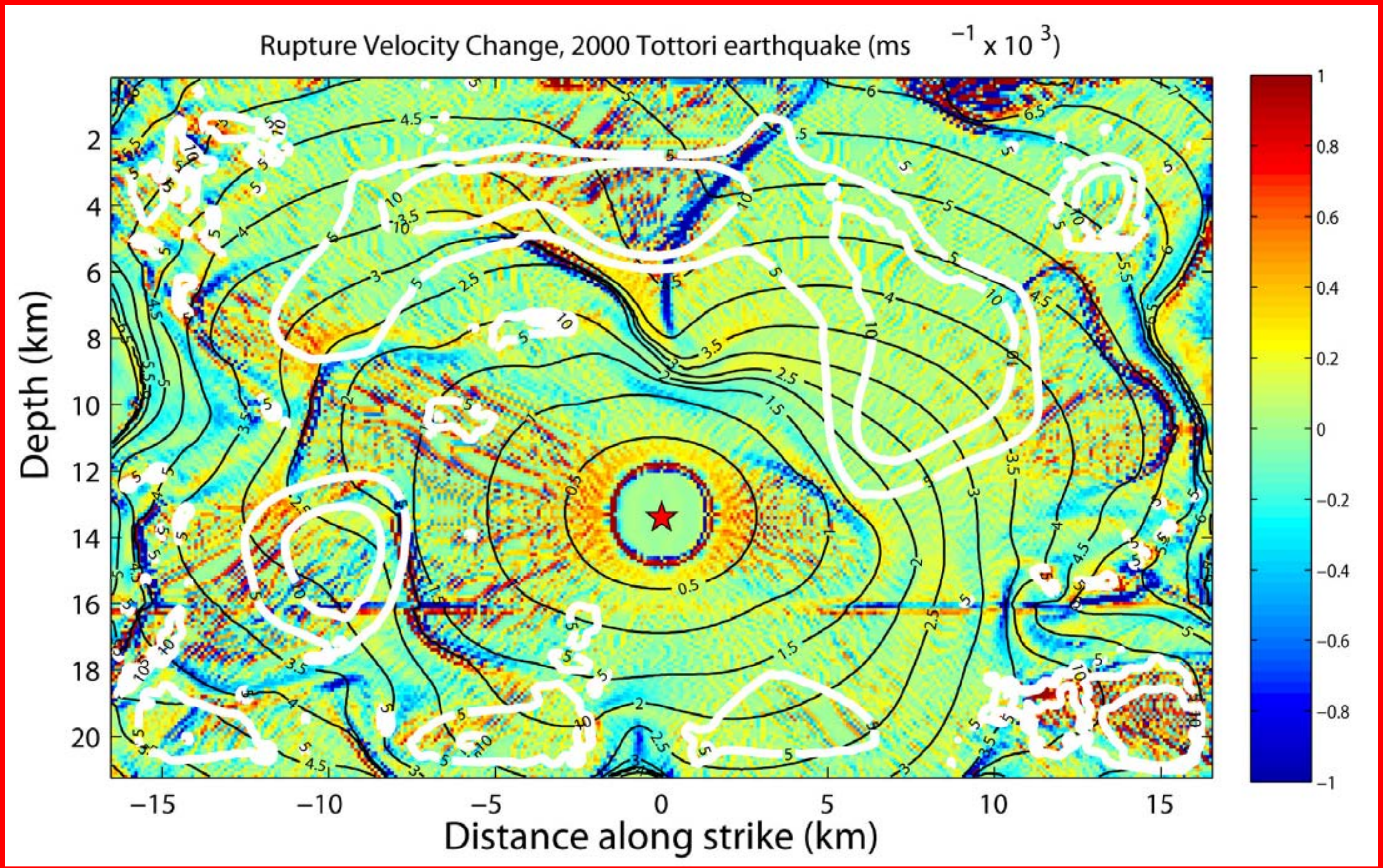
Local Rupture Velocity

$$V_{rup_{ij}} = \left|\vec{V}_{r_{ij}}\right|$$



Local Rupture Velocity Changes

$$\Delta V_{r_{ij}} = \nabla \cdot \vec{V}_{r_{ij}} = \frac{\partial(\cos\varphi_{ij} / |\nabla t|_{ij})}{\partial x} + \frac{\partial(\sin\varphi_{ij} / |\nabla t|_{ij})}{\partial y}$$

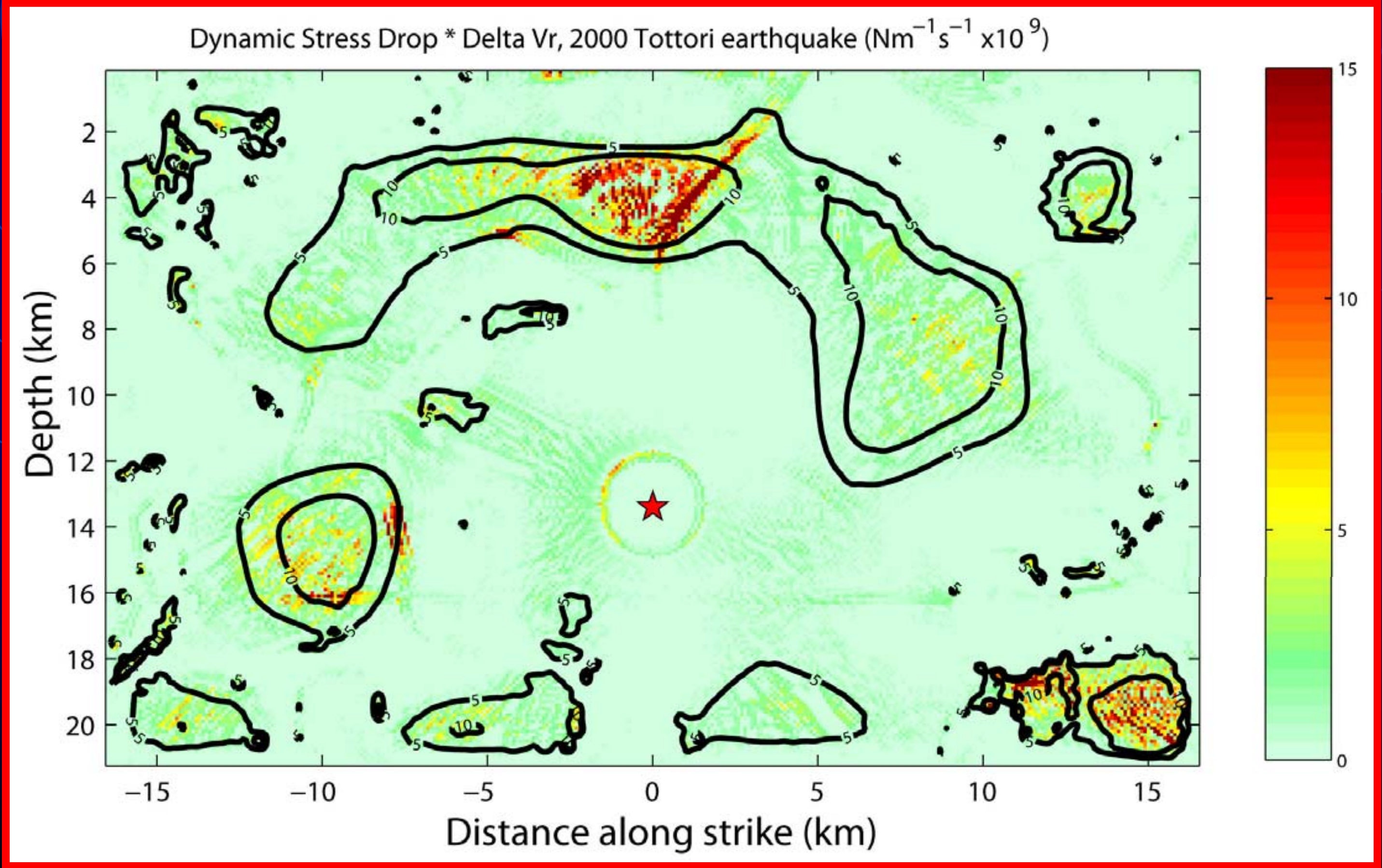


High frequency radiation as inferred from dynamic model

HF far field radiation of a suddenly stopping crack

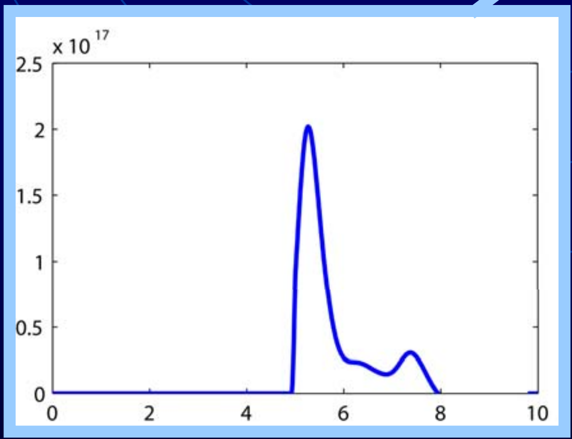
$$\sim \nabla V_r * \Delta\sigma$$

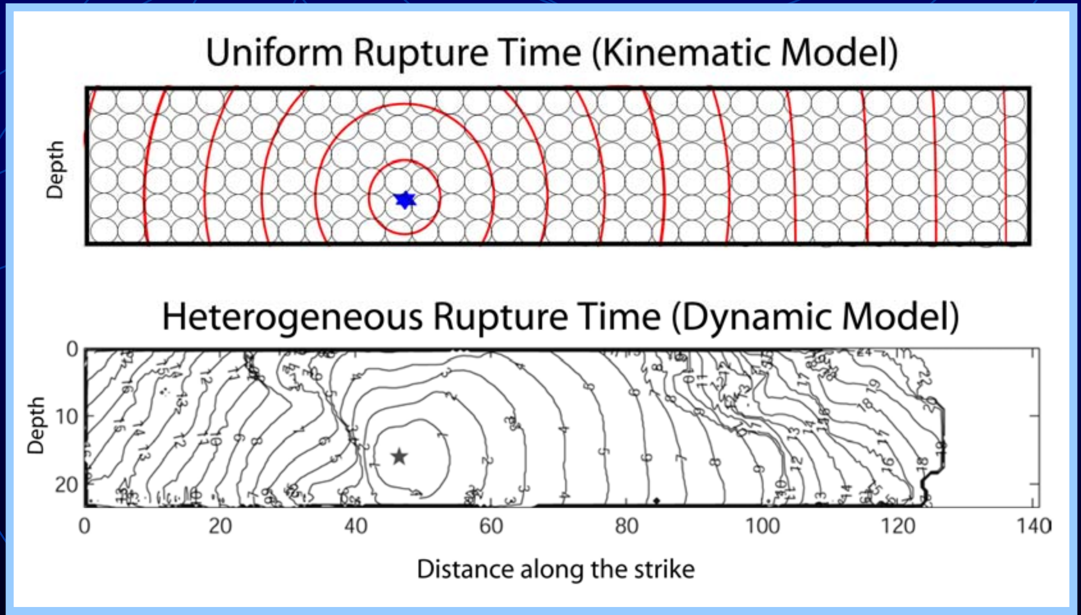
$$\Delta V_{r_{ij}} = \nabla \cdot \vec{V}_{r_{ij}}$$



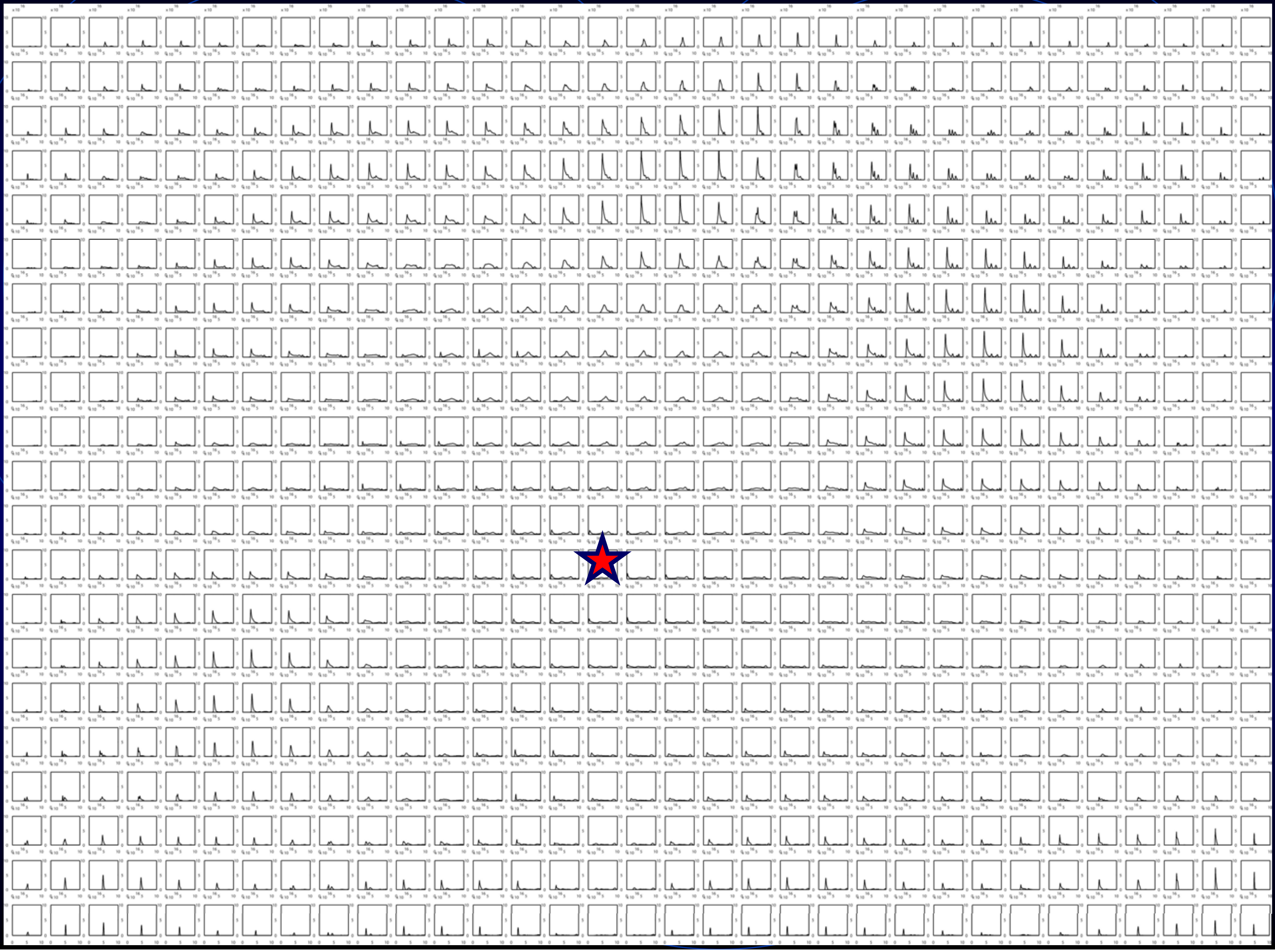
Ground motion simulation combining dynamic fault rupture model and Empirical Green's Tensor Derivatives

$$\dot{u}_i(x,t) = \sum\sum \dot{M}^{j}_{pq}(\xi_j, t) * G_{ip,q}(x, \xi_0, t, 0)$$





Slip velocities from dynamic model

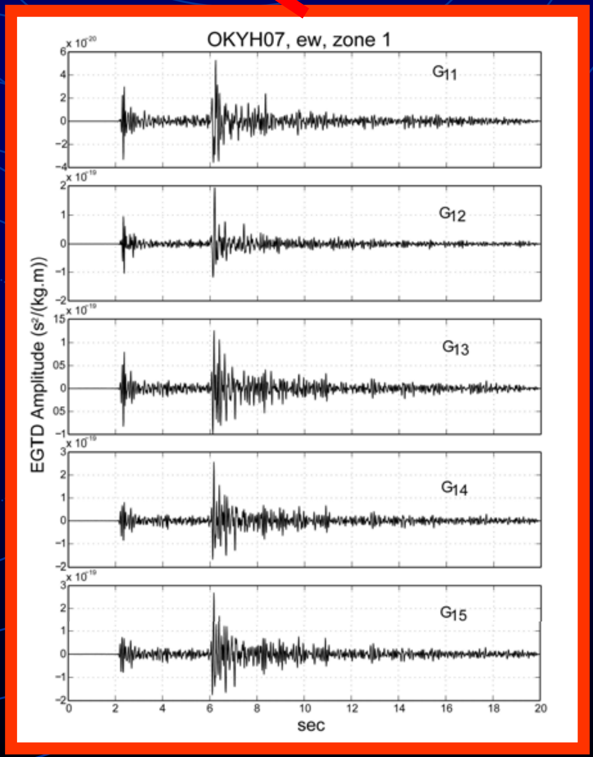


Ground motion simulation combining dynamic fault rupture model and Empirical Green’s Tensor Derivatives

$$\dot{u}_i(x,t) = \sum\sum \dot{M}^{\,j}_{pq}(\xi_j,t) * G_{ip,q}(x,\xi_0,t,0)$$

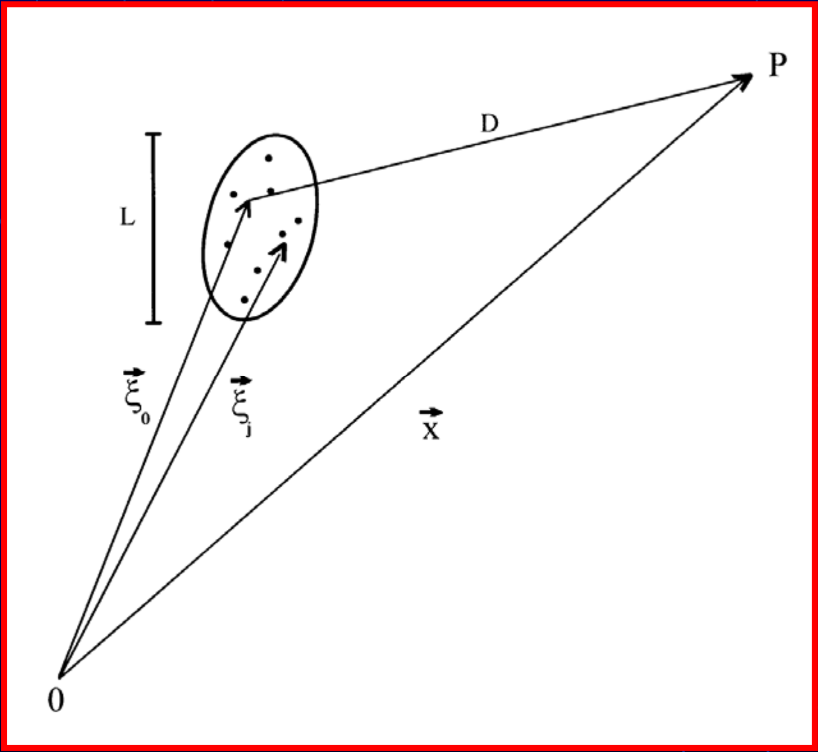
Greens Functions are usually calculated using FDM, FEM, Discrete wave number method but have a limitation to the low frequencies.

For Higher frequencies an alternative is to use EGTD



Empirical Green's Tensor Derivatives method (Plicka and Zahradnik 1998)

Earthquake cluster



$$u_i^j(x,t) = M_{pq}^j(\xi_j,t) * G_{ip,q}(x,\xi_0,t,0)$$

Using 5 moment tensor components assuming non-isotropic component

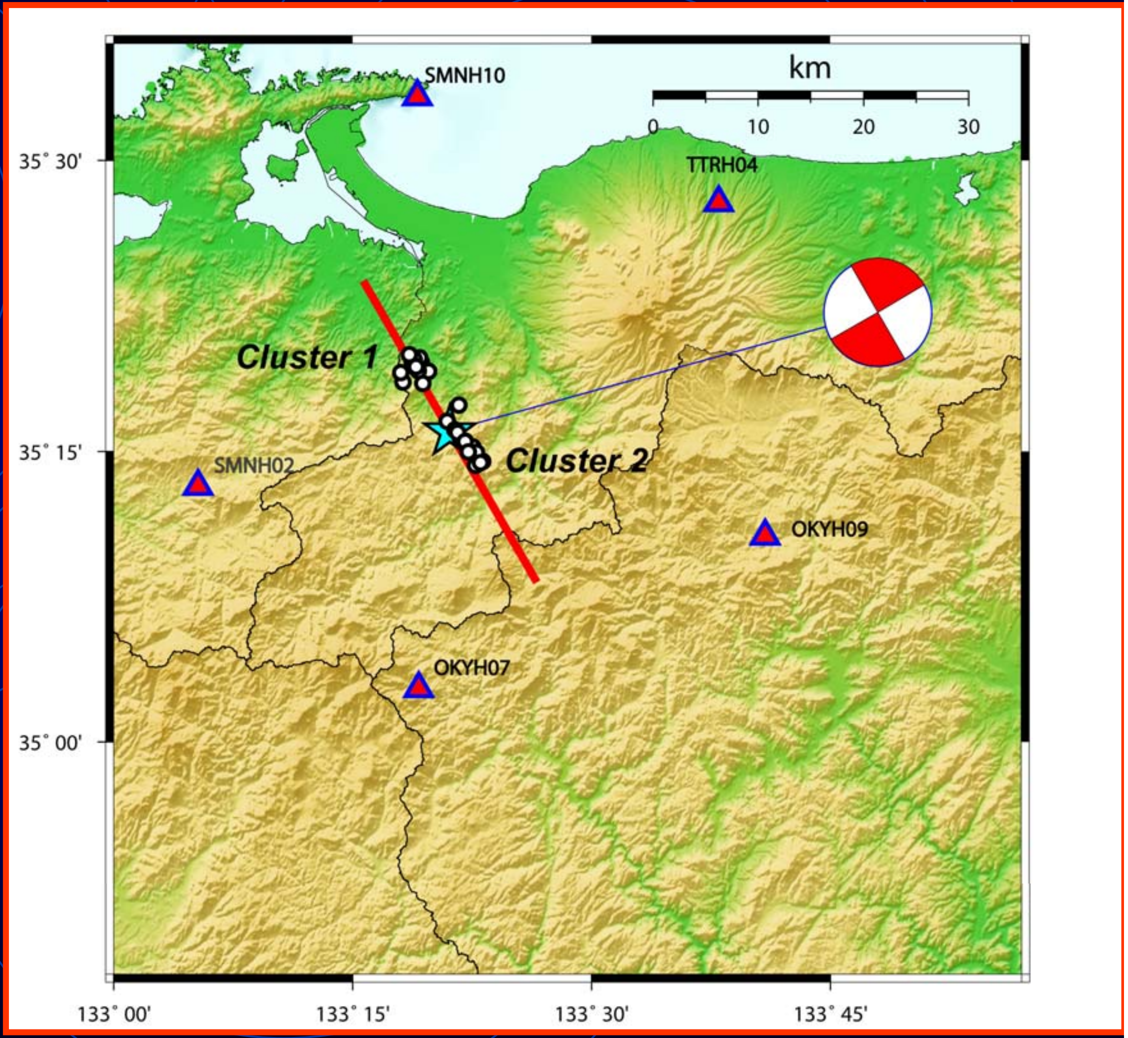
$$\begin{pmatrix} u_1^1 \\ u_1^2 \\ . \\ . \\ . \\ u_1^m \end{pmatrix} = \begin{pmatrix} M_1^1 & M_2^1 & M_3^1 & M_4^1 & M_5^1 \\ M_1^2 & M_2^2 & M_3^2 & M_4^2 & M_5^2 \\ . \\ . \\ . \\ M_1^m & M_2^m & M_3^m & M_4^m & M_5^m \end{pmatrix} \begin{pmatrix} G_{11} \\ G_{12} \\ G_{13} \\ G_{14} \\ G_{15} \end{pmatrix}$$

Stations and Data for EGTD inversion

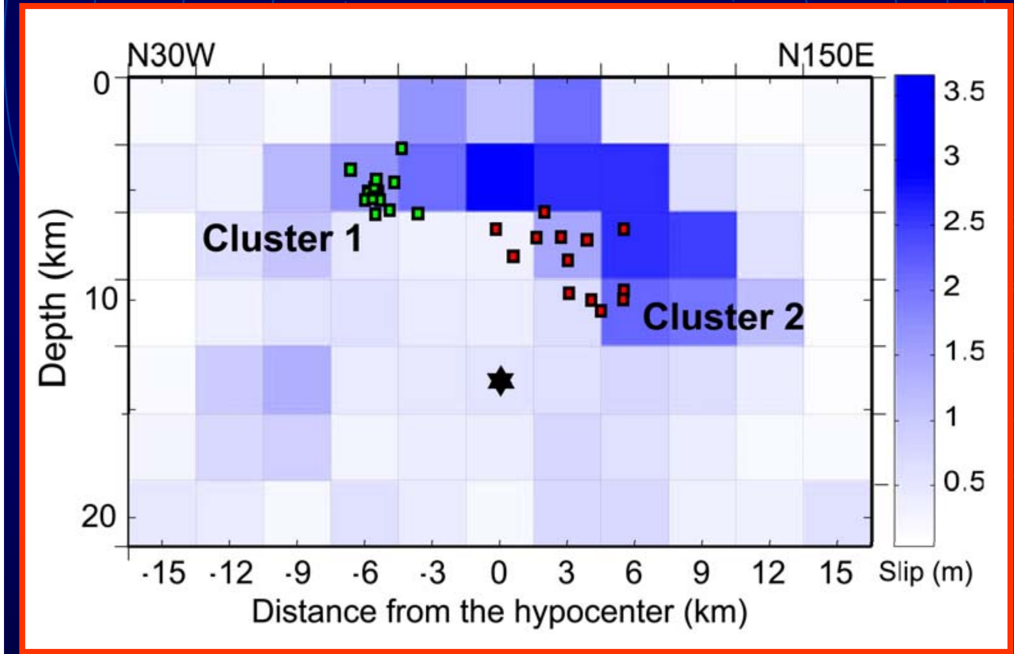
• 30 events with moment magnitudes from Mw=2.5 to 3.7

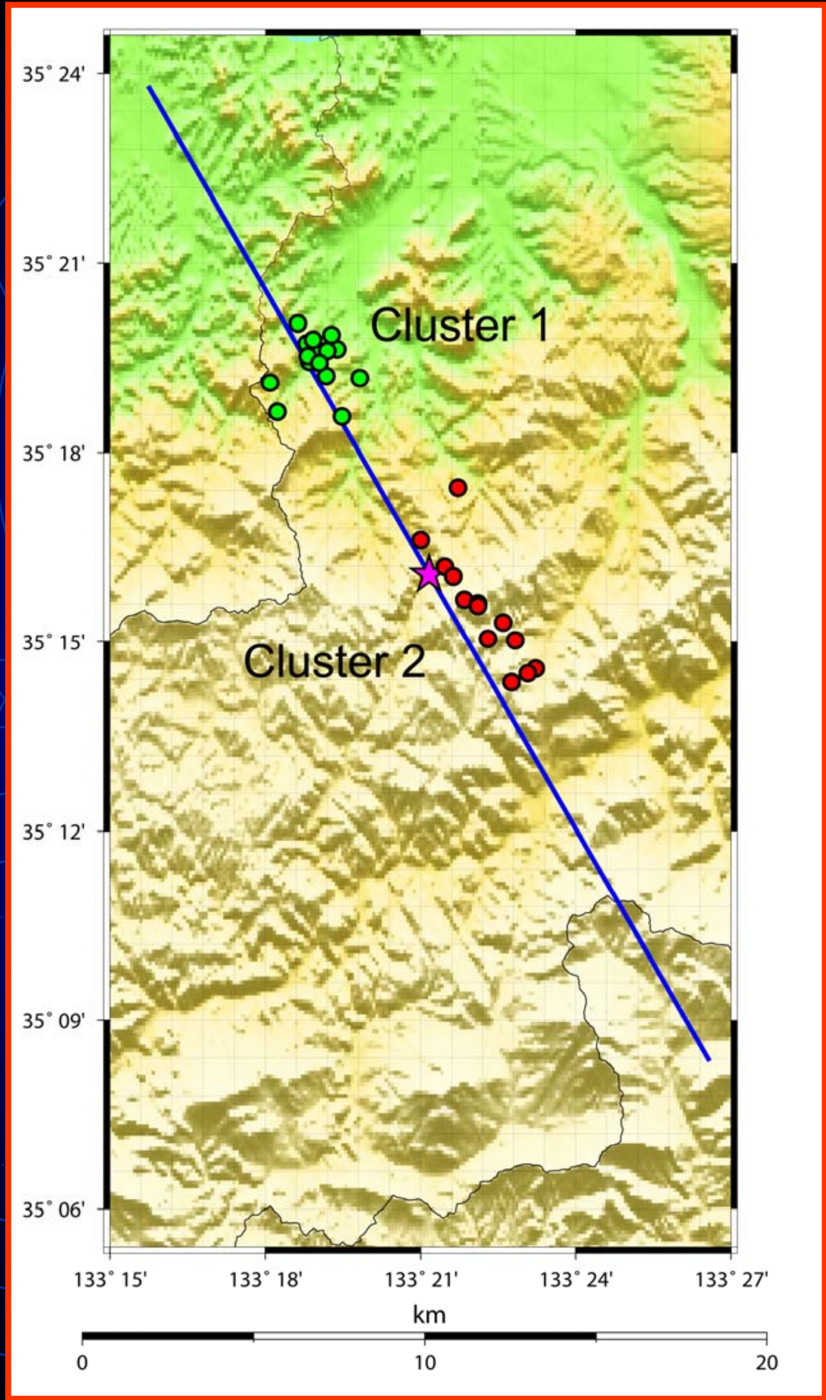
•Relocated events with DD (Fukuyama 2003, Okada 2004)

• Moment tensor solutions events (Fukuyama 2003, Ito 2005)

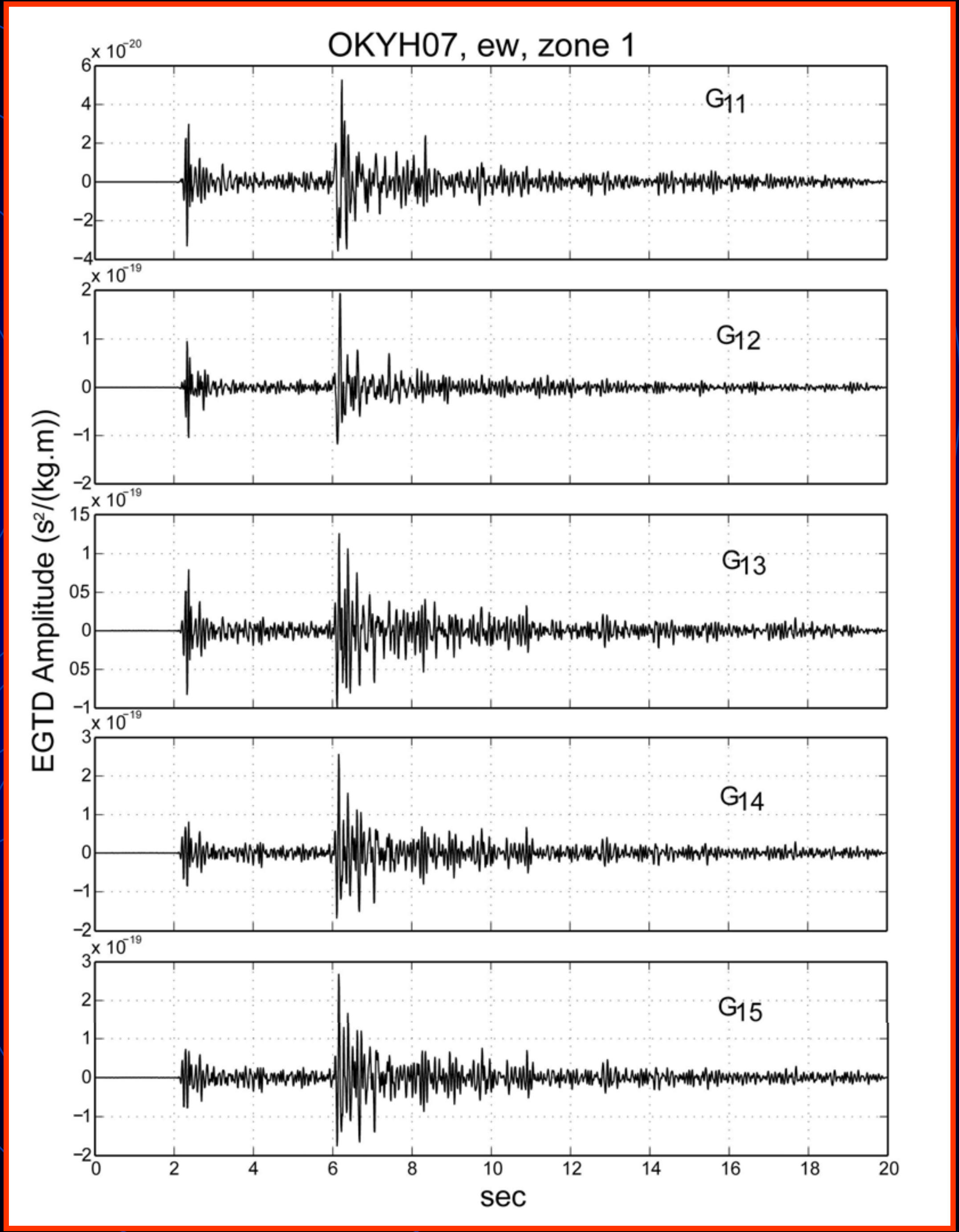


Aftershocks clusters Tottori earthquake



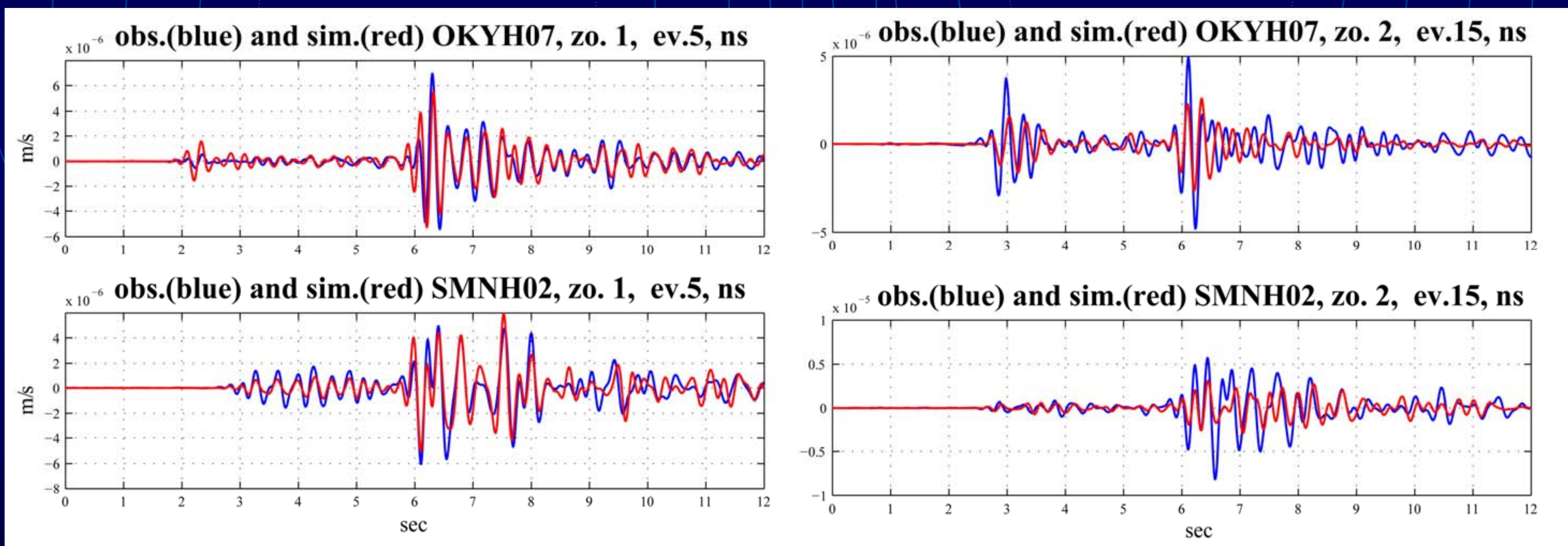


Empirical Green's Tensor Components (Assuming non isotropic component)



Simulated Seismograms (2 to 10Hz) at Hinet stations corresponding to OKYH07 and SMNH02 (NS)

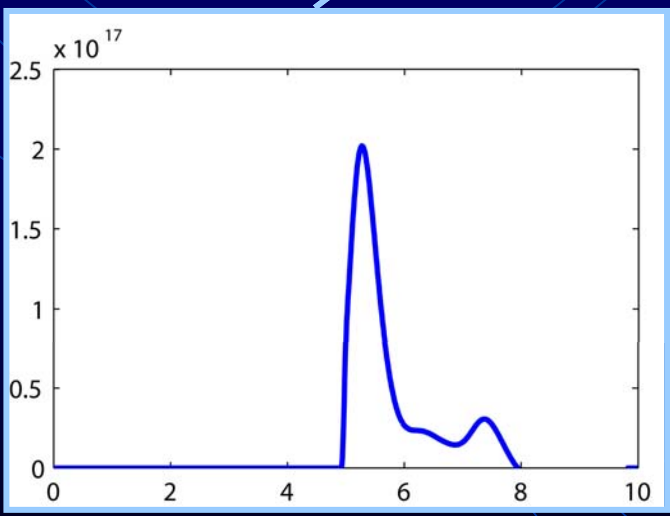
Cluster 1 event M2.6 | Cluster 2 event M2.8

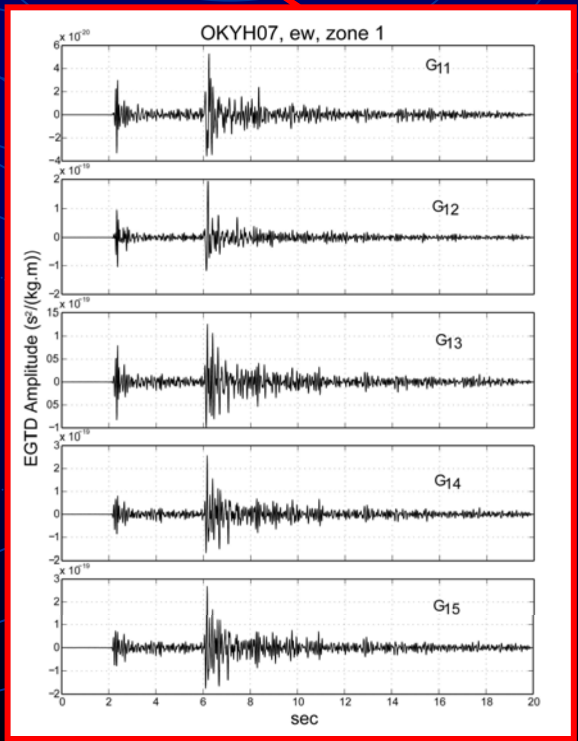


These events are not included in the EGTD inversion for this comparison

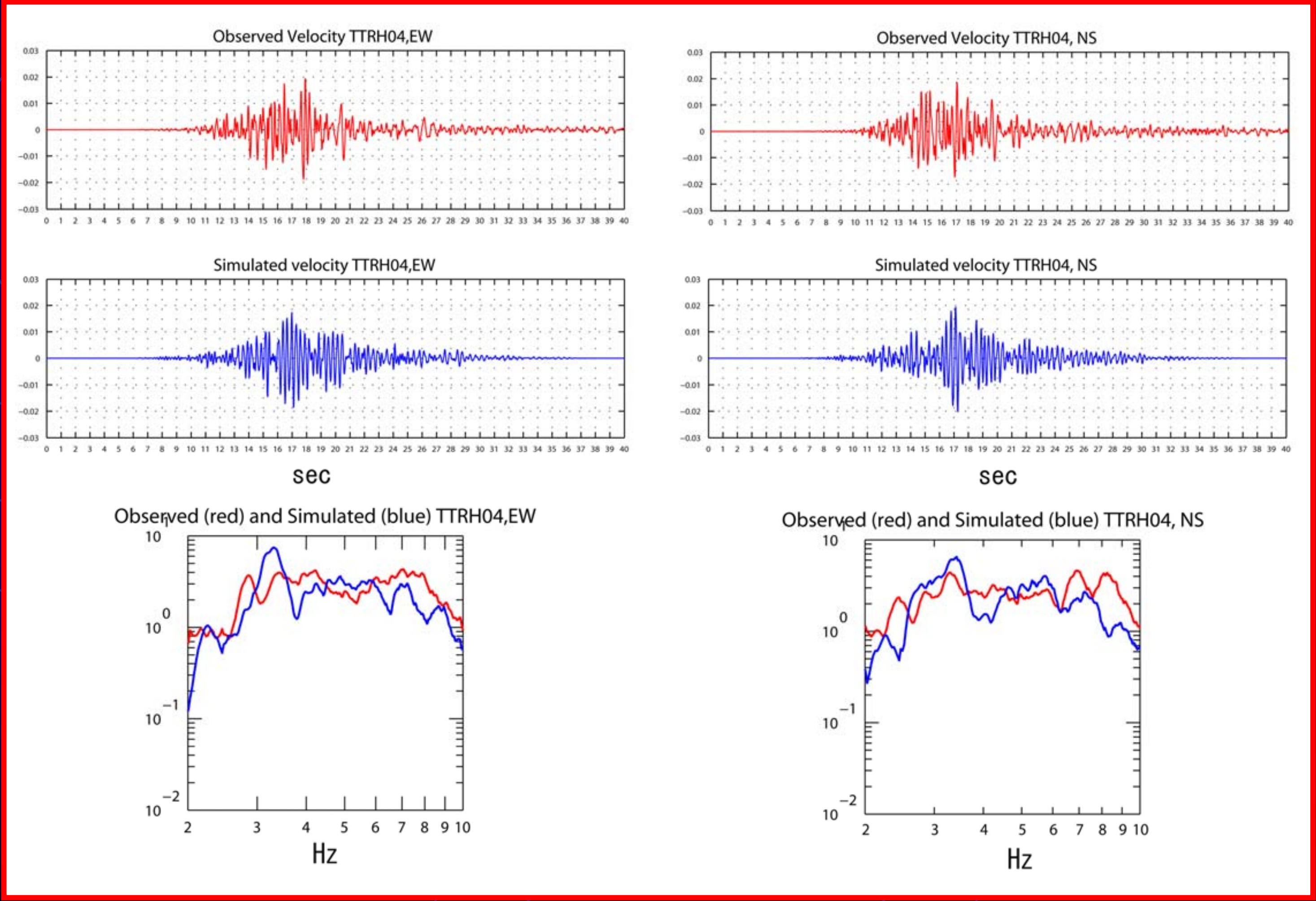
HF ground motion simulation combining dynamic fault rupture model and Empirical Green's Tensor Derivatives

$$\dot{u}_i(x,t) = \sum \sum \dot{M}^{\,j}_{pq}(\xi_j, t) * G_{ip,q}(x, \xi_0, t, 0)$$



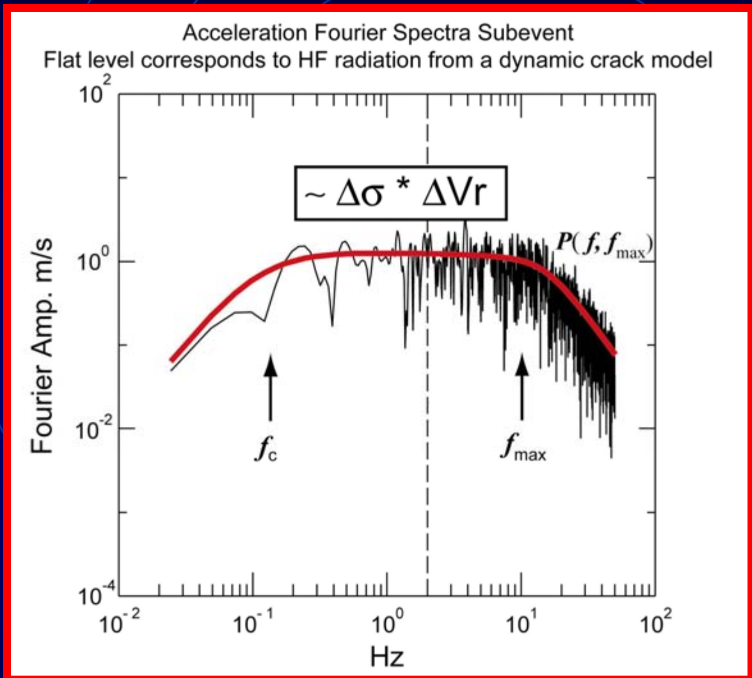


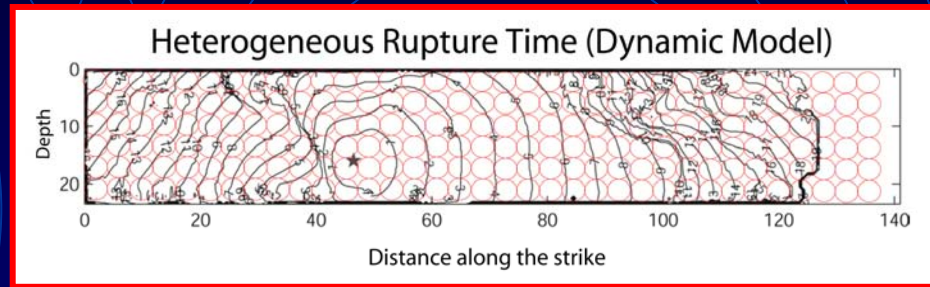
Simulated HF Seismogram for the Tottori earthquake at TTRH04 (2 to 10Hz)



Strong motion simulation when Empirical Green's tensor derivatives (EGTD) are not available

Strong ground motion simulation
Far-field radiation of point sources

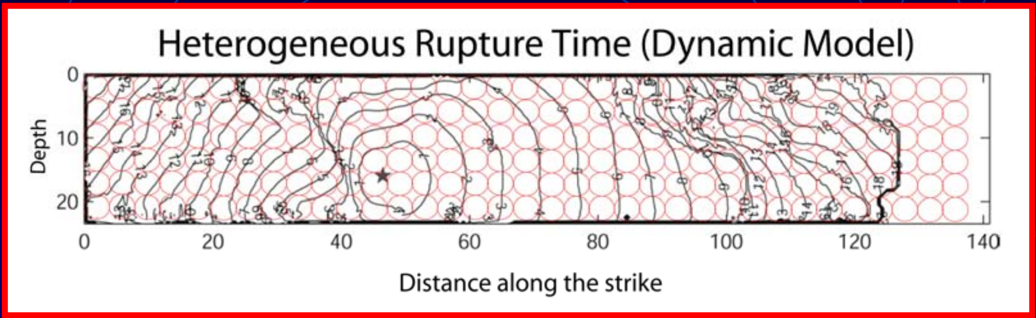


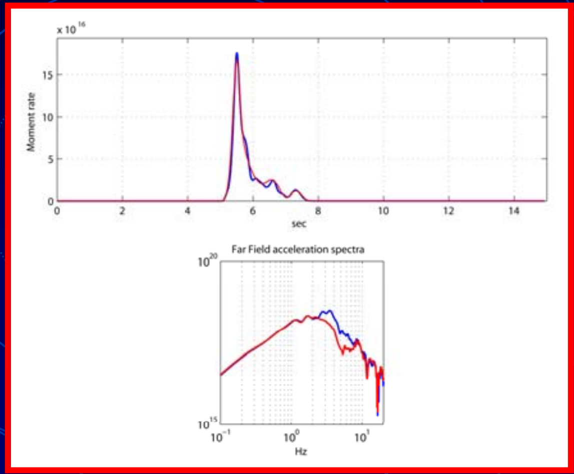


HF spectra from point sources is controlled by dynamic stress drop and rupture velocity changes from the dynamic model, and assuming a random phase to obtain the time series. We also include approximate propagation and scattering effects.

$$A^k{}_{ij}(f) = \frac{F^e R_{\theta\phi\psi} \Delta\sigma_{ij} \Delta V_{r_{ij}} \, r e^{\pi f R_{ijk}/Q(f)\beta}}{R_{ijk}\rho\beta^2} \left[1+\left[f/f_{max}\right]^a\right]^{-b} C_I$$

Summation of HF ground motion of point sources with modified EGF method





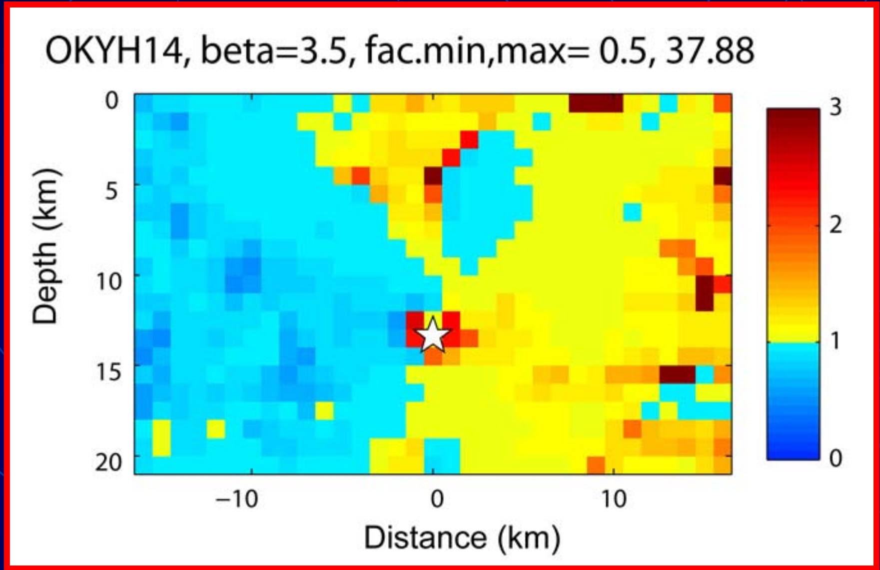
$$U(t) = \sum_{i=1}^{Ns} \sum_{j=1}^{Nd} F(t) * u_{ij}(t)$$

We modified the original formulation of EGF method which assumes Kostrov-like slip velocity function (Irikura 1997, Miyake et al. 2003), to incorporate the slip velocity function from the dynamic model.

$$F(t) = \delta[t - t_{ij}] + \frac{N_t - 1}{V_{ij}} \sum_{k=1}^{(Nt-1)n'} \delta[t - t_{ij} - \frac{(k-1)\tau_{ij}}{(N_t - 1)n'}]\, v_{ij}(k-1)$$

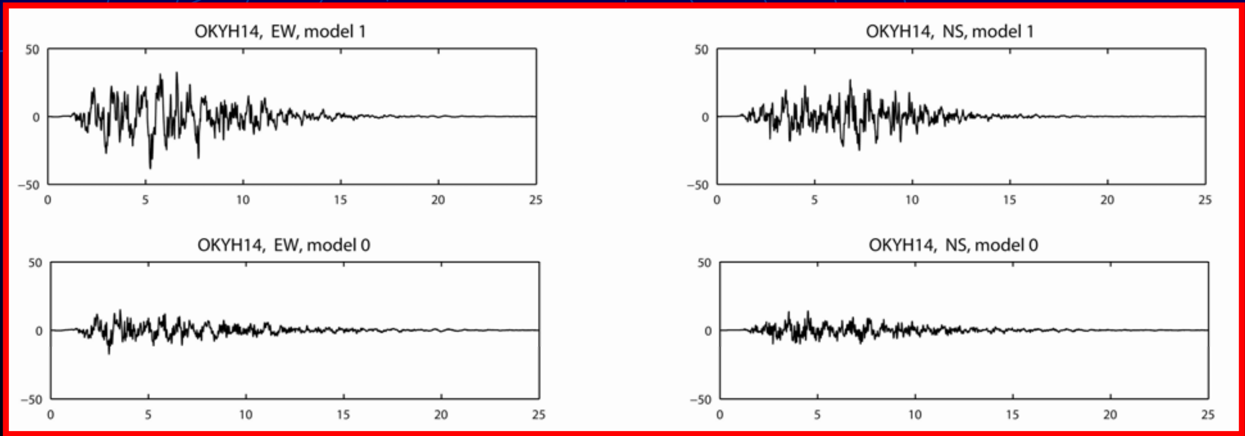
Radiation Pattern including directivity effect at OKYH14

$$R_{\theta\phi\psi} = \frac{R_{\theta\phi}}{1-\Delta V_{r_{ij}} \cos(\psi)/\beta}$$

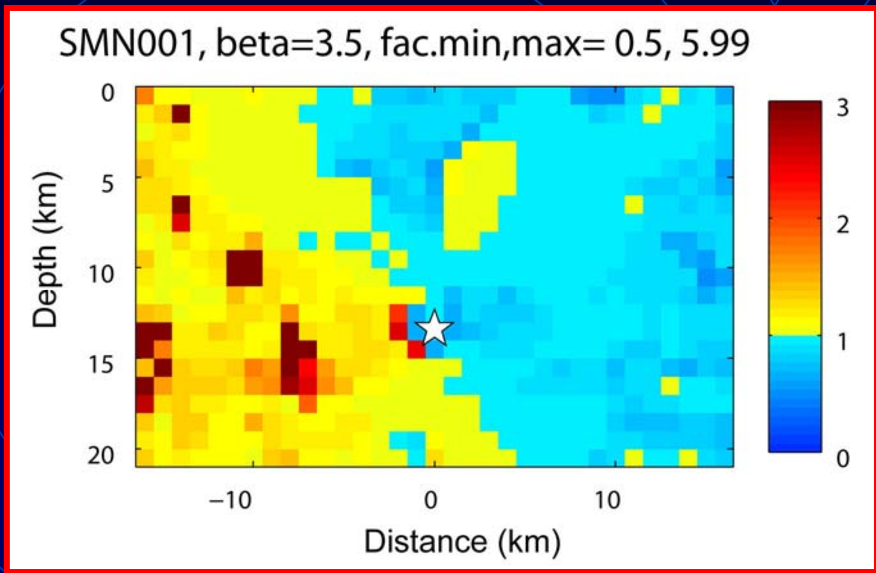


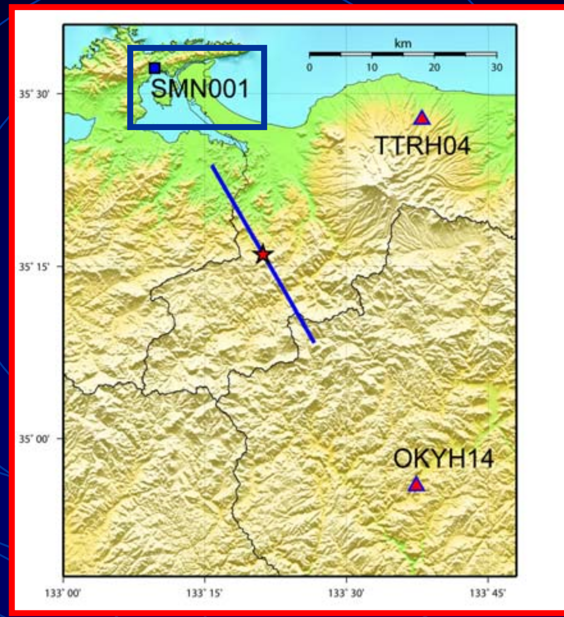
With directivity factor

Without directivity factor



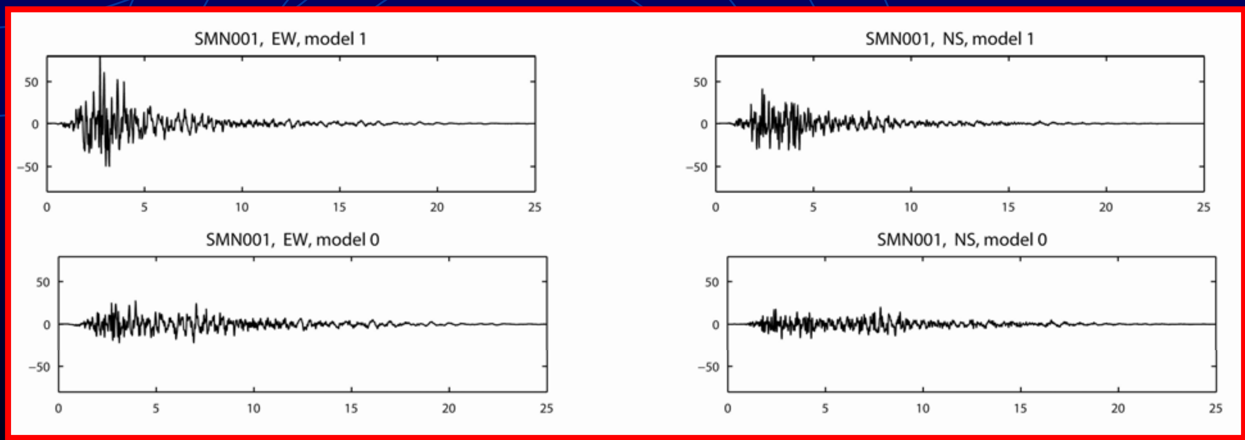
Radiation Pattern including directivity effect at SMN001



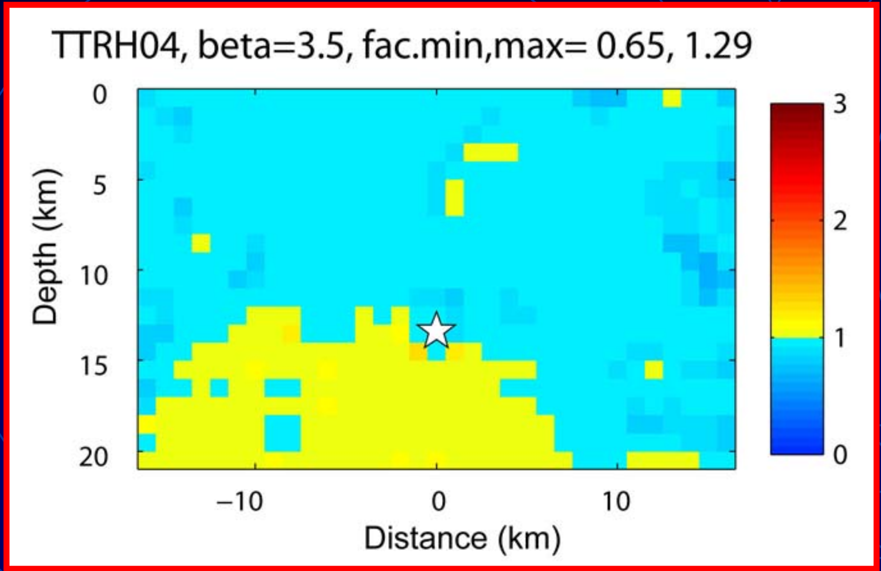


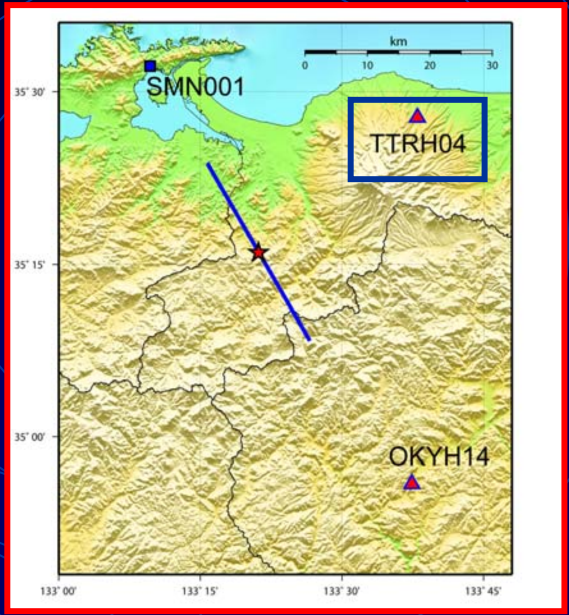
With directivity factor

Without directivity factor



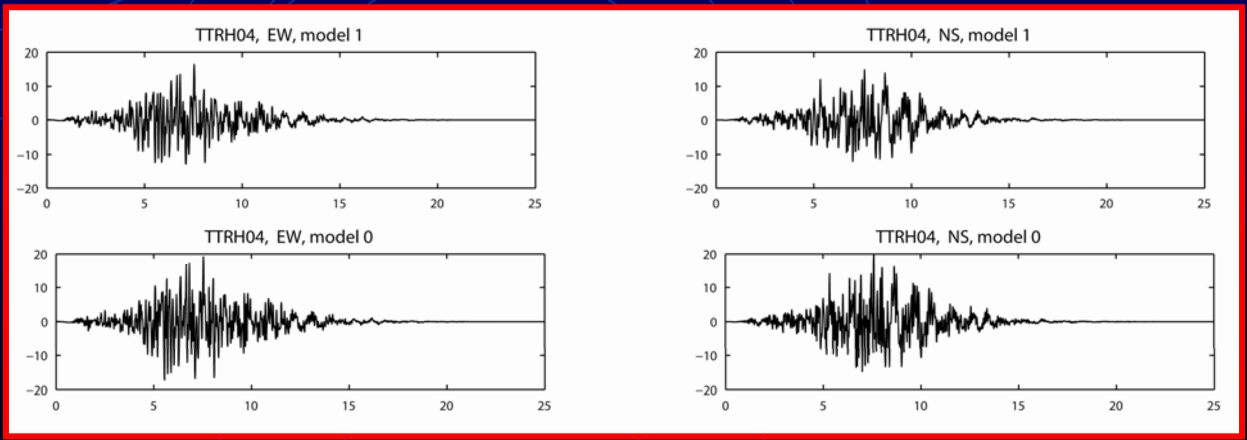
Radiation Pattern including directivity effect at TTRH04





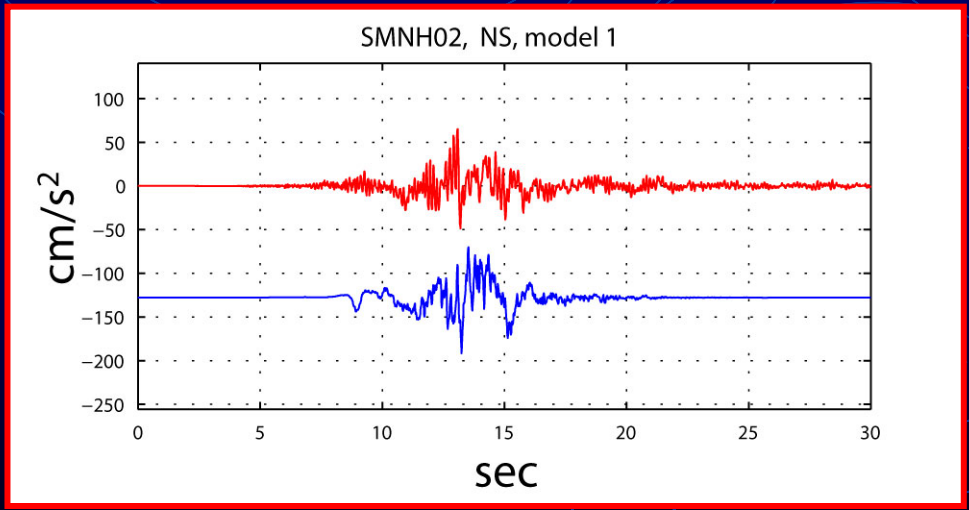
With directivity factor

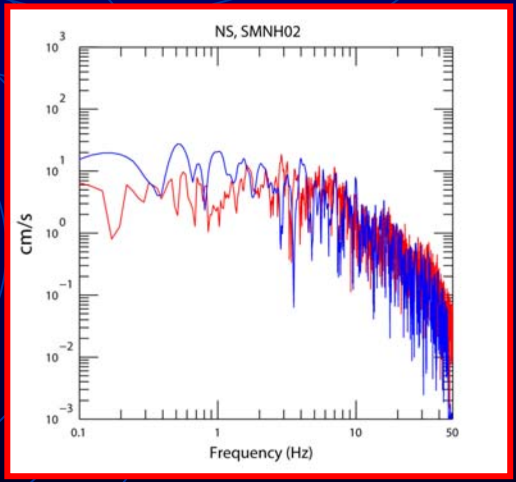
Without directivity factor



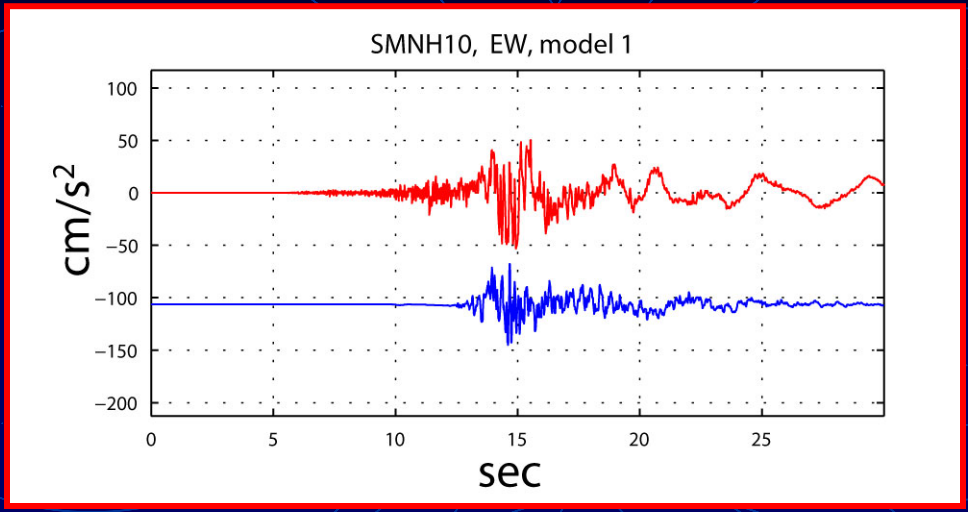
Observed and Simulated Broadband waveforms at SMNH02

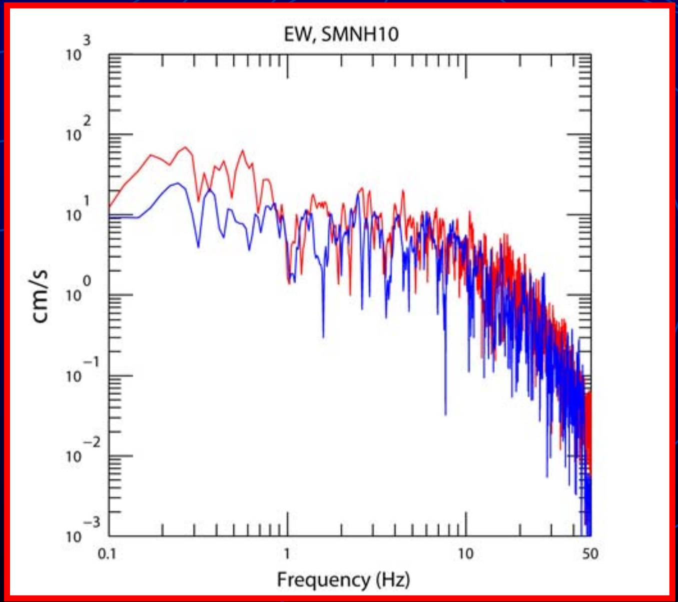
Broadband frequency strong ground motion at a specific site is obtained by adding in time domain the low frequency waveform obtained by the SGSN method and the HF ground motions. The frequency range of the simulations is between 0.1Hz to 30Hz.





Observed and Simulated Broadband waveforms at SMNH10





Conclusions and Discussion

- We developed a methodology for the simulation of broadband strong ground motion based on a dynamic model of fault rupture.
- We obtained that HF ground motion is basically controlled by barriers because of their strong influence on the local variation of the rupture front (rupture velocity).
- The LF ground motion characteristics are basically controlled by asperities.
- Several scaling relationships have been proposed to characterize asperities for strong motion simulation of future earthquakes. However the barriers also seem to play an important role, specially for the generation of HF.

Future directions

- To investigate the relationship between asperities and barriers of well recorded past earthquakes by modeling their dynamic rupture process.
- To explore possible scaling relationships for barriers and their characterization for future earthquakes.
- To seek for simple relations between locations and strength of barriers and the subsequent rupture propagation characteristics, to be used for strong motion simulation.