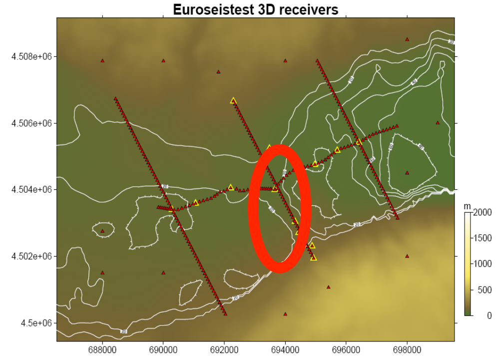
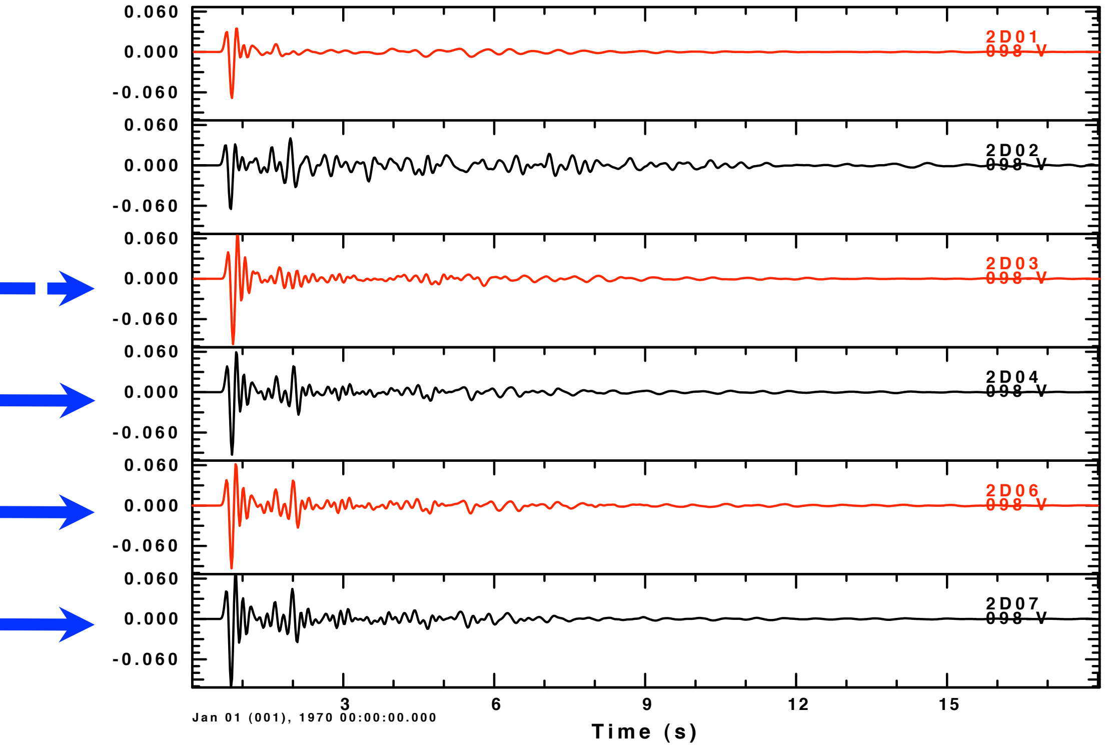
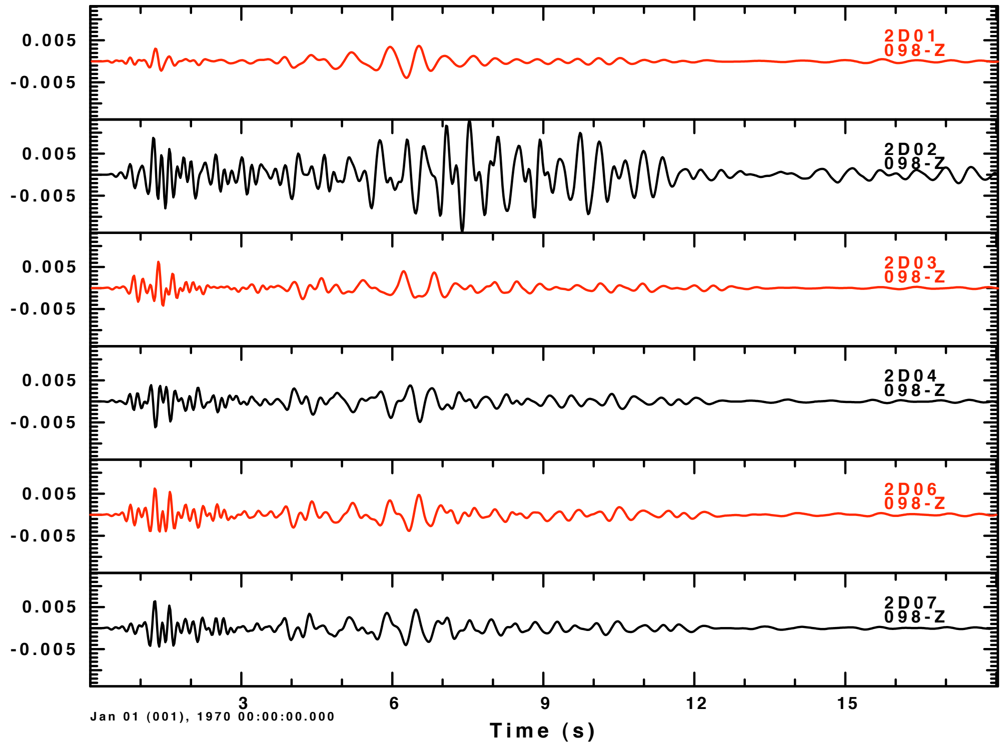
Results, 2DL, Q - TST - 0-8 Hz



Radial component



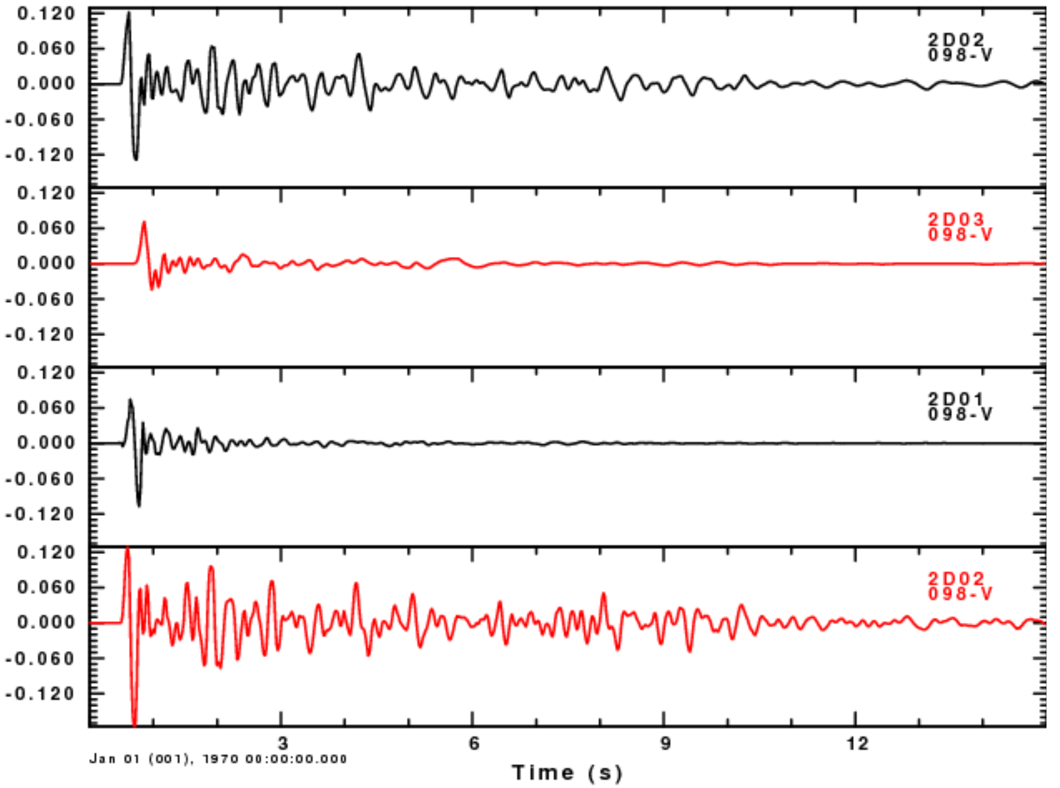
Vertical component



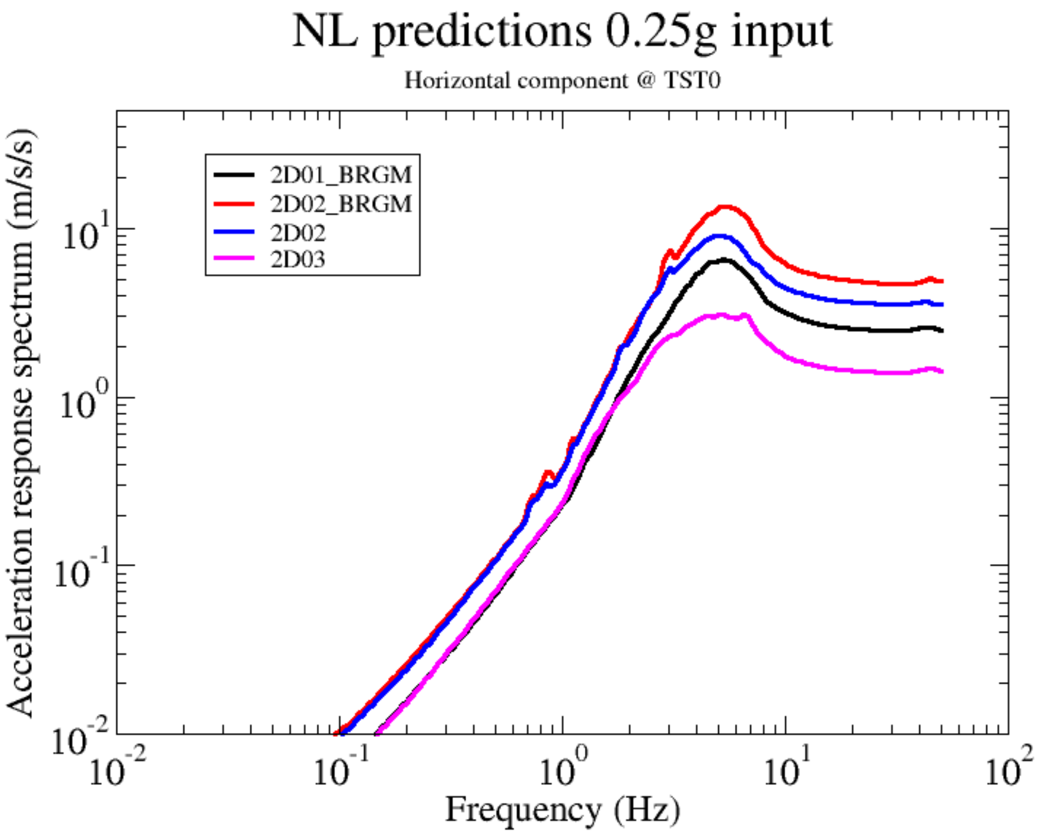
Good fit : (2D03), 2D04, 2D06, 2D07

Cross-model comparison, NL 0.25 g (TST)

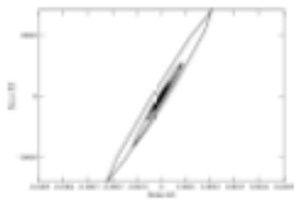
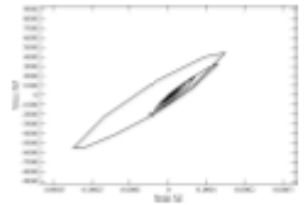
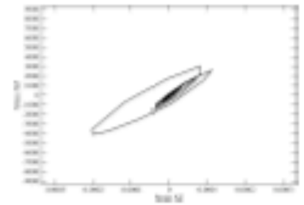
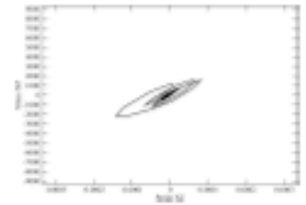
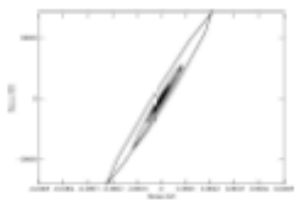
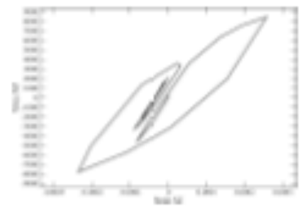
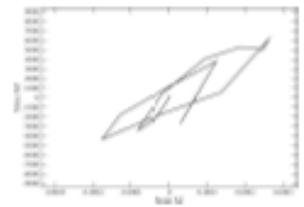
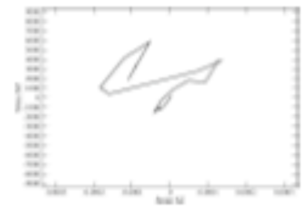
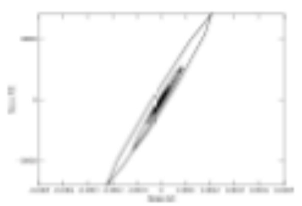
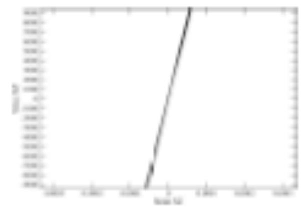
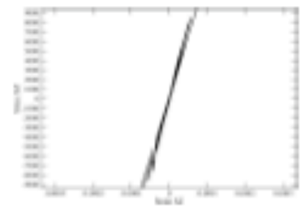
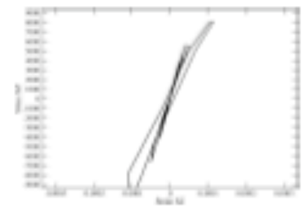
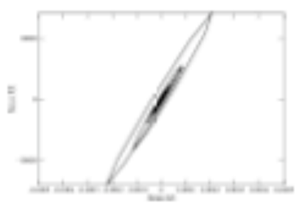
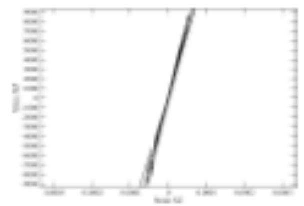
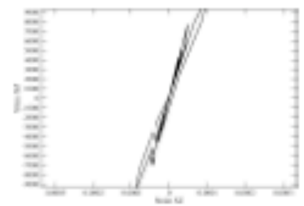
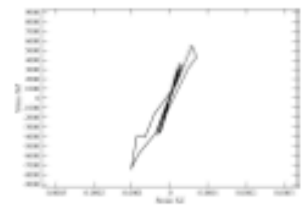
Horizontal time histories



Response spectra



Stress-strain curves
TST surface, all available computations

TST0	Linear Viscoe-lastic, 0.1 g	0.05g, NL	0.1g, NL	0.25g, NL
IRSN_VOLVI				
BRGM				
CEA_BRGM				
CEA_VOLVI				

Main results from 2D verifications

2D linear not yet straightforward

- ➢ needs iterations and cross-checks with other techniques

Key importance of damping in NL models

- ➢ classical "Seed like" curves yield strong NL effects at least in deep deposits
  - already significant at 0.05 g (0.12 g surface)
  - ? Large effects at high frequencies because of damping ?
    - ??? Is it realistic ???

Large variability in NL results

- ➢ Same G-ζ-γ curve implemented in different codes yield different results
    - large differences in time histories, strain / pga / pgv profiles
- ➢ Effects on 5% response spectra less apparent
  - not so sensitive to diffracted waves
  - (but large differences between the 2 NL models)

3D Linear, Verification

Goals

- Compare 3D simulation results from different codes for various sources
- Frequency range : 0 - 4 Hz (λ_{min} = 25 m)
- Identify the key issues and parameters for accurate modelling (or at least progressing in that direction…)
    - free-surface condition
    - absorbing boundary conditions
    - representation / discretization of 3D heterogeneities
    - numerical dispersion
    - …

Partners and codes

Institu-tions	Methods (all 2nd-order in time)			
		characterization	attenuation	ABC
CUB	FDM	finite-difference, 4th-order velocity-stress volume arithmetic and harmonic averages of density and moduli arbitrary discontinuous staggered grid	GZB 4 rel. mechanisms	CPML
UJF	SEM	spectral-element, Legendre 4th-order polynomial Gauss-Lobatto-Legendre integration	GZB 3 rel. mechanisms	Lysmer & Kuhlemeyer
DPRI	FDM	finite-difference, 4th-order velocity-stress non-uniform staggered grid	linear Q(f) f_0 = 2 Hz	Clayton & Engquist A1 + Cerjan
OGS	PSM	Fourier pseudospectral, vertically stretching staggered grid	GZB 3 rel. mechanisms	CPML
NIED	FDM	finite-difference, 4th-order velocity-stress discontinuous staggered grid	linear Q(f) f_0 = 2 Hz	Clayton & Eng-quist A1 + Cerjan
CEA	DEM -SEM	hybrid discrete-element – spectral element, Voronoï particles (6 dof – 3 translation + 3 rotation), 2nd-order	hysteretic damping	Lysmer & Kuhlemeyer
CMU	FEM	finite-element, tri-linear elements, octree-based discontinuous mesh	Rayleigh att. in the bulk	Lysmer & Kuhlemeyer
UNICE	DGM	discontinuous Galerkin, 2nd-order polynomial	n.a.	CPML

3D Verification : How ?

Items for the cross technique comparison

- Overall patterns
  - cross-sections
  - PGV maps
- Individual traces : Measure of the goodness of fit
  - Time-frequency analysis
  - 1C - 3C
  - Amplitude / Phase
    - Broad band or limited frequency bands
- identification of the origin of differences
  - Plane wave / point source
  - Elastic case / including damping
  - smooth velocity gradients / discrete velocity jumps

Considered 3D models

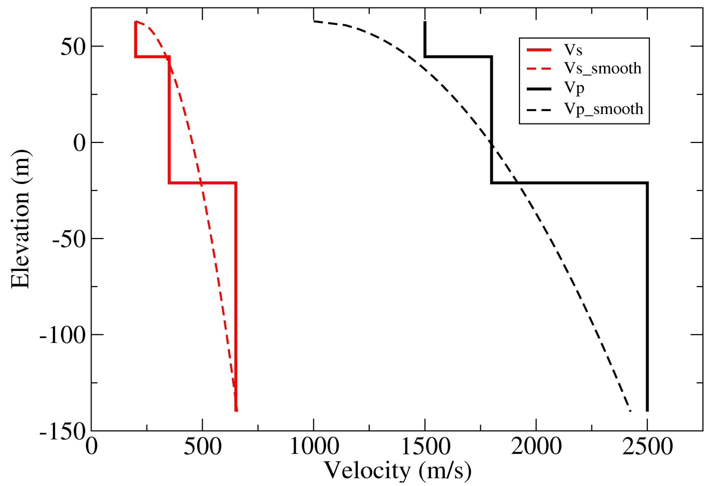
Bc/ Bd

3D heterogeneous model (3 irreg. homog. layers)					
Layer	V_S (m/s)	V_P (m/s)	ρ (kg/m^3)	Q_S	Q_κ
A+B	200	1500	2100	20	∞
C+D	350	1800	2200	35	∞
E+F	650	2500	2200	65	∞
Bedrock	2600	4500	2600	260	∞

3D heterogeneous model (3 irreg. constant-gradient layers)					
Layer	V_S (m/s)	V_P (m/s)	ρ (kg/m^3)	Q_S	Q_κ
A+B	200 - 250	1500 - 1600	2100	20 - 25	∞
C+D	250 - 500	1600 - 2200	2100 - 2130	25 - 50	∞
E+F	500 - 900	2200 - 2800	2130 - 2250	50 - 90	∞
Bedrock	2600	4500	2600	260	∞

Be/Bf

laterally homog. model, vertical gradient



Bb - Elastic

Computational cases, point source

<table>
<tr><th colspan="5">Model configurations for the hypothetical point DC source</th><th></th></tr>
<tr><th rowspan="2">ID</th><th colspan="2">sediments</th><th colspan="2">bedrock</th><th rowspan="2"></th></tr>
<tr><th>geometrical heterogeneity</th><th>rheology</th><th>geometrical heterogeneity</th><th>rheology</th></tr>
<tr><td>Ba (I2a)</td><td>n.a.</td><td>n.a.</td><td>homog.</td><td>viscoelastic</td><td></td></tr>
<tr><td>Bb (III1)</td><td>laterally homog., vertical gradient</td><td>elastic</td><td>1D</td><td>elastic</td><td>3</td></tr>
<tr><td>Bc (I2c)</td><td rowspan="2">3D heterog. (3 irreg. homog. layers)</td><td>elastic</td><td rowspan="2">1D</td><td>elastic</td><td>2</td></tr>
<tr><td>Bd (I2b)</td><td>viscoelastic</td><td>viscoelastic</td><td>1</td></tr>
<tr><td>Be (IV2)</td><td rowspan="2">3D heterog. (3 irreg. constant-gradient layers)</td><td>elastic</td><td rowspan="2">1D</td><td>elastic</td><td>5</td></tr>
<tr><td>Bf (IV1)</td><td>viscoelastic</td><td>viscoelastic</td><td>4</td></tr>
</table>

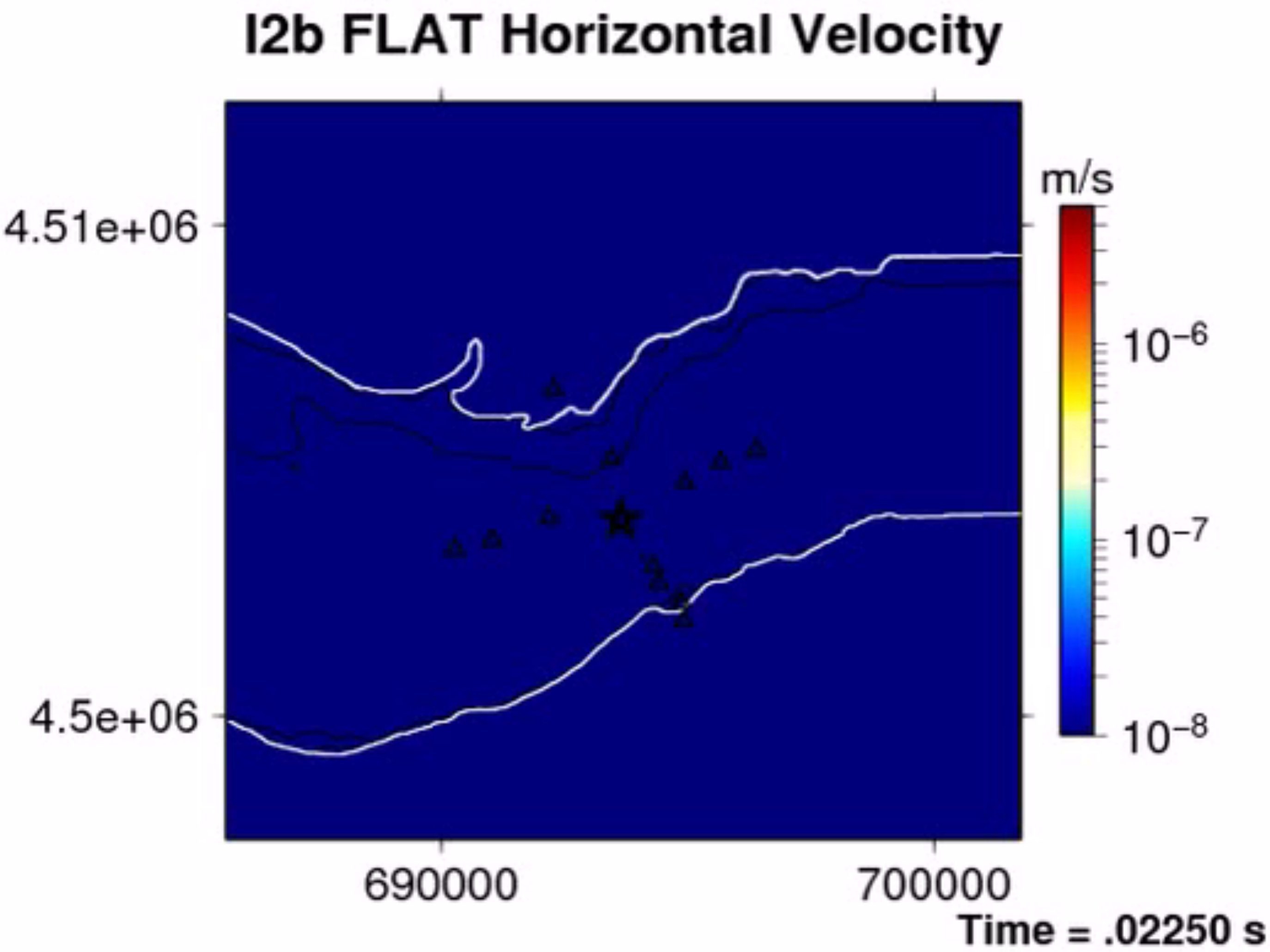
Available computations

Table of submitted solutions (✓ = under preparation)

		CUB FDM 3D01	UJF SEM 3D02	DPRI FDM 3D03	OGS PSM 3D04	NIED FDM 3D05	CEA DEM 3D06	CMU FEM 3D07	UNICE DGM 3D09	
Bb	**1D Gradient, No Q**	✓	✓		✓		(✓)	✓	✓	3
Bc	**3 homogeneous layers, No Q**	✓	✓	✓	✓	✓	(✓)	✓	✓	2
Bd	**3 homogeneous layers, With Q**	✓	✓	✓	✓	✓	(✓)	✓		1
Be	**3 irregular, constant gradient layers, No Q**	✓	✓	(✓)	✓	(✓)	(✓)	(✓)	✓	5
Bf	**3 irregular, constant gradient layers, With Q**	✓	✓		✓		(✓)	(✓)		4

Example valley response

(3D, H, Q)

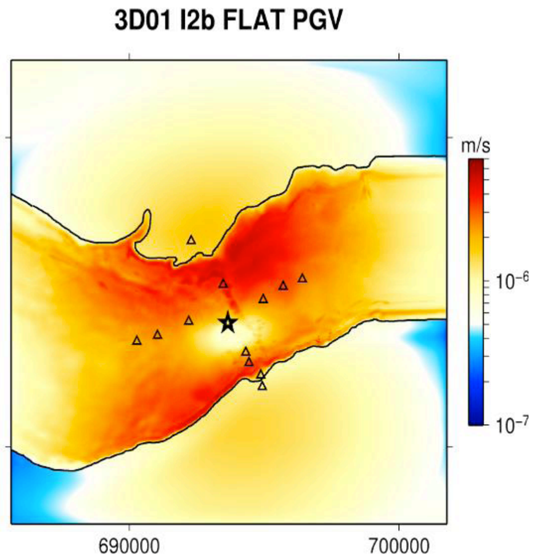


Event	Mag	Depth	Strike	Dip
Ver	1.3	3 km	268°	45°

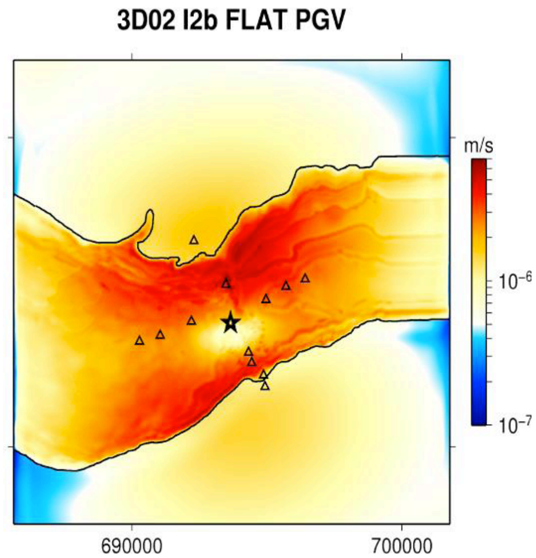
3D Verification 1 (Bd): 3H layers with damping

Event	Mag	Depth	Strike	Dip	Rake
Ver	1.3	3 km	268°	45°	-94°

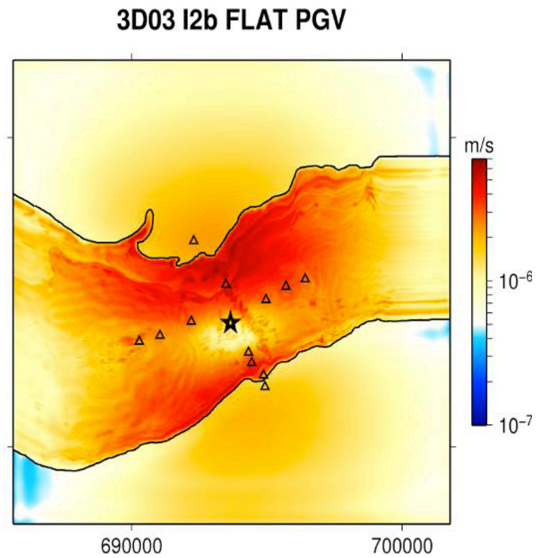
FDM



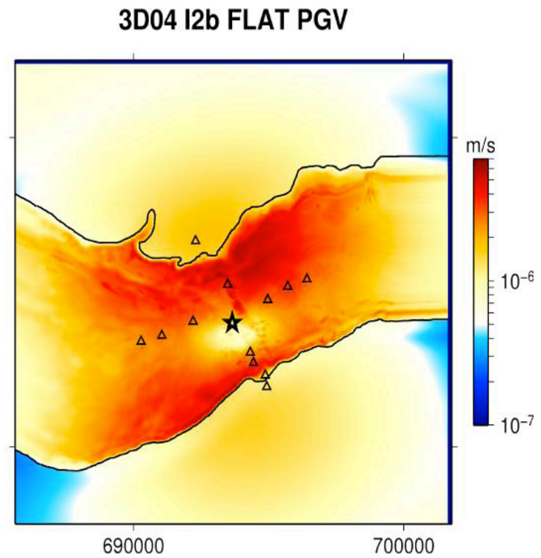
SEM



FDM

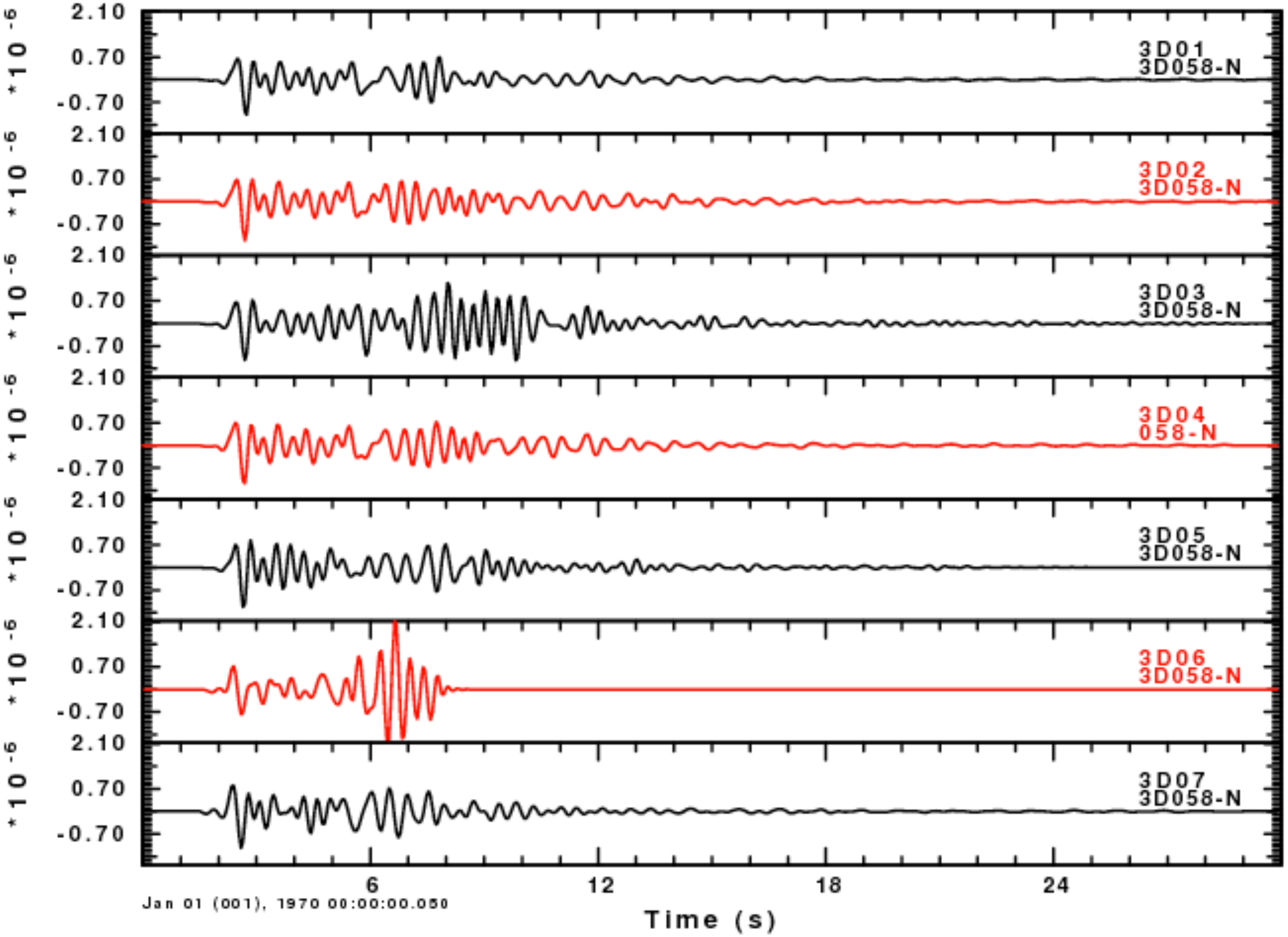


PSM



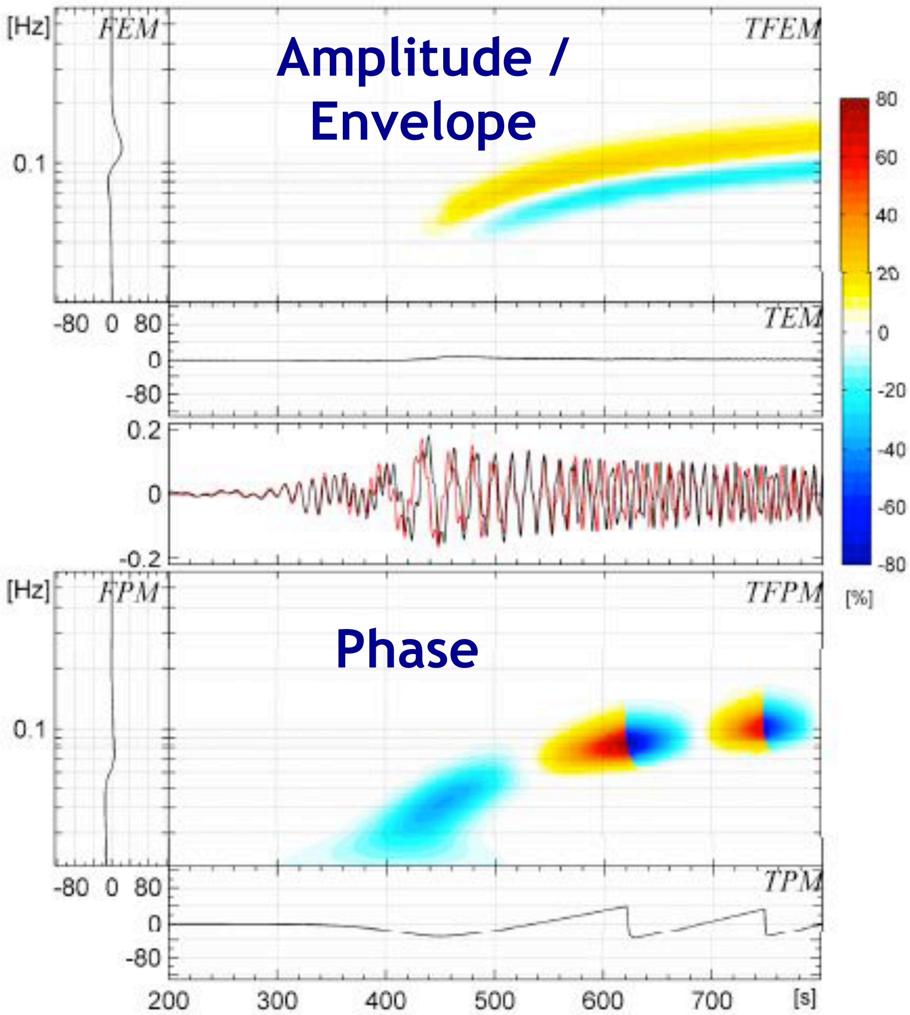
Good initial agreement only for 2 computations, improved for 2 other after iterations

Example Time histories (TST, H)



Quantitative measure of fit using time-frequency misfit criteria (Kristekova et al., 2009)

Wavelet analysis



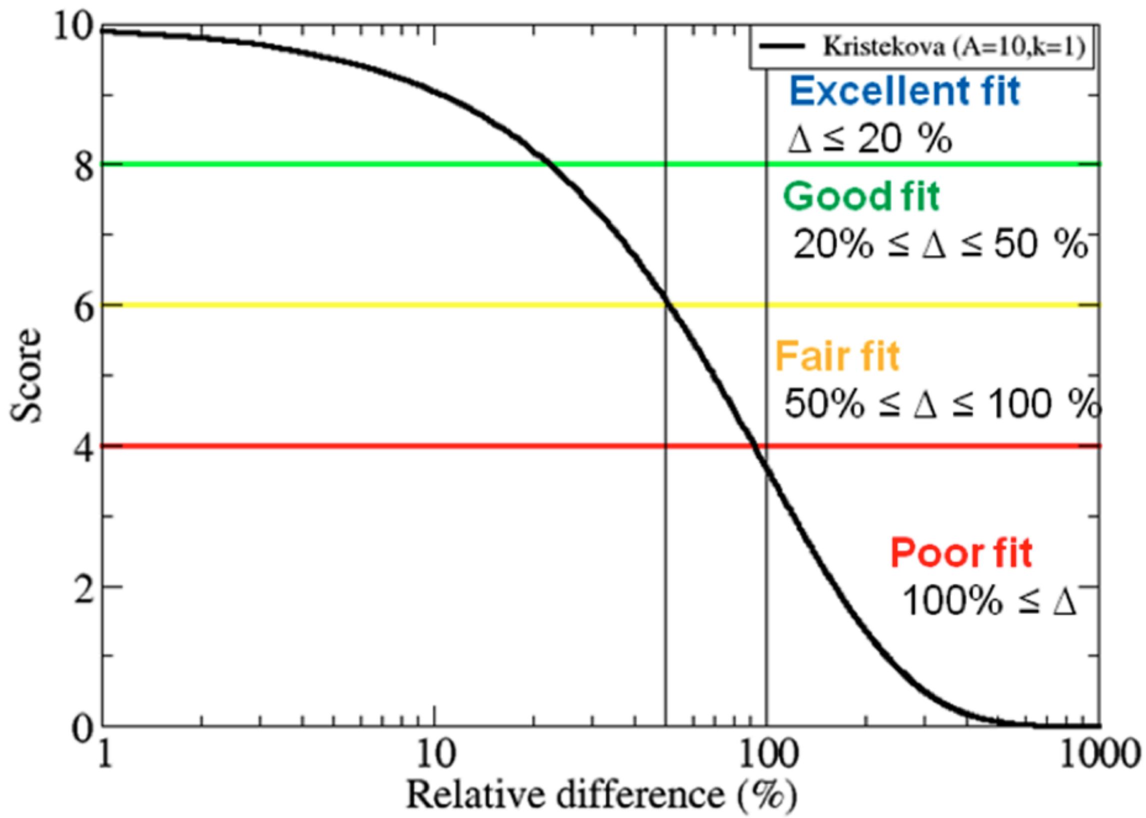
For each site

- each component
  - averaging misfit for all frequencies / all signal
  - one score for envelope / amplitude
  - one for phase
  - → one global score
- average the score for the 3 components
- 1 global score

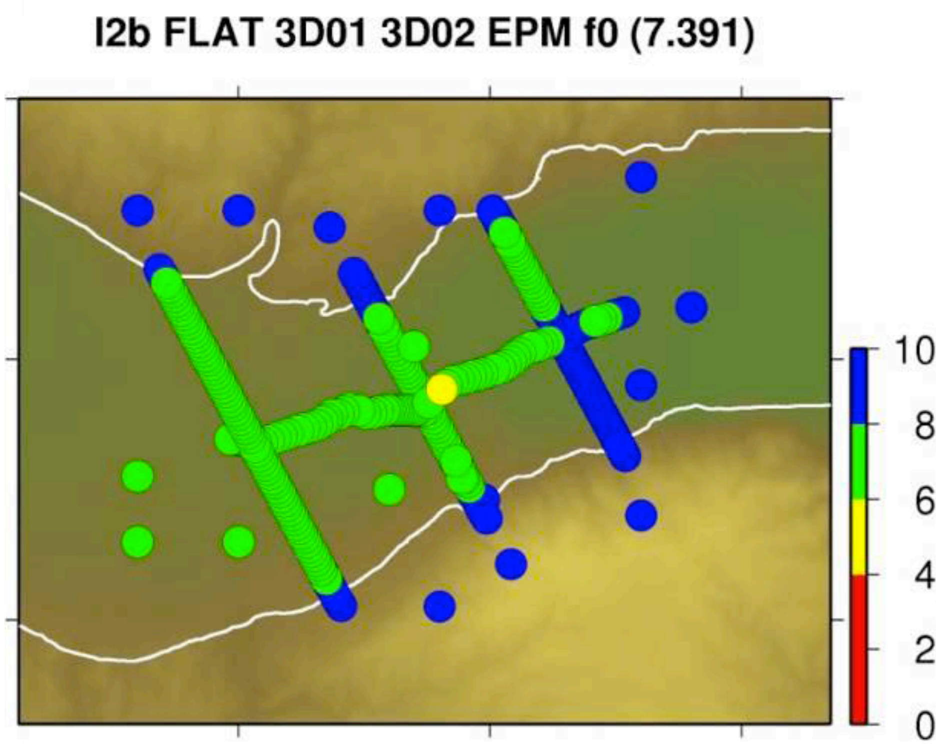
(Can be done in different frequency bands)

Scaling and mapping

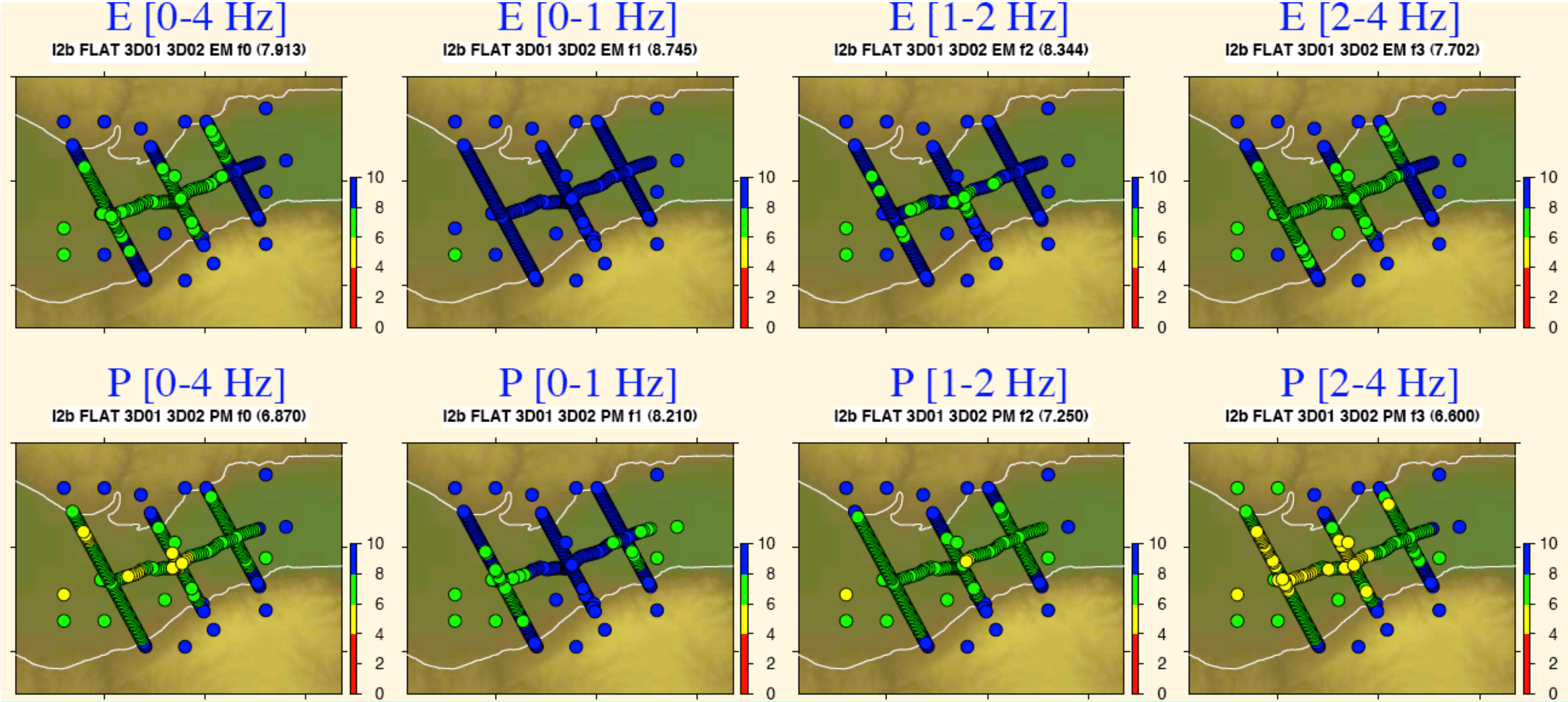
Goodness of fit scaling
10. exp (-misfit)



FDM /SEM



Goodness-of-fit, Detail FDM/SEM
[broad-band 0-4 Hz, + narrower bands 0-1, 1-2, 2-4 Hz]



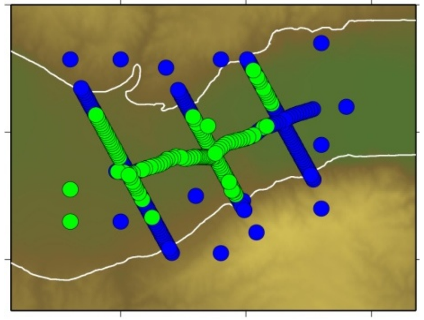
Envelope (Amplitude) fit better than phase fit
Fit decreases with increasing frequency

Bd (homogeneous layers, with damping) : overall comparison (wrt 3D01-FDM)

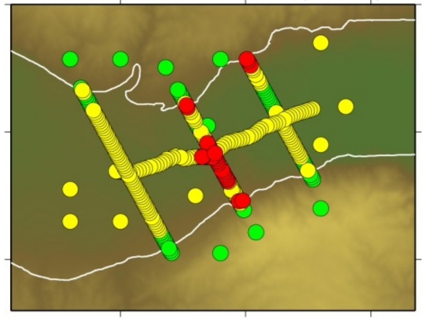
SEM	FDM	PSM	FDM	FEM

Amplitude

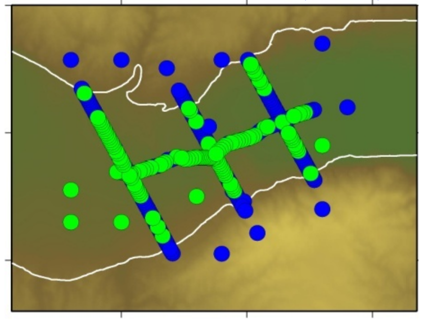
E-GOF 3D02 (7.91)



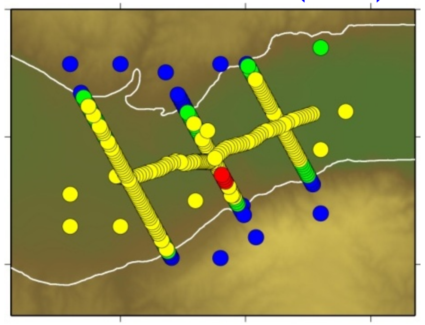
E-GOF 3D03 (5.36)



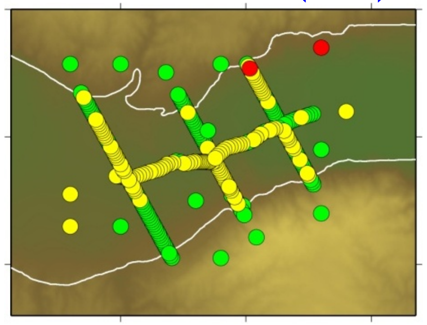
E-GOF 3D04 (7.99)



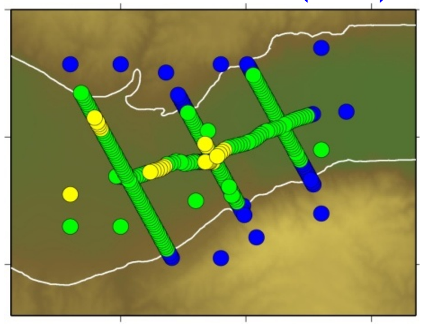
E-GOF 3D05 (5.50)



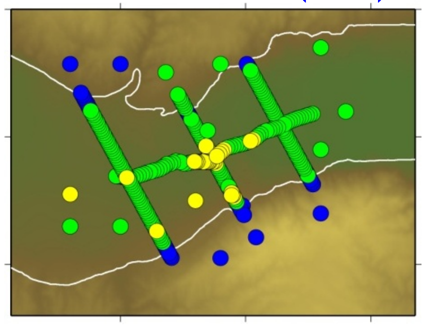
E-GOF 3D07 (6.00)



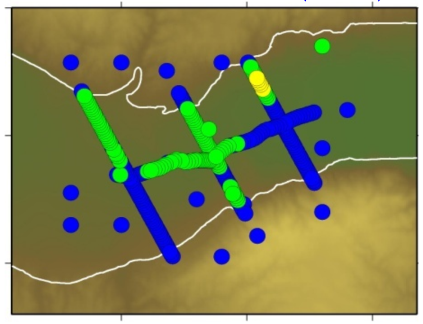
P-GOF 3D02 (6.87)



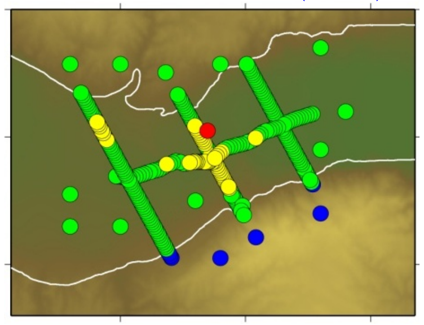
P-GOF 3D03 (6.81)



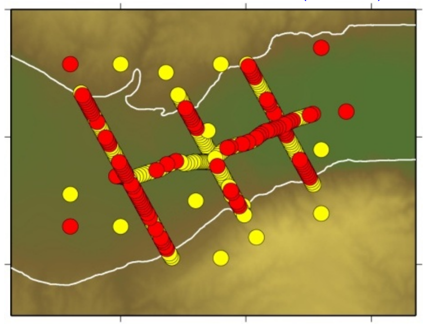
P-GOF 3D04 (7.73)



P-GOF 3D05 (6.52)



P-GOF 3D07 (4.04)



Phase

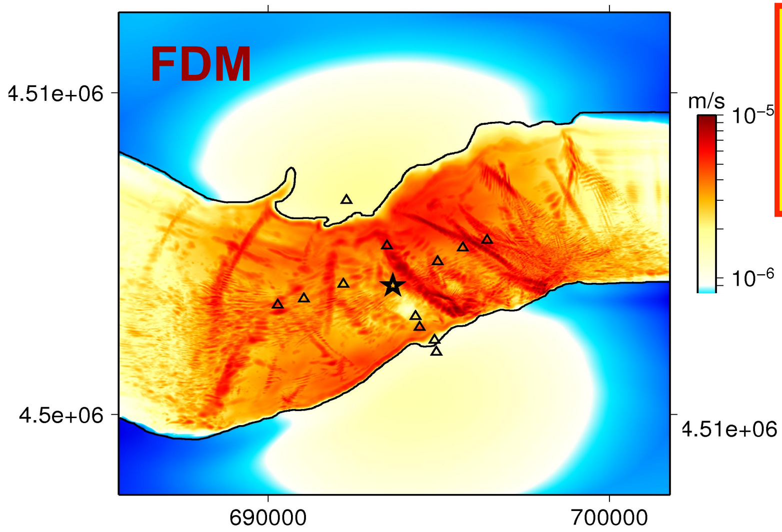
FDM (3D03): Non constant Q (= $Q_0.f/f_0$)

FDM (3D05): Non constant Q (= $Q_0.f/f_0$)

FEM (3D07): Rayleigh damping on bulk, limited V_P/V_S

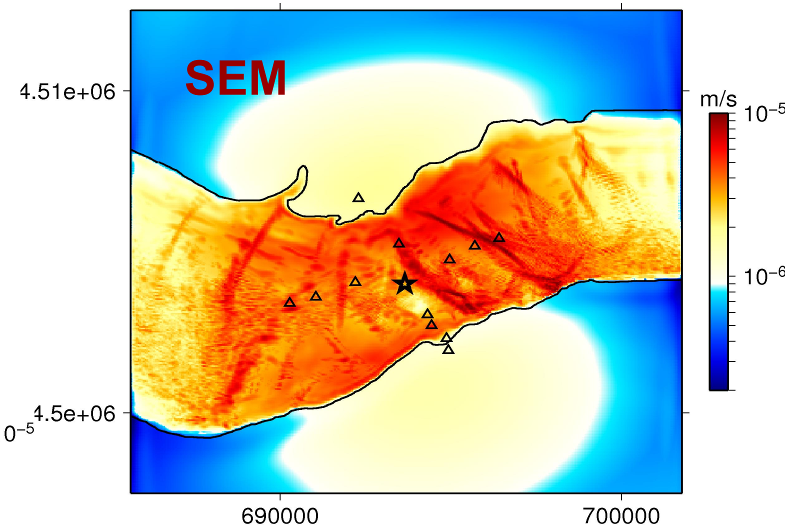
3D Verification 2 : 3H layers, NO damping (Bc)

3D01 I2c FLAT PGV

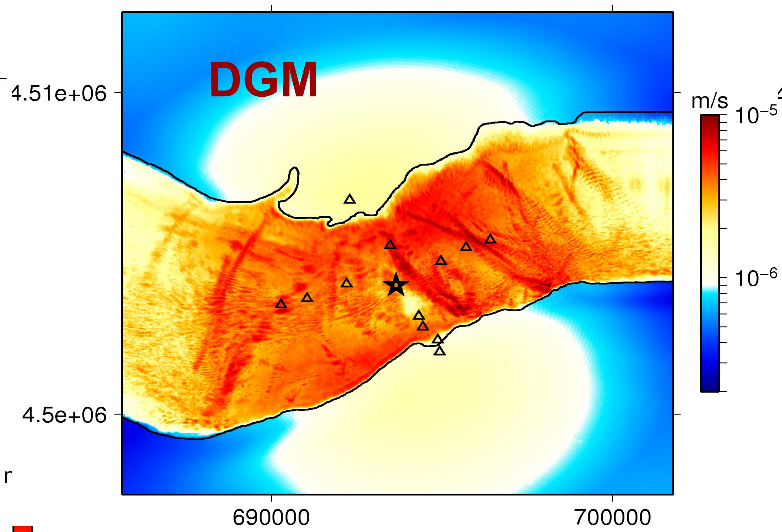


Rather consistent PGV maps

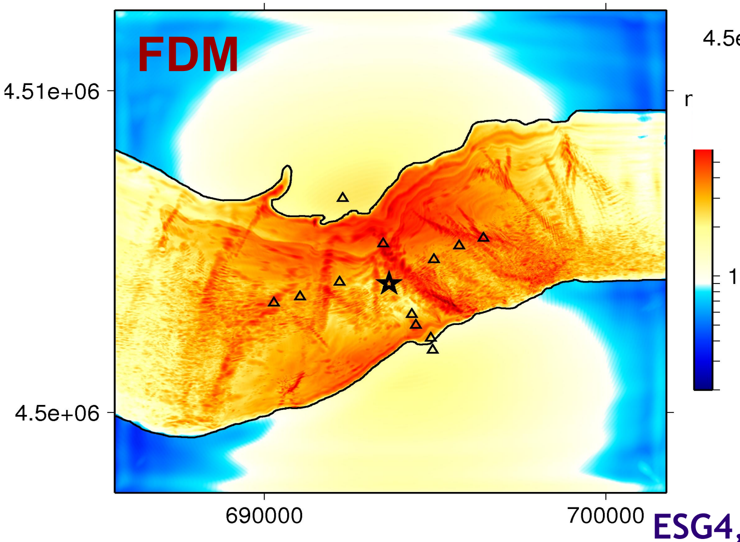
3D02 I2c FLAT PGV



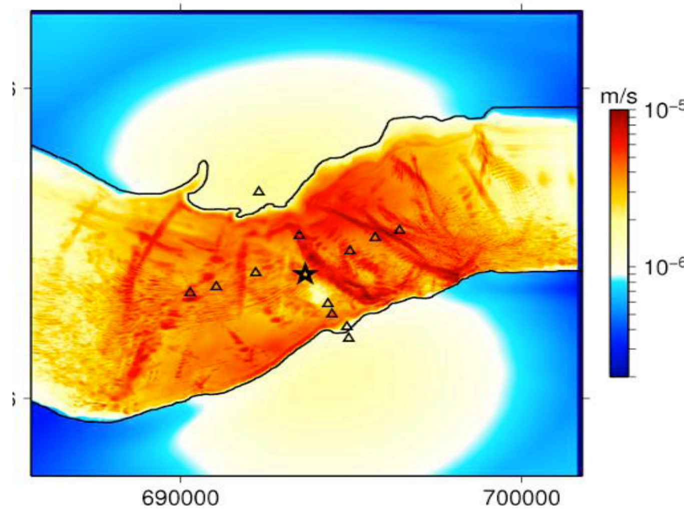
3D09 I2c FLAT PGV



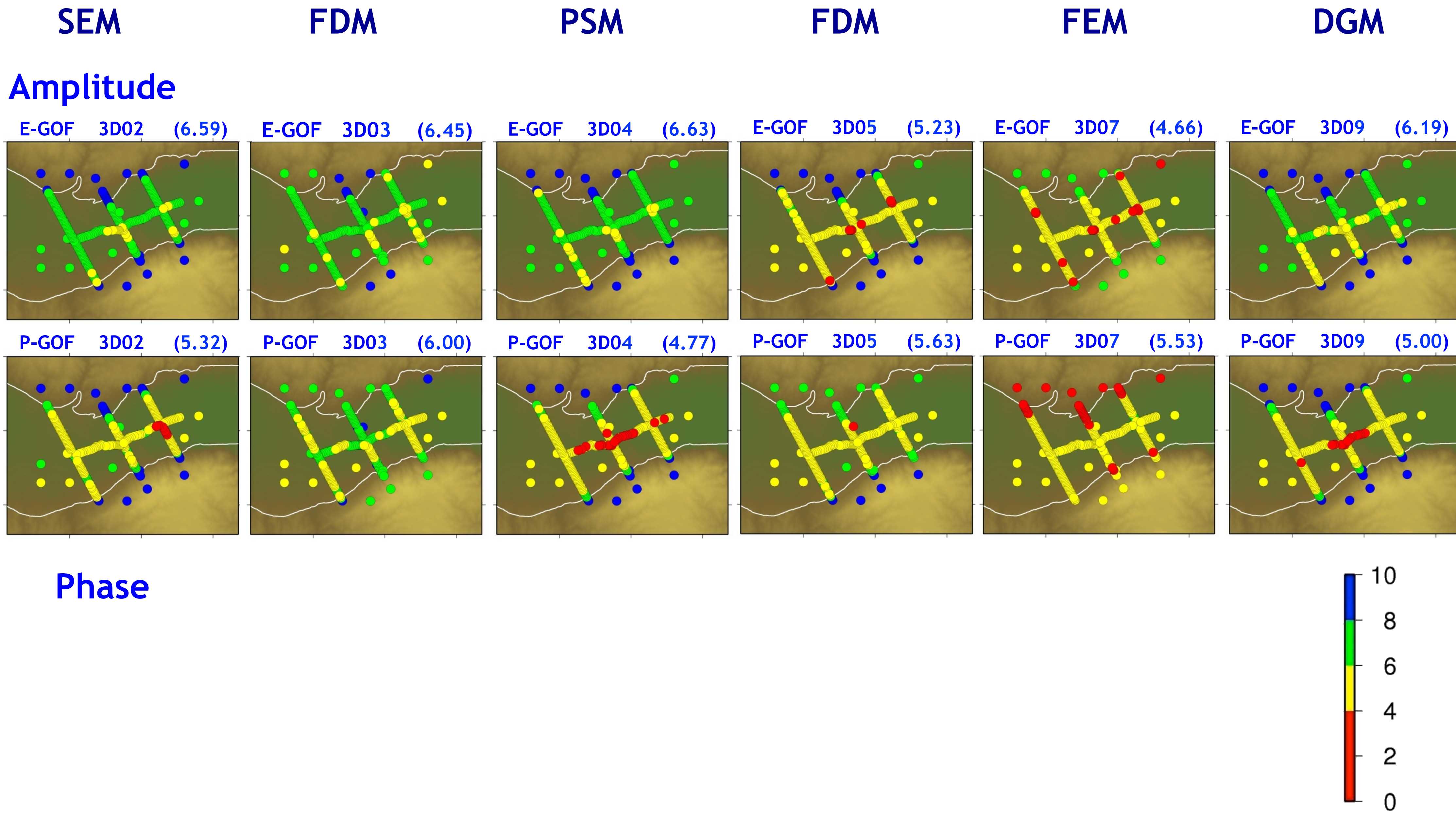
3D03 I2c FLAT PGV



3D04 I2c FLAT PGV

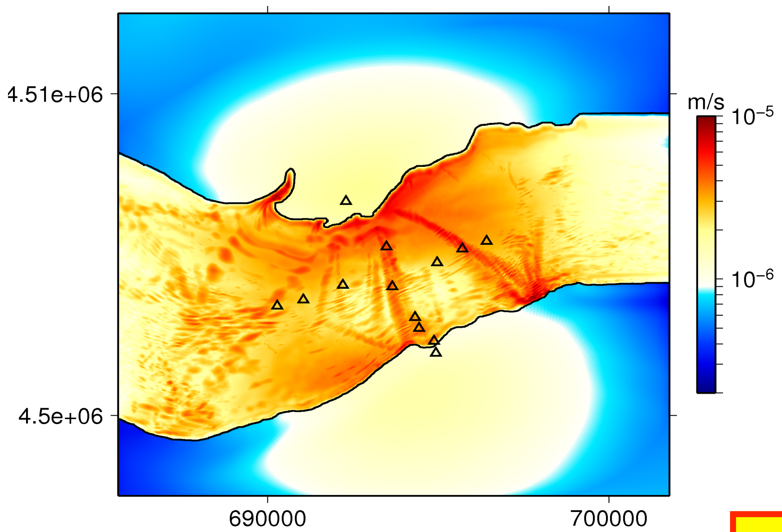


Bc (3H layers, no damping)

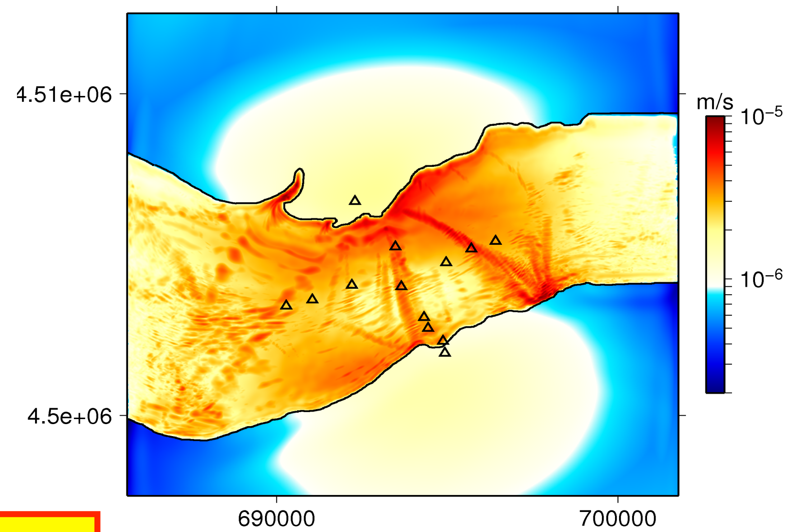


3D Verification 3 (Bb): 1D gradient, no damping

3D01 III1 FLAT PGV

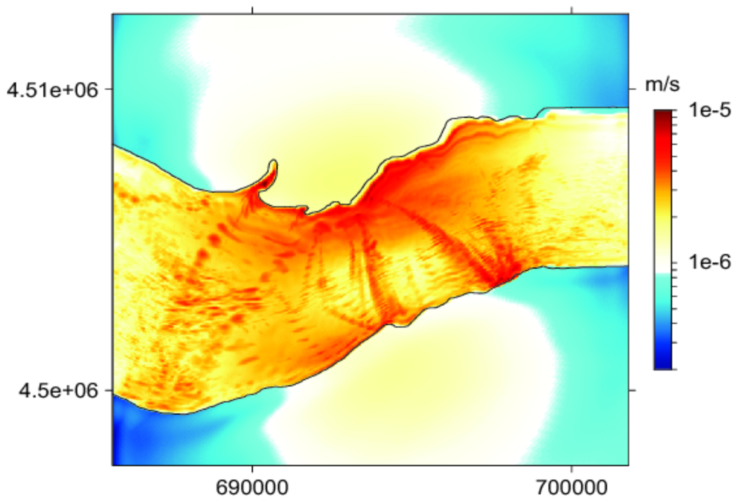


3D02 III1 FLAT PGV



Quite good !

3D07 III-1 FLAT PGV



3D09 III1 FLAT PGV