2-D and 3-D FEM Derived Elastic Green's Functions - Application to the coseismic and postseismic deformation of the 2005 M_w8.7 Nias-Simeulue, Sumatra earthquake

Ya-Ju Hsu[1,2], Mark Simons[2], Charles Wiliams[3], Emanuele Casarotti [2]

1. Institute of Earth Sciences, Academia Sinica, Taiwan
2. Division of Geological and Planetary Sciences, California Institute of Technology, USA
3. Department of Earth and Environmental Sciences, Rensselaer Polytechnic Institute, USA

Why use 3-D FEM?

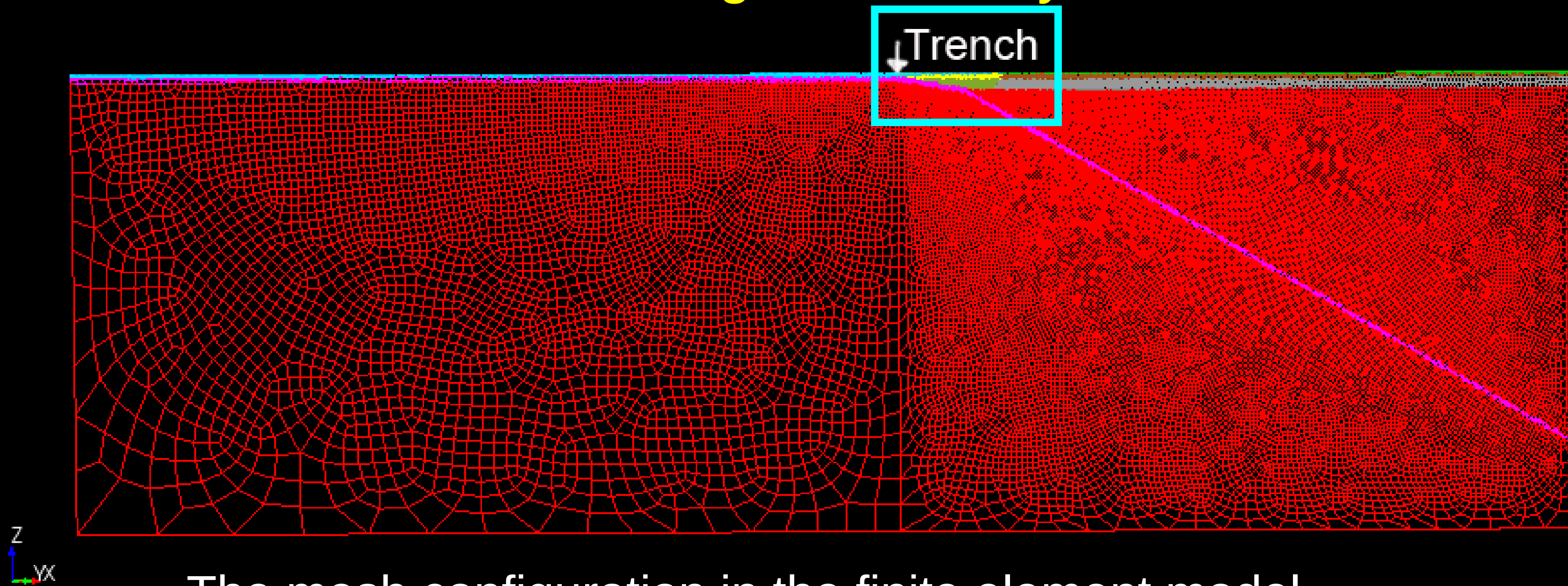
- Modeling coseismic slip distribution of 1999 M_w7.6 Chi-Chi Taiwan Earthquake show systematic misfits (~30 cm) between horizontal and vertical GPS displacements and between displacements from the foot and hanging walls.

- Understand the influence of 3D variation of material properties in inland thrust and megathrust in the subduction zone.

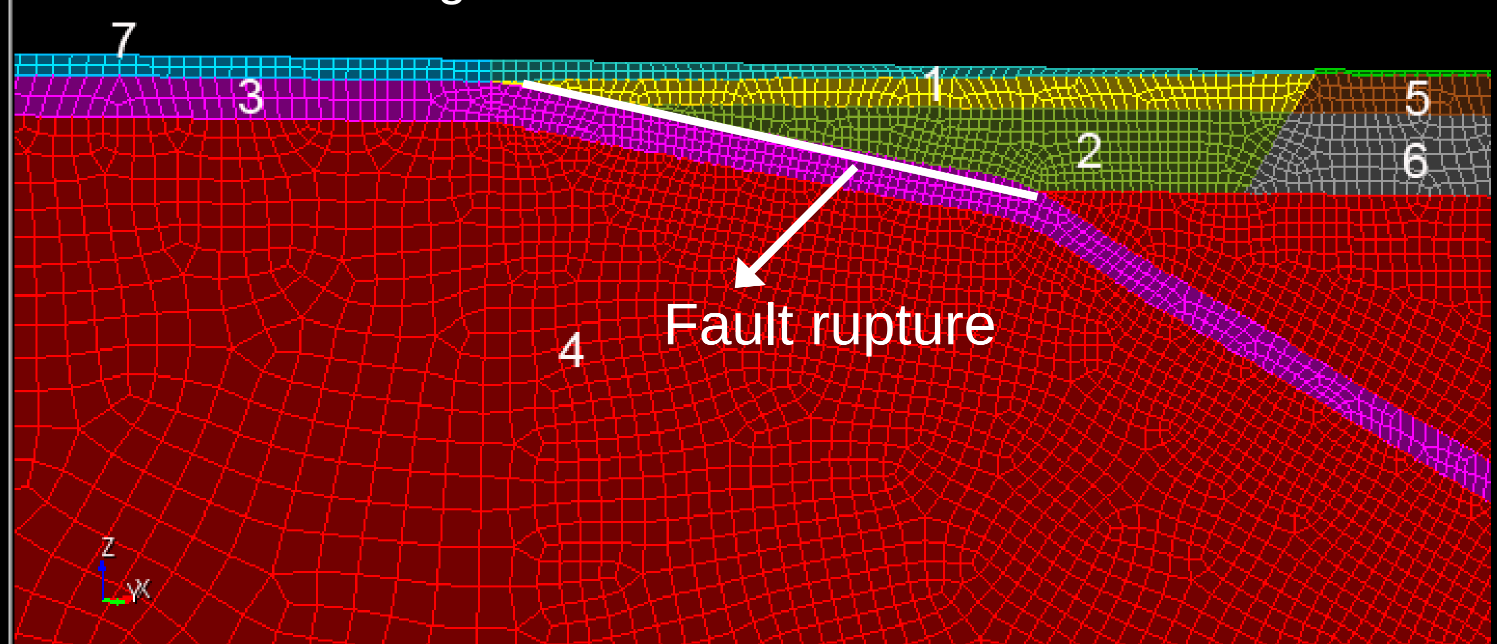
Long-term goal

- Build internally consistent continuum models that explain observations spanning the entire earthquake cycle including, the interseismic, coseismic, and postseismic periods.

2D FEM mesh generated by Cubit

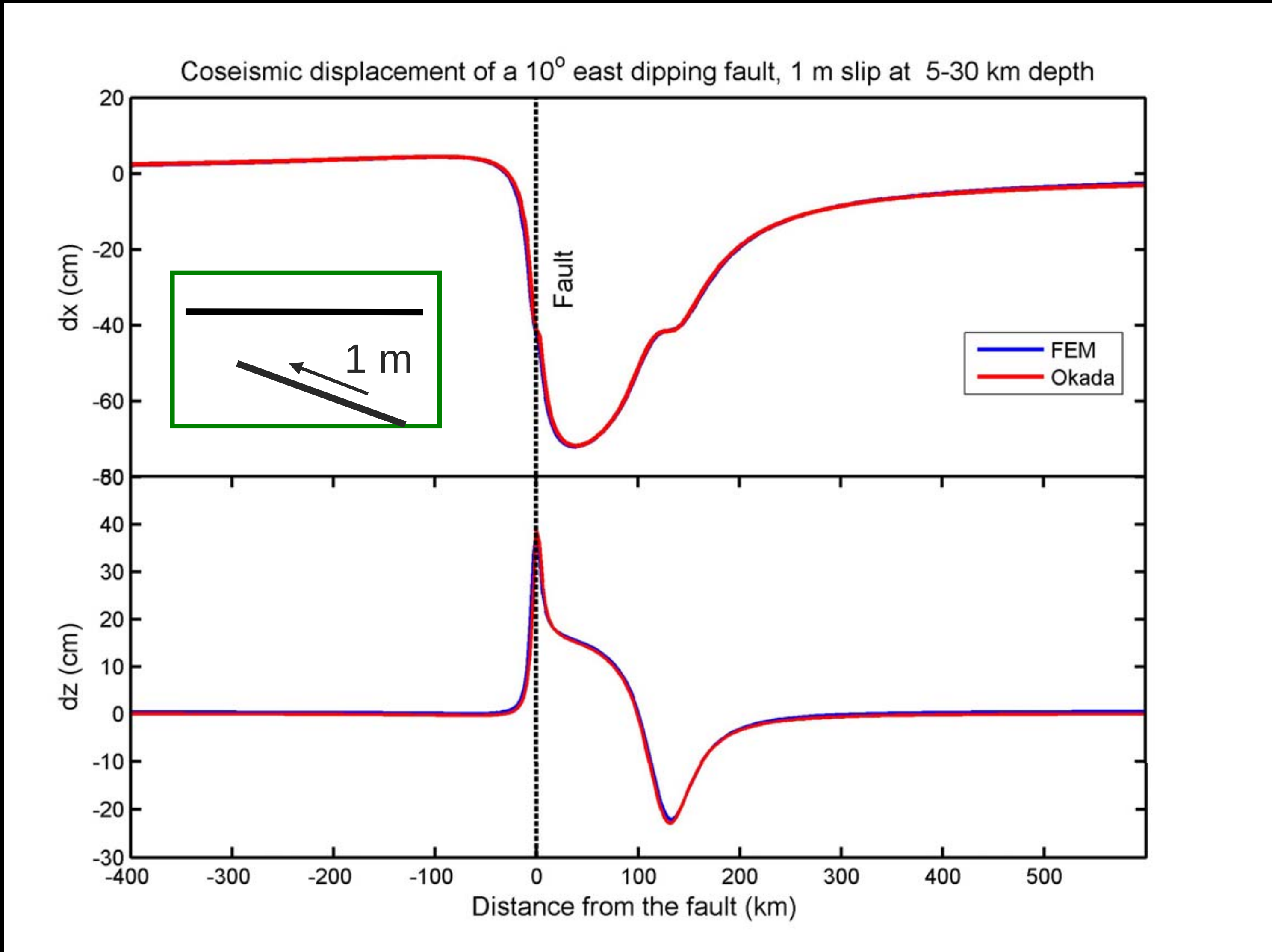


The mesh configuration in the finite element model



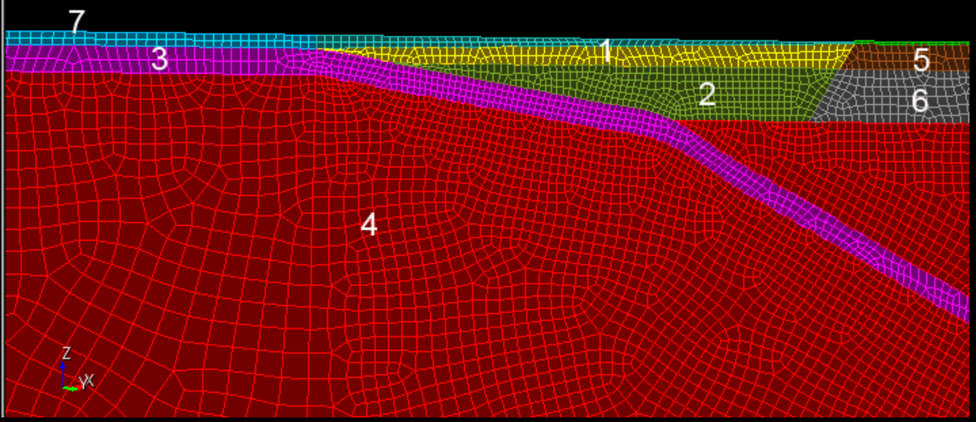
Benchmark : Okada vs. PyLith

1 m coseismic dip-slip at 5-28 km depth on the plate interface



The material properties in the heterogeneous model

$$G=V_p^2 * \rho /3, E=G*2(1+\nu)$$



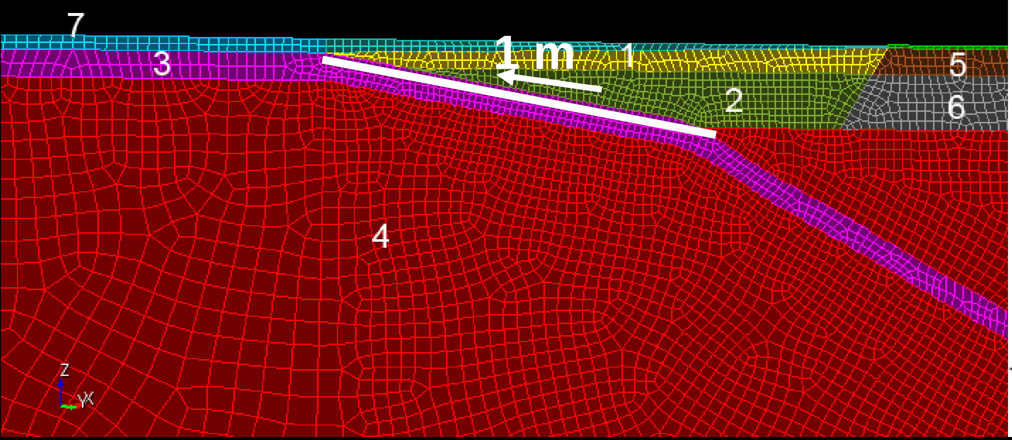
ID	Material	V_p (km/s)	Density ρ (cm3/g)	Poisson Ratio (ν)	Shear modulus G (1e10 Pa)	Young's modulus E (1e10 Pa)	$E/E_{smallest}$
1	Upper wedge	4.80	2.50	0.25	1.92	4.80	1
2	Lower wedge	6.60	2.70	0.25	3.92	9.80	2
3	Oceanic plate	8.00	3.00	0.25	6.40	16.00	3.3
4	Mantle	8.20	3.40	0.25	7.62	19.05	4
5	Upper crust	6.10	2.70	0.25	3.35	8.37	1.7
6	Lower crust	7.50	3.10	0.25	5.81	14.53	3
7	Sea	1.45	1.03	0.49	0.07	0.22	

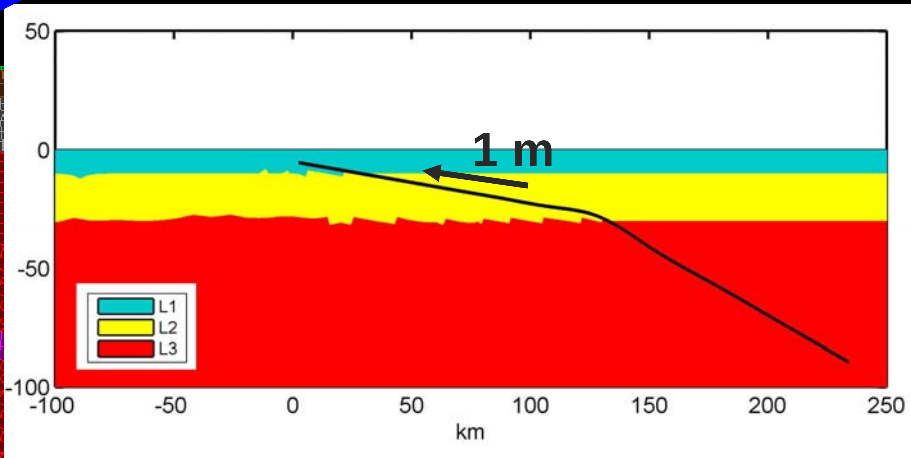
Use bathymetry, remove this region in 3D model

3D elastic structure

Elastic layered structure

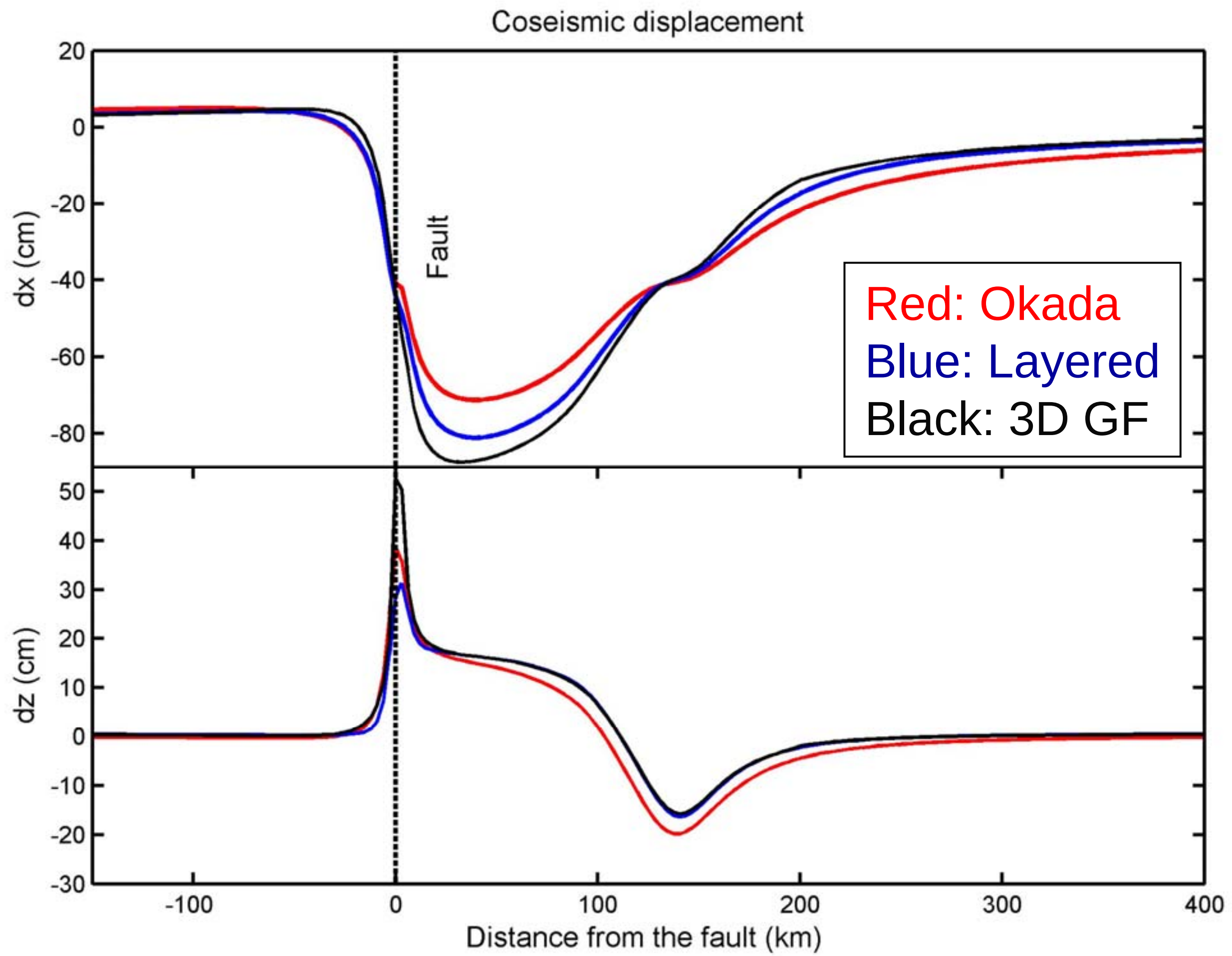
Taking average from 3D elastic structure

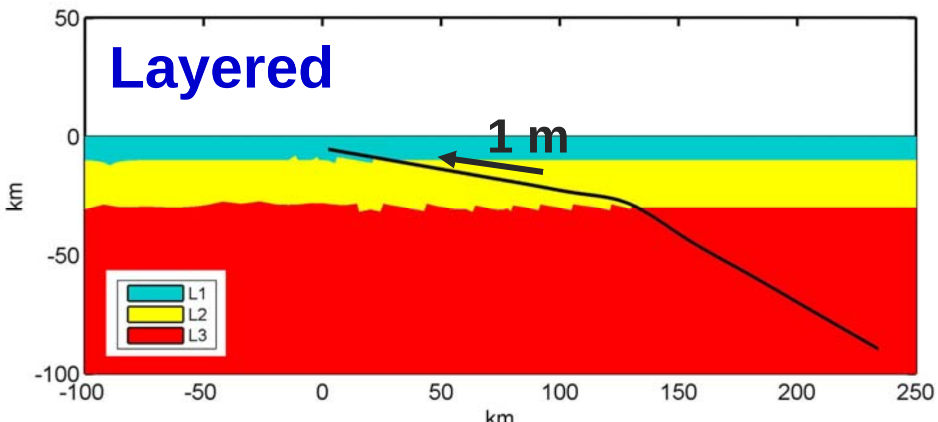


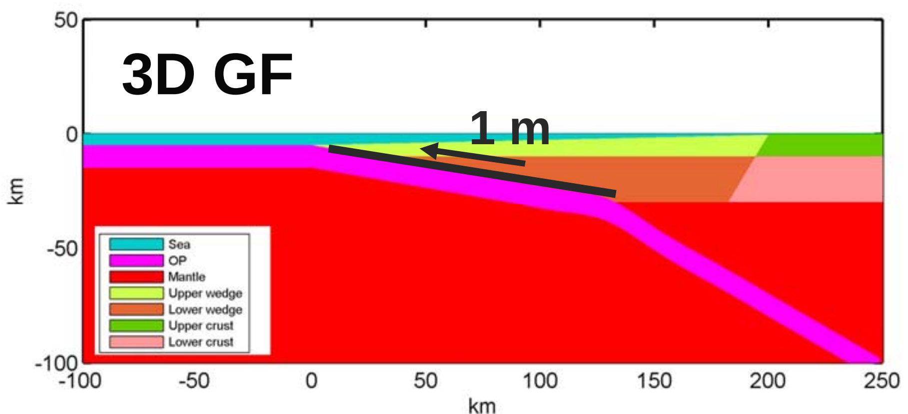


ID	Material	Vp (km/s)	density (cm^3/g)	Poisson ratio	Shear modulus G (1e10 Pa)	Young's modulus E (1e10 Pa)	
1	<10 km	4.45	2.62	0.25	1.73	4.32	1
2	10~30 km	7.58	3.05	0.25	5.83	14.58	3.4
3	>30 km	8.20	3.40	0.25	7.62	19.05	4.4

$E/E_{smallest}$

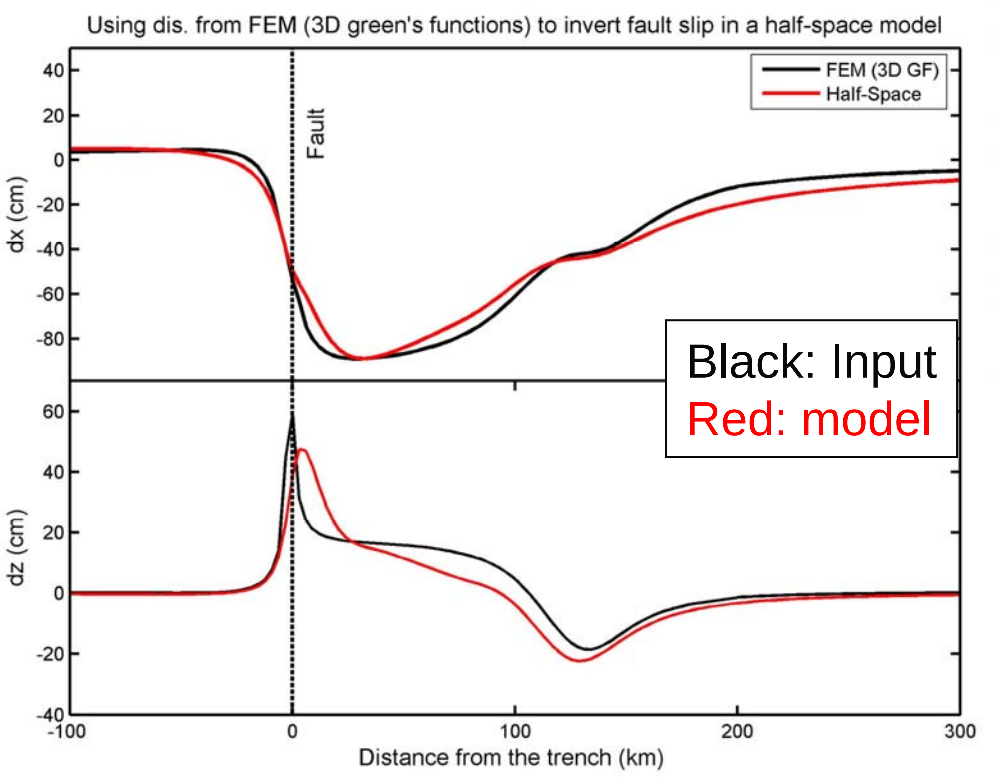

Coseismic displacement
dx (cm)
dz (cm)
Fault
Red: Okada
Blue: Layered
Black: 3D GF
Distance from the fault (km)

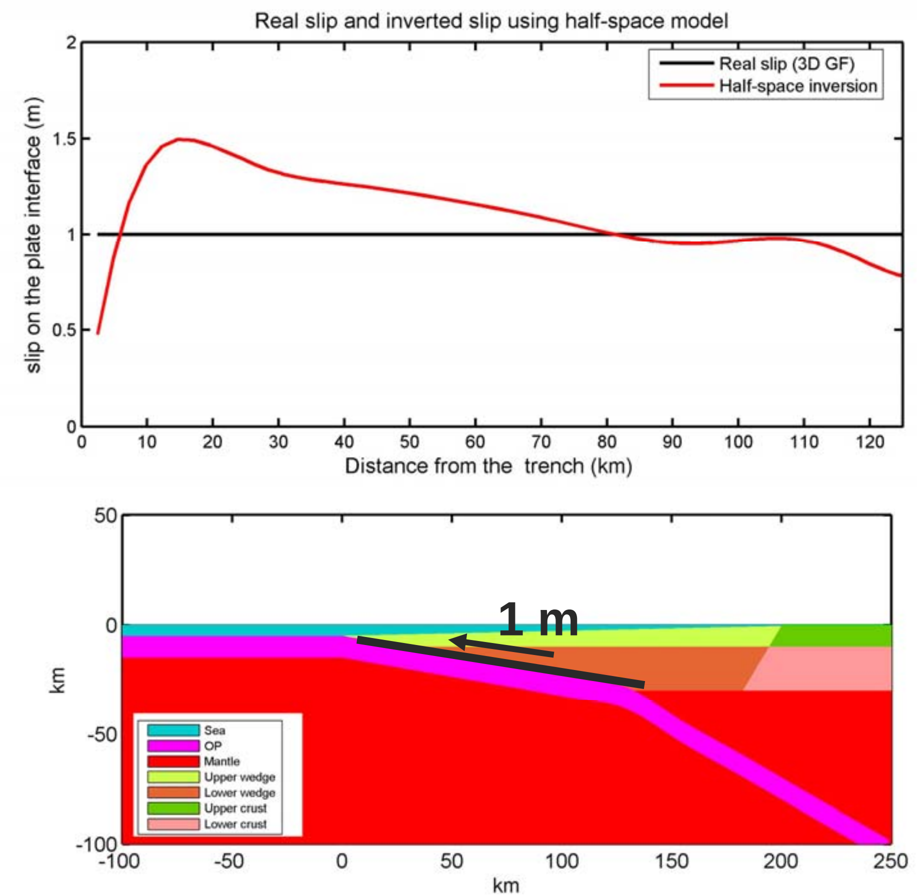

Layered
1 m
L1
L2
L3
km
km


3D GF
1 m
Sea
OP
Mantle
Upper wedge
Lower wedge
Upper crust
Lower crust
km
km

Using surface displacements predicted from a heterogeneous model to invert for fault slip in a elastic half-space earth

Fault geometry is identical to the input model

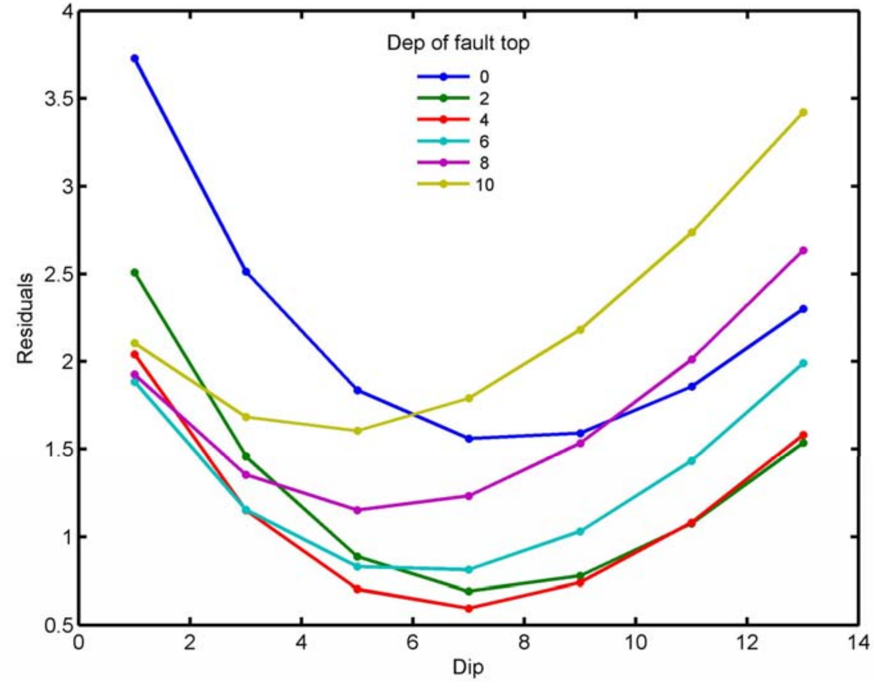


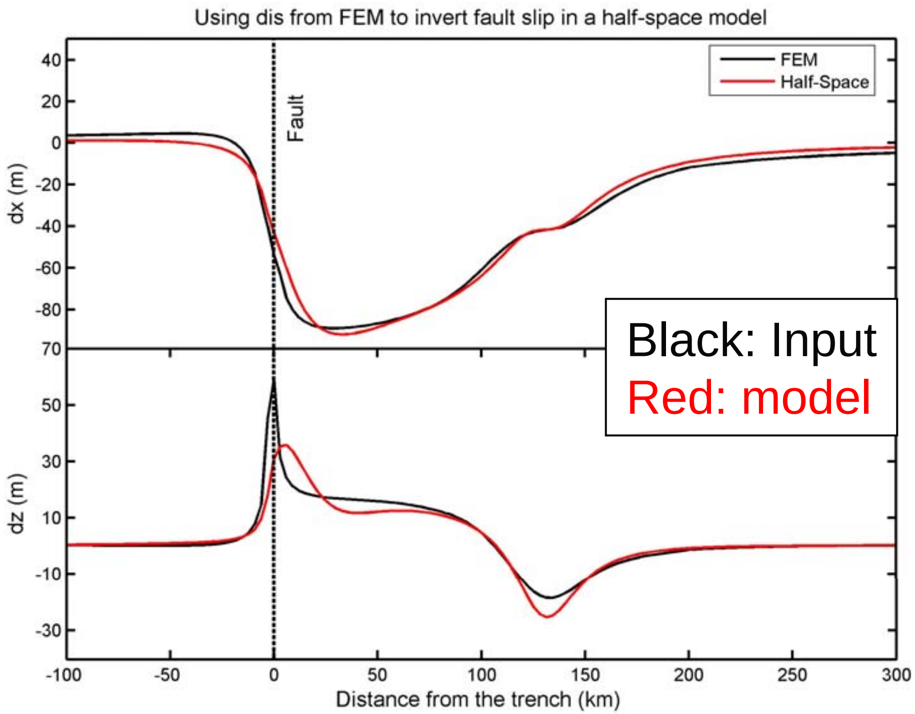


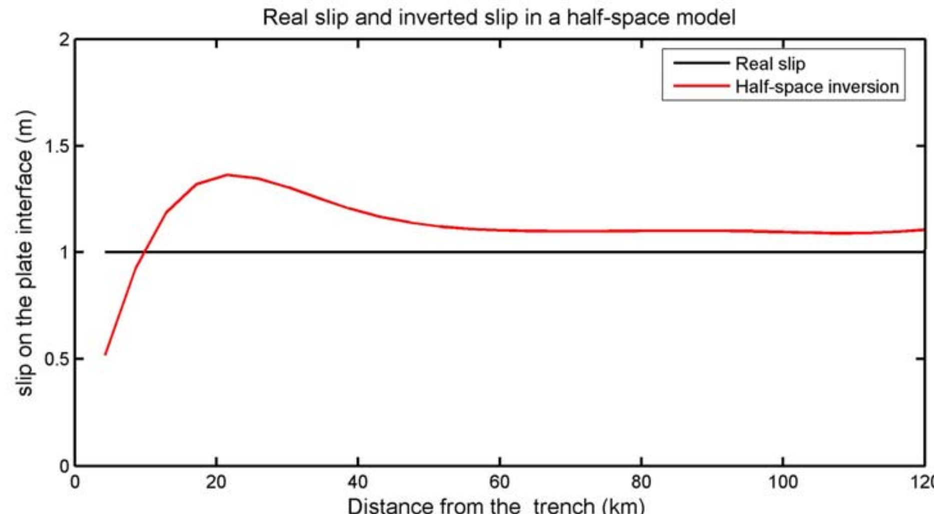
It is difficult to fit both horizontal and vertical displacements without systematic residuals on two sides of the fault

Invert for the optimal fault geometry and fault slip

The optimal fault dip and top depth is 7° and 4 km, those fault parameters are different from 10° and 5 km in the input model







What we have learned from 2D model?

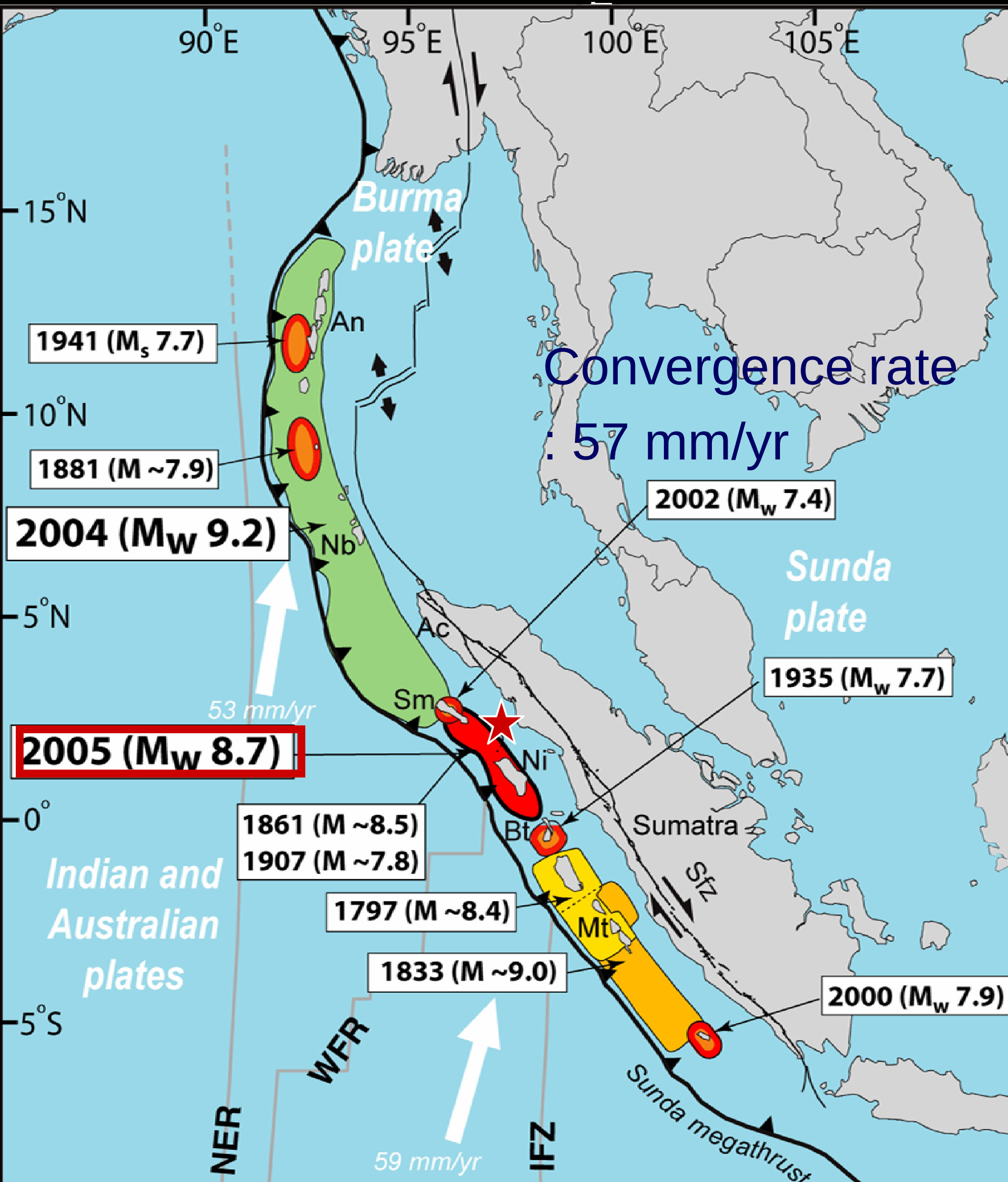
- Green's Functions in a heterogeneous model are important for inverting fault slip distribution. The difference of surface displacement calculated from homogeneous and heterogeneous models can be as large of 25%.
- Ignoring the spatial variation of material properties leads to systematic misfits in surface horizontal and vertical displacements.
- Inverting for fault slip distribution with the assumption of a homogeneous and isotropic earth results in inaccurate fault slip distributions and fault geometries in our synthetic tests.

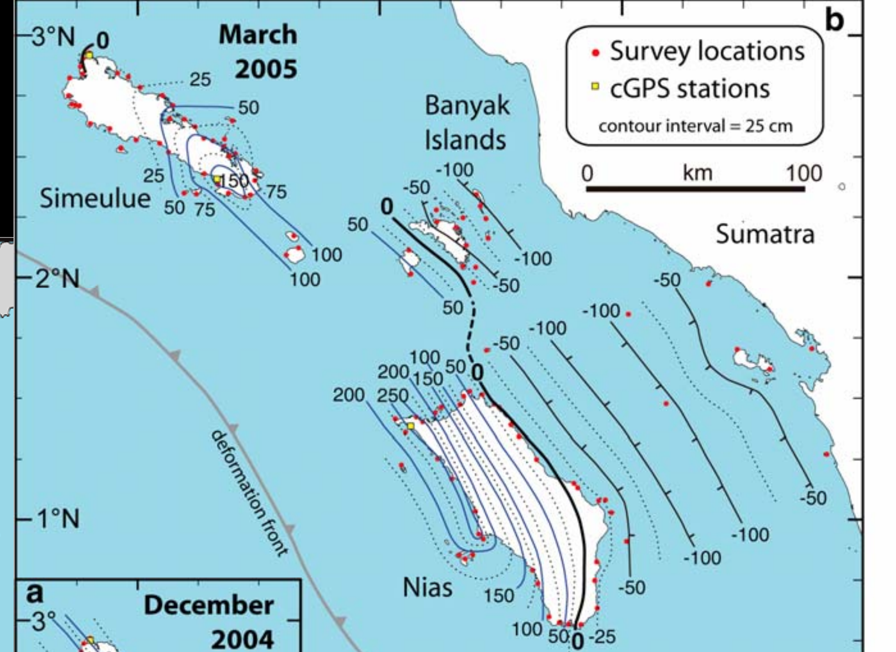
From 2D to 3D elastic model

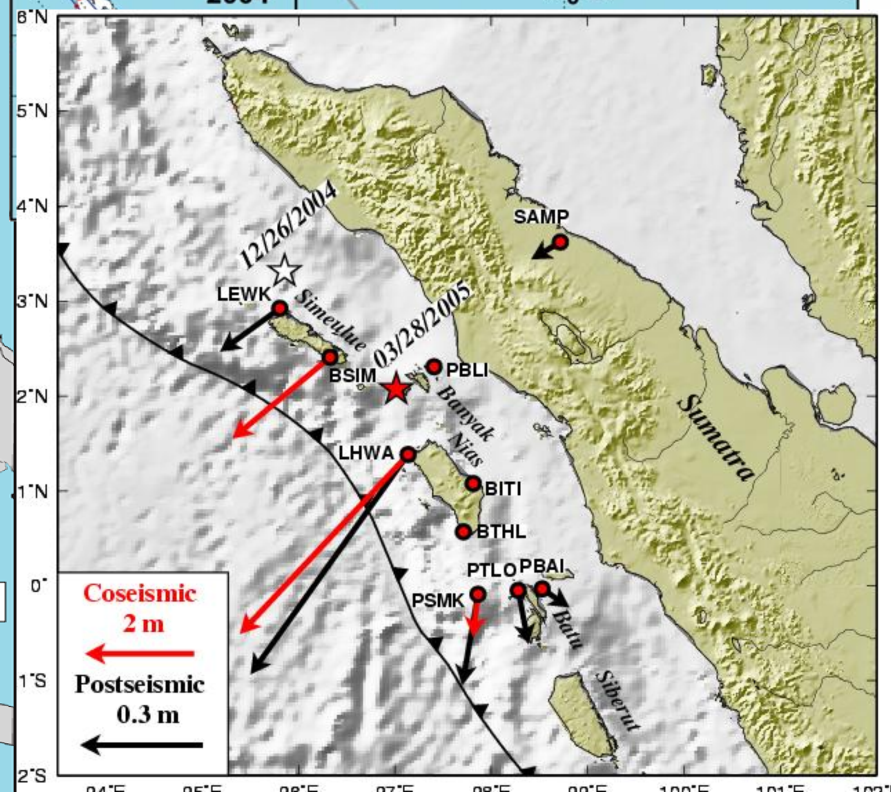
2005 Nias-Simeulue, Sumatra Earthquake

Nias-Simeulue Earthquake

(Briggs et al., 2006, Hsu et al., 2006)

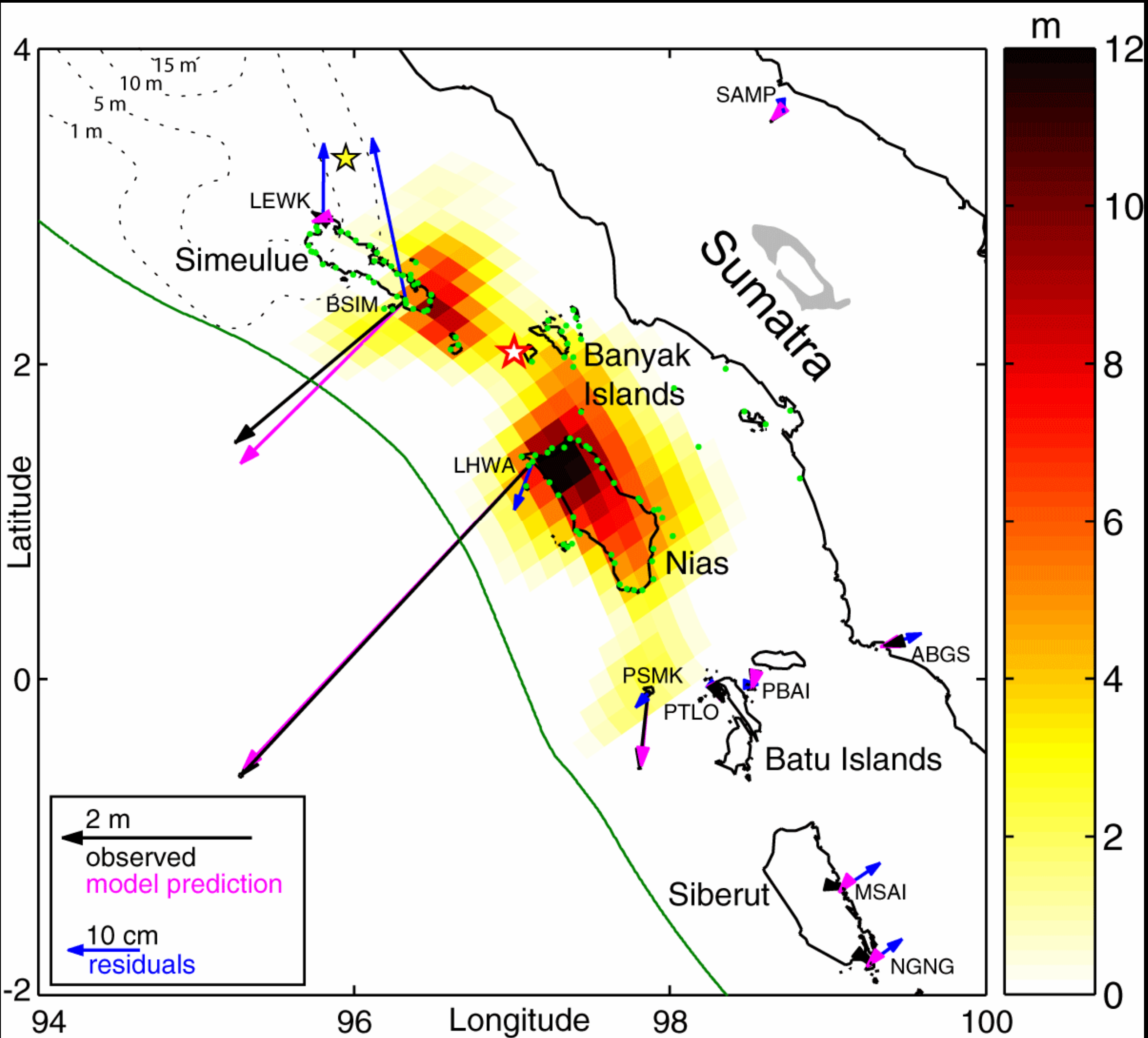






Coseismic slip distribution

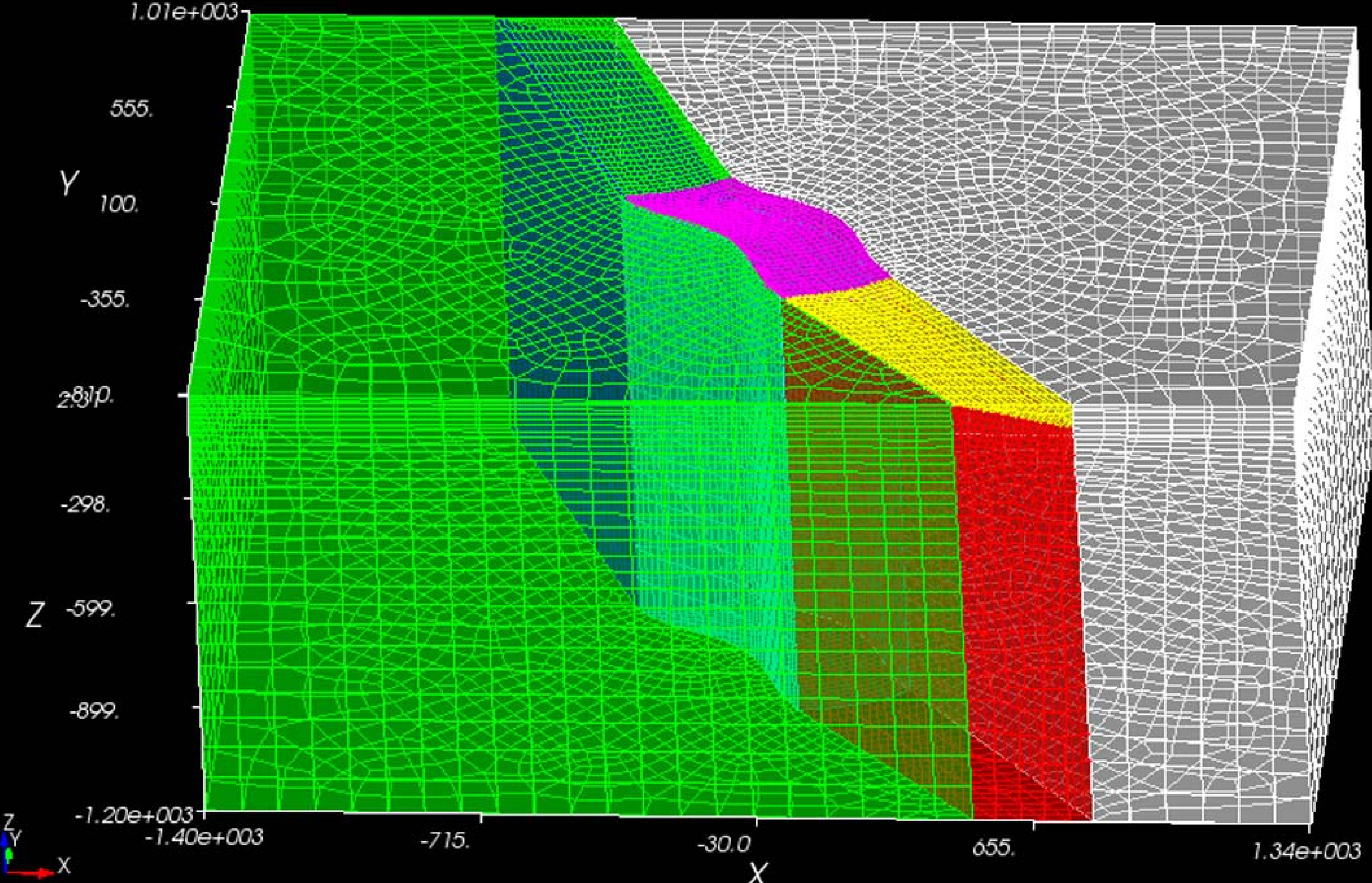
Data: 102 coral measurements + 16 GPS sites



Generate finite element mesh using Cubit

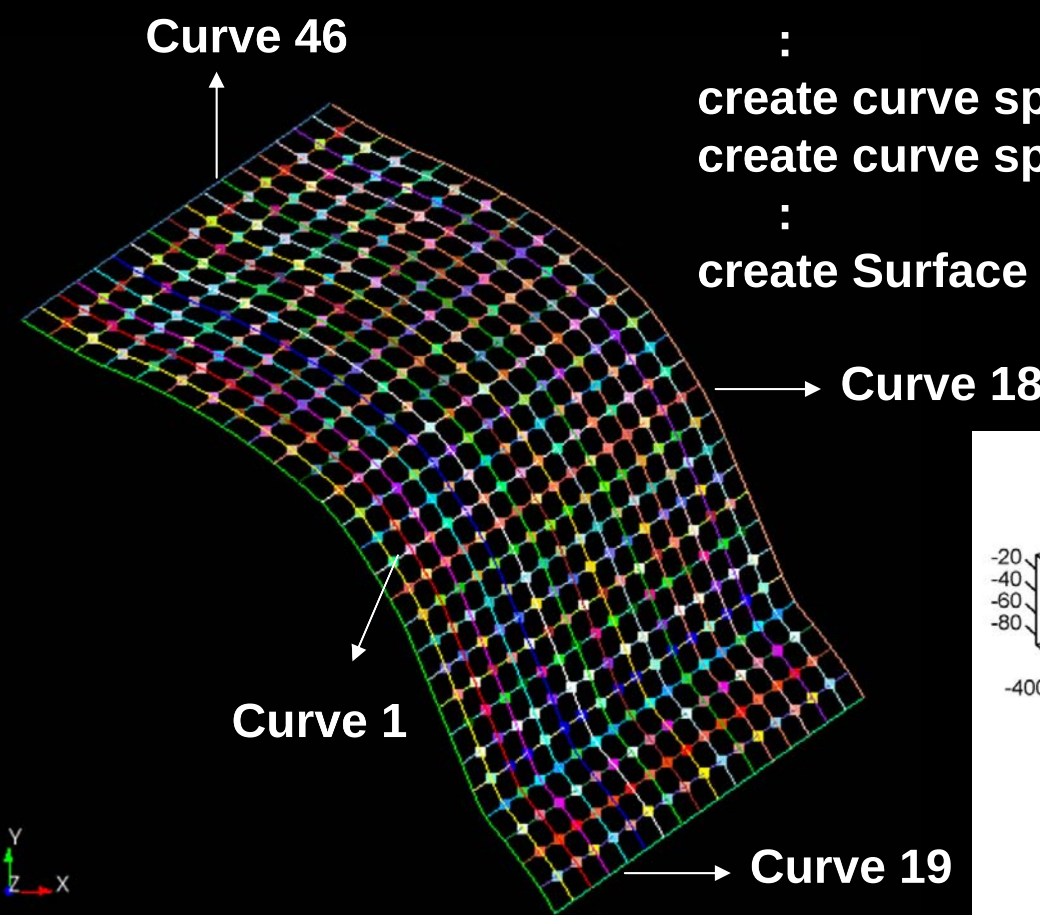
- Construct the fault plane (Spline)
- Divide geological regions
- Meshing

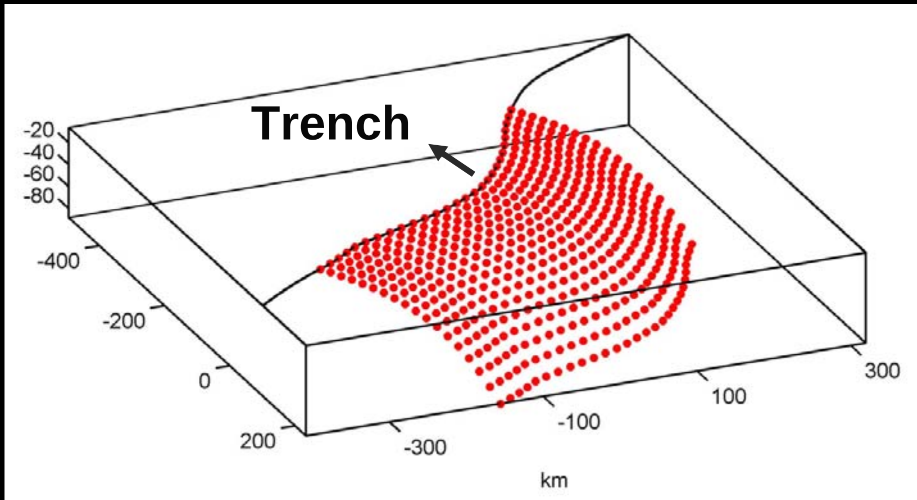
68,412 nodes, 64,662 elements



Construct the fault geometry

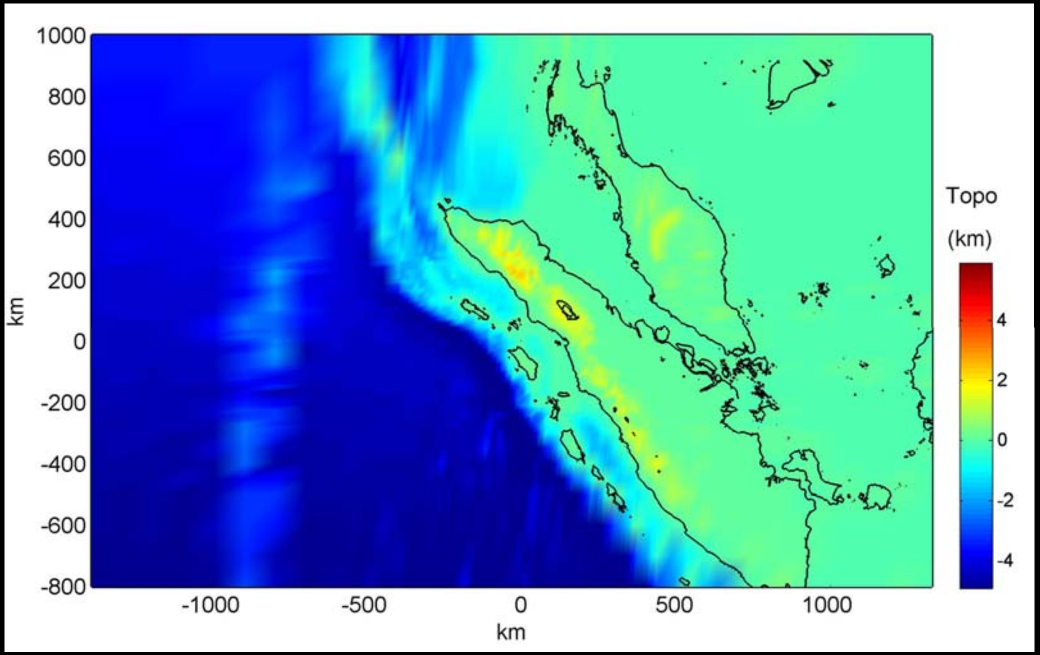
create vertex 24.6017 -301.5747 -6.0000
create vertex 14.3240 -284.4255 -6.0000
create vertex 2.6541 -268.2099 -6.0000
: : : :
: : : :
create curve spline vertex 1 to 28
create curve spline vertex 29 to 56
: : : :
create Surface Net U Curve 1 to 18 V Curve 19 to 46



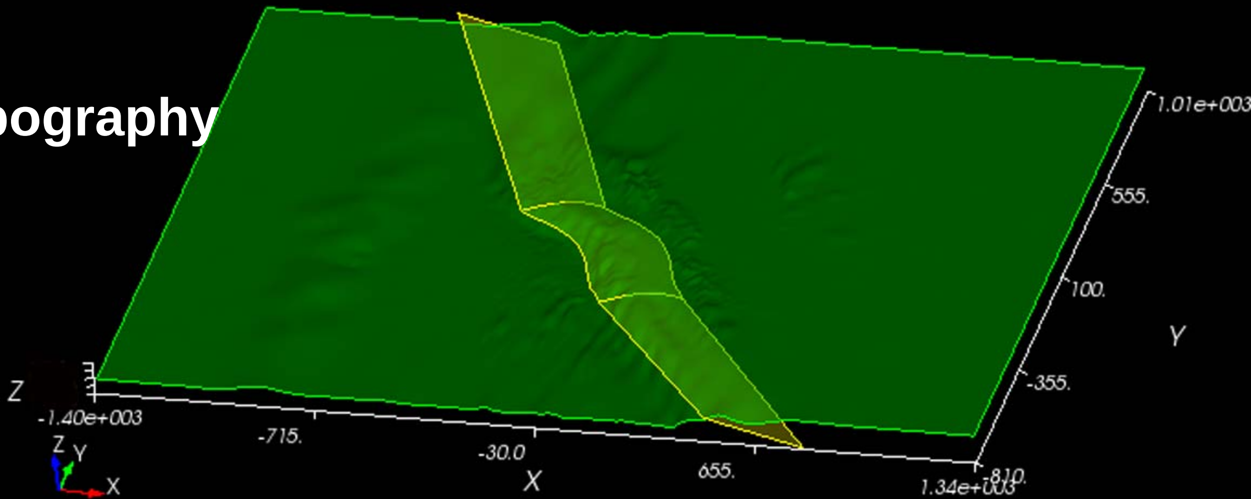


Divide geological regions (1)

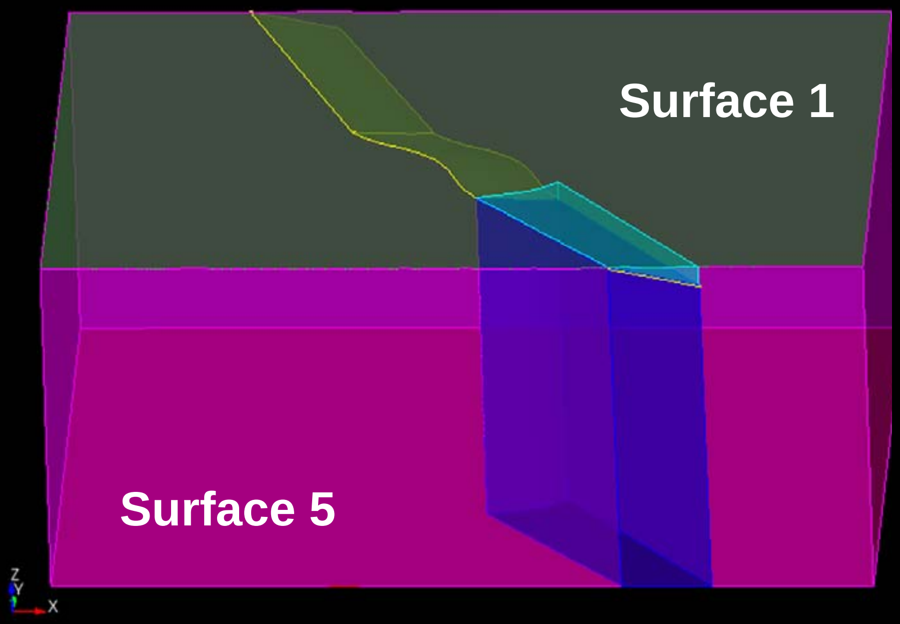
Construct the top surface using Python script " surface.py " (by Emanuele Casarotti)

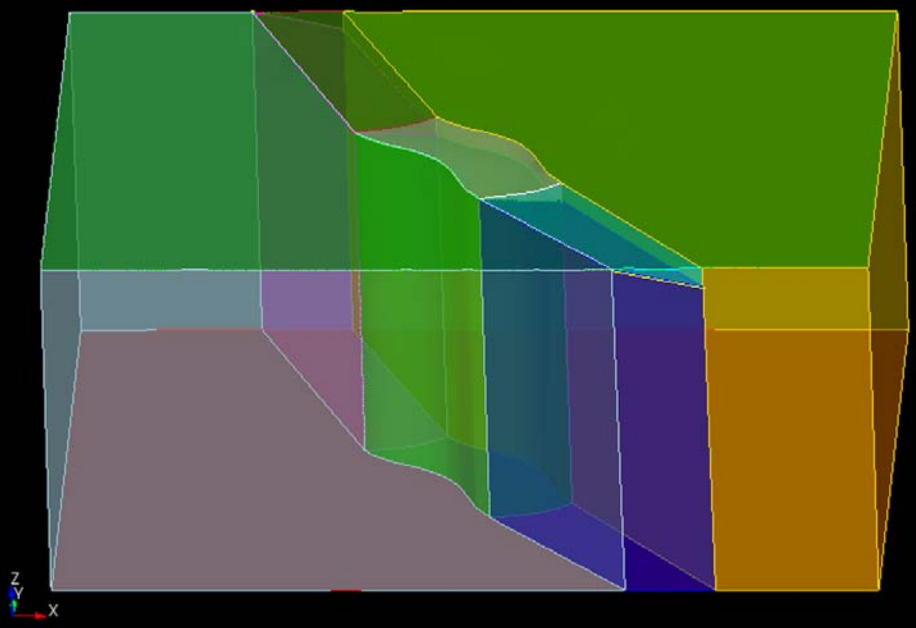


Combine bathymetry, topography and the fault structure



Divide geological regions (2)

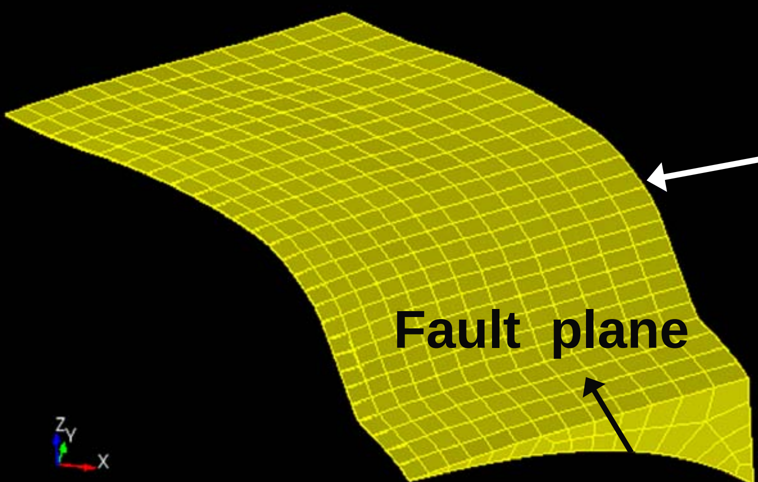


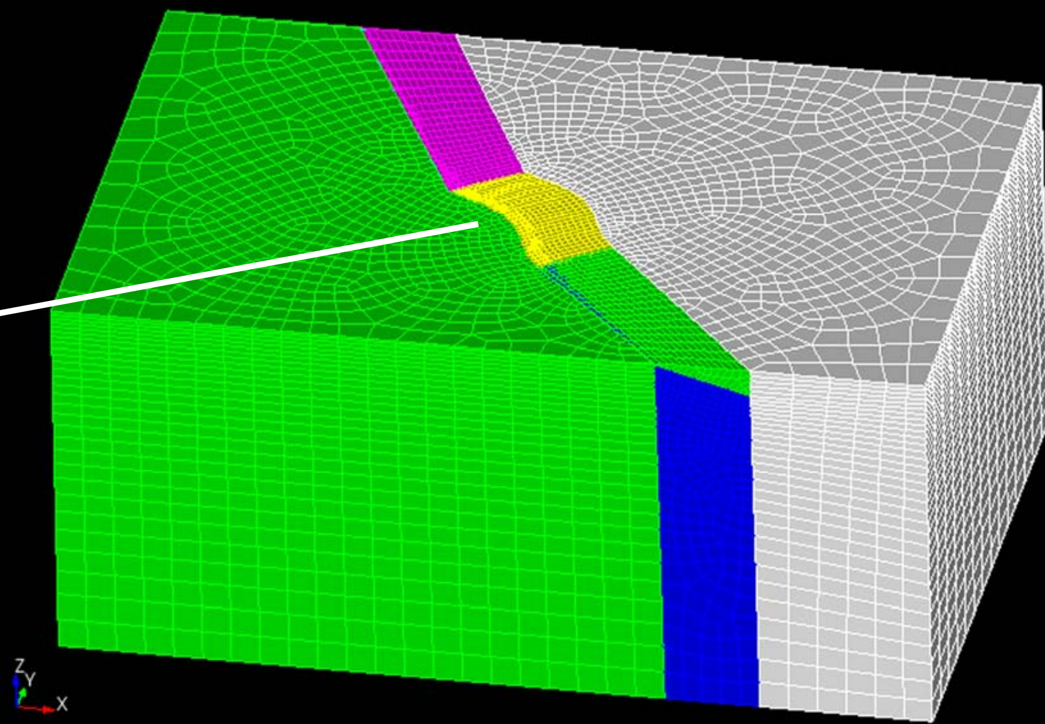


create planar surface with plane zplane offset -1200
create volume loft surface 1 5
webcut volume 4 sweep surface 3 vector 0 0 1 through_all
webcut volume 4 sweep surface 3 vector 0 0 -1 through_all
:   :   :   :
:   :   :   :
imprint all
merge all
compress all

Meshing

 # mesh volume 2
curve 11 scheme bias fine size 15 coarse size 25 start vertex 1
: : :
curve 12 scheme bias fraction 0.065 start vertex 12
curve 13 interval 27
curve 13 scheme equal
surface 5 scheme pave
mesh surface 5
volume 2 scheme Sweep source surface 5 target surface 7 rotate off
volume 2 sweep smooth Auto
mesh volume 2





Post processing

Generate input files for PyLITH (Matlab scripts)

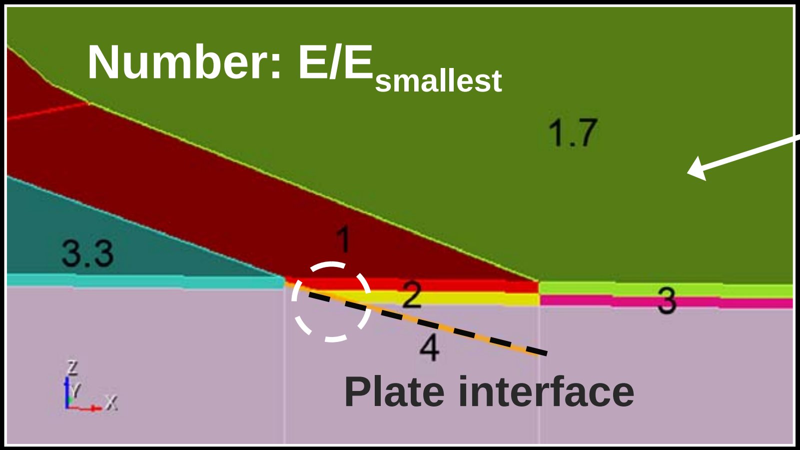
*.coord

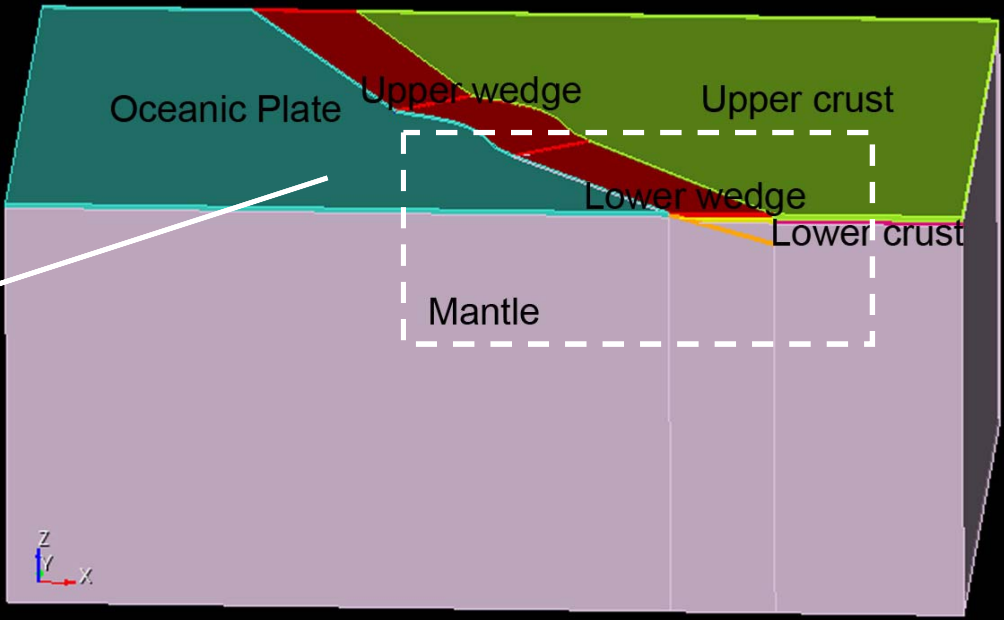
*.bc (displacement=0 on side and bottom walls)

*.connect

*.split

3D Material properties





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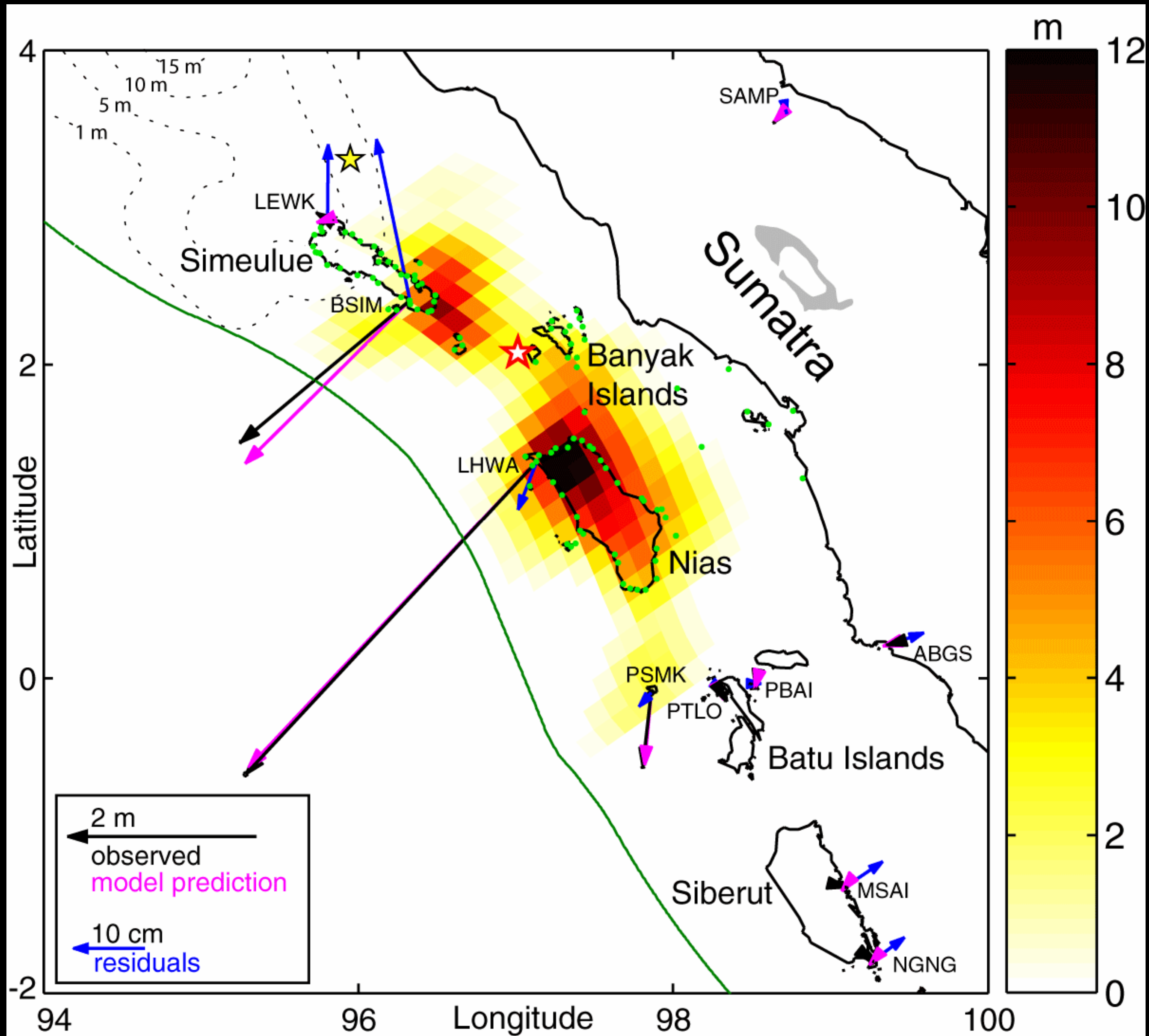
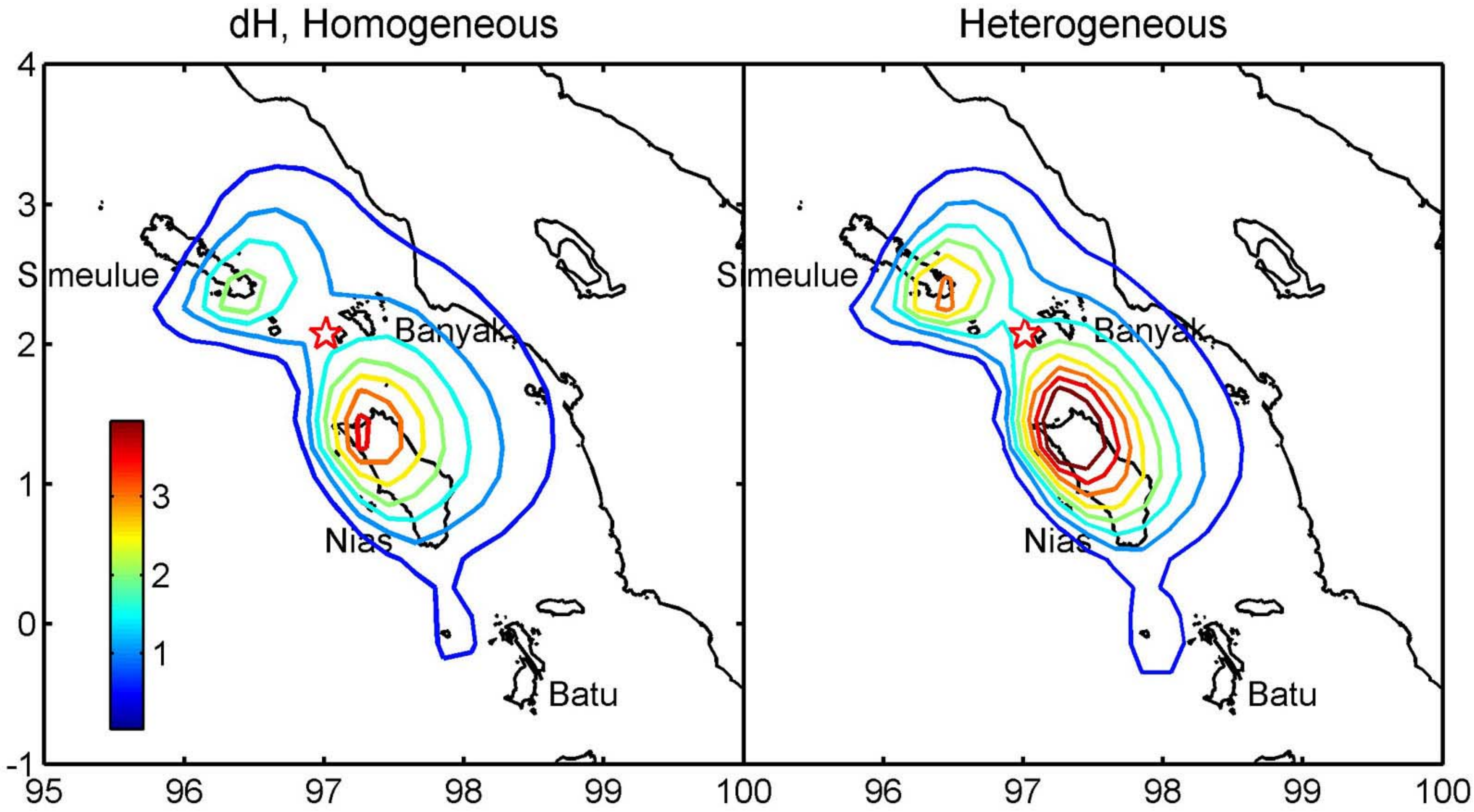
4	Mantle	8.20	3.40	0.25	7.62	19.05	4
5	Upper crust	6.10	2.70	0.25	3.35	8.37	1.7
6	Lower crust	7.50	3.10	0.25	5.81	14.5	3

Coseismic slip distribution



prescribe Nias-Simeulue coseismic slip (Hsu et al. 2006) at each fault node to estimate surface displacements in an uniform model and a 3D elastic model

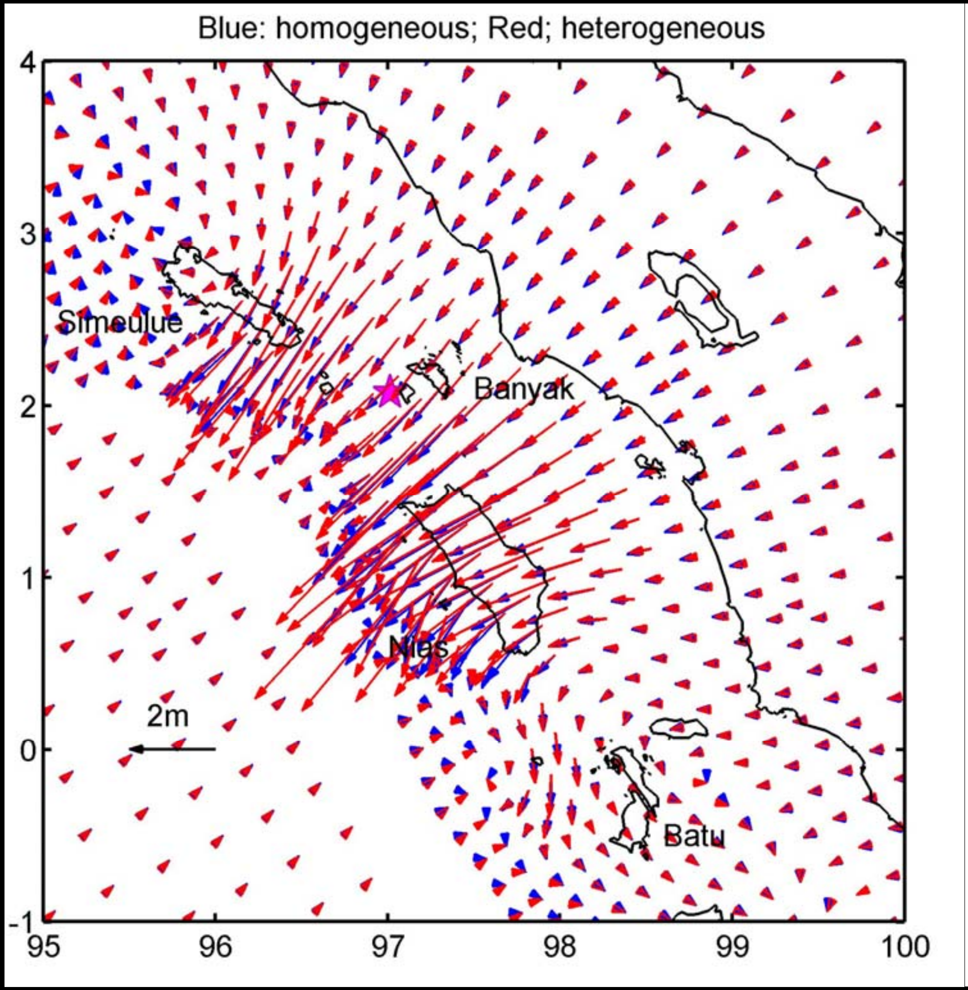


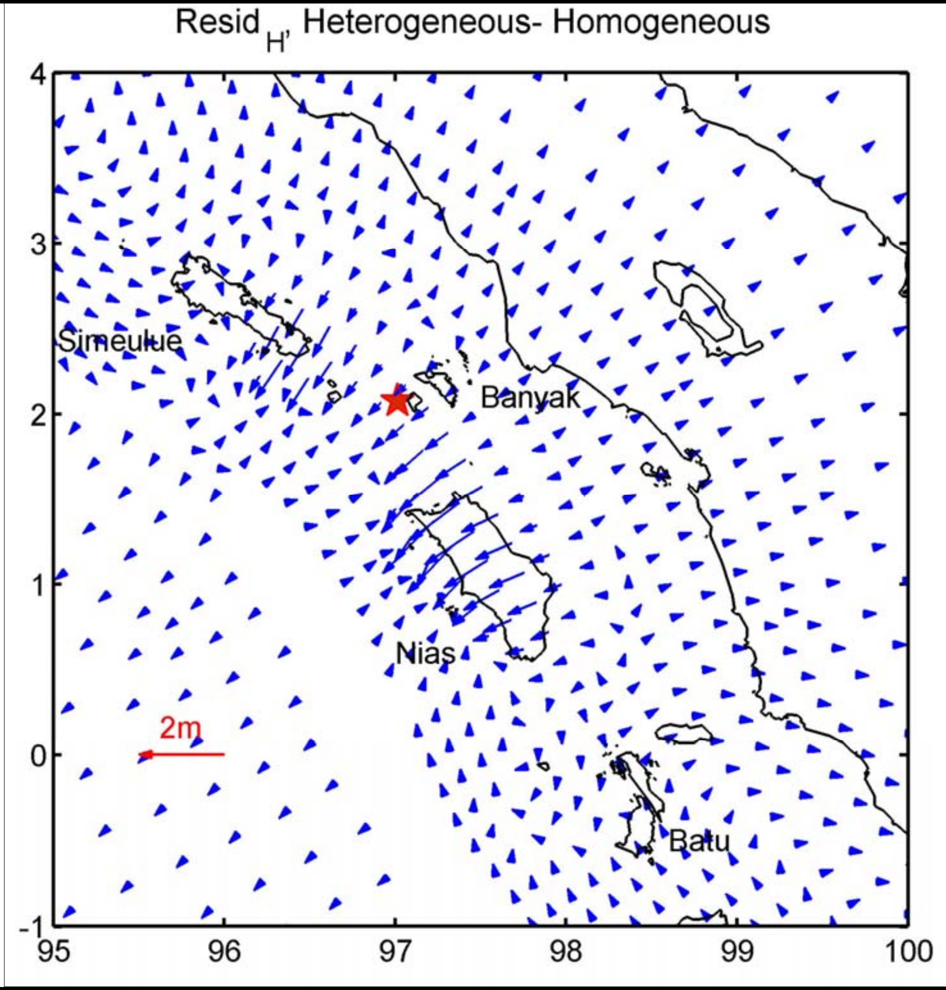
Horizontal Displacement

Homogeneous

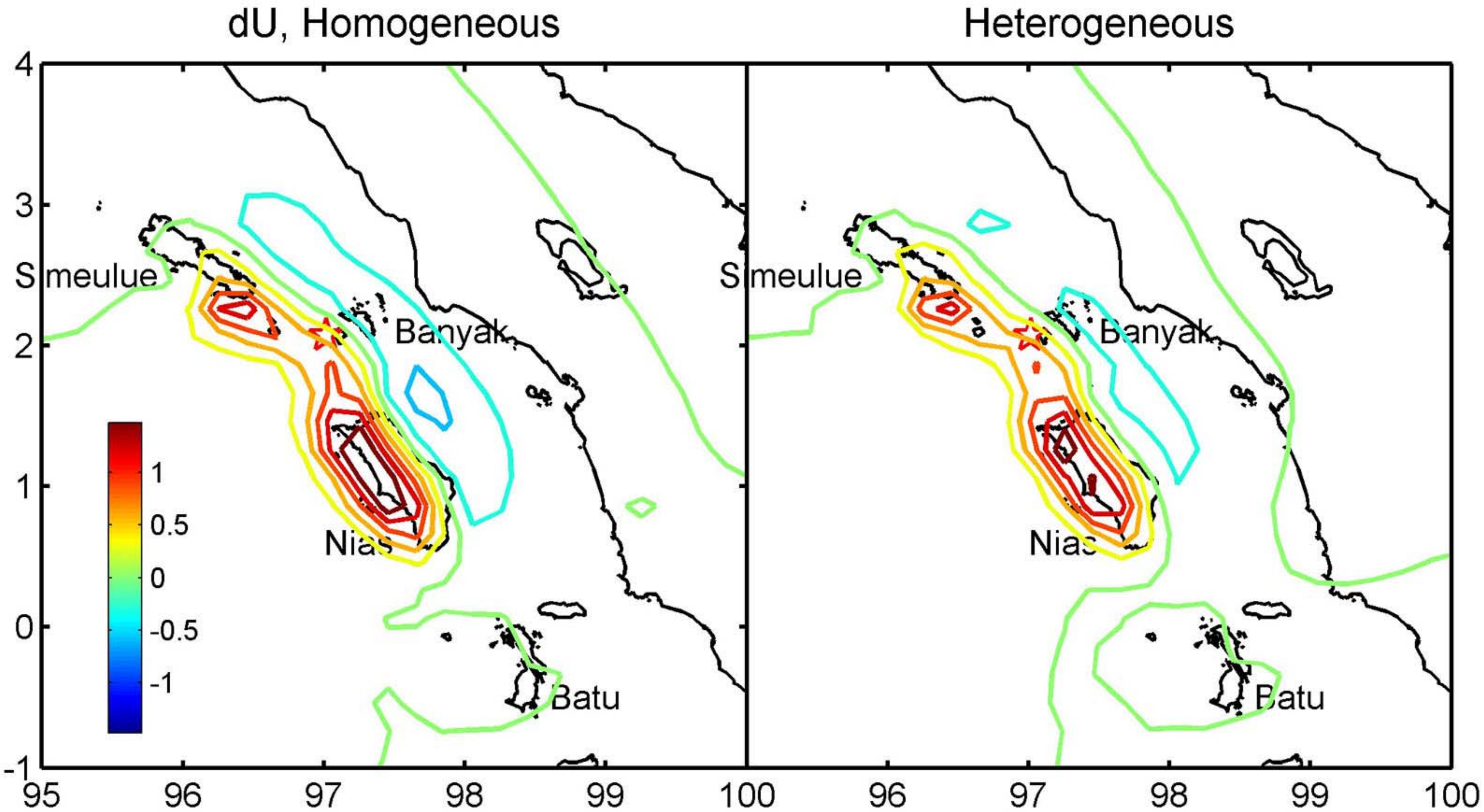
Heterogeneous

$H_{heterogeneous} - H_{homogeneous}$



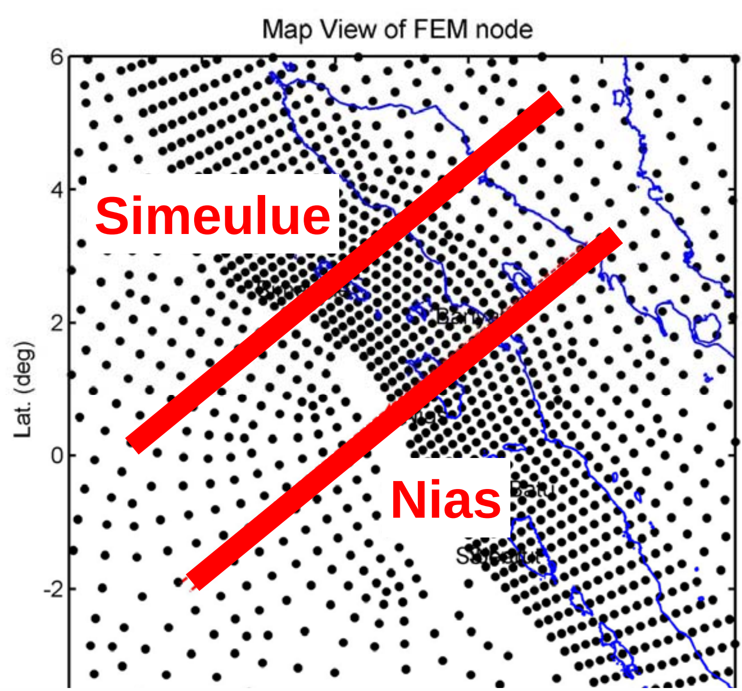


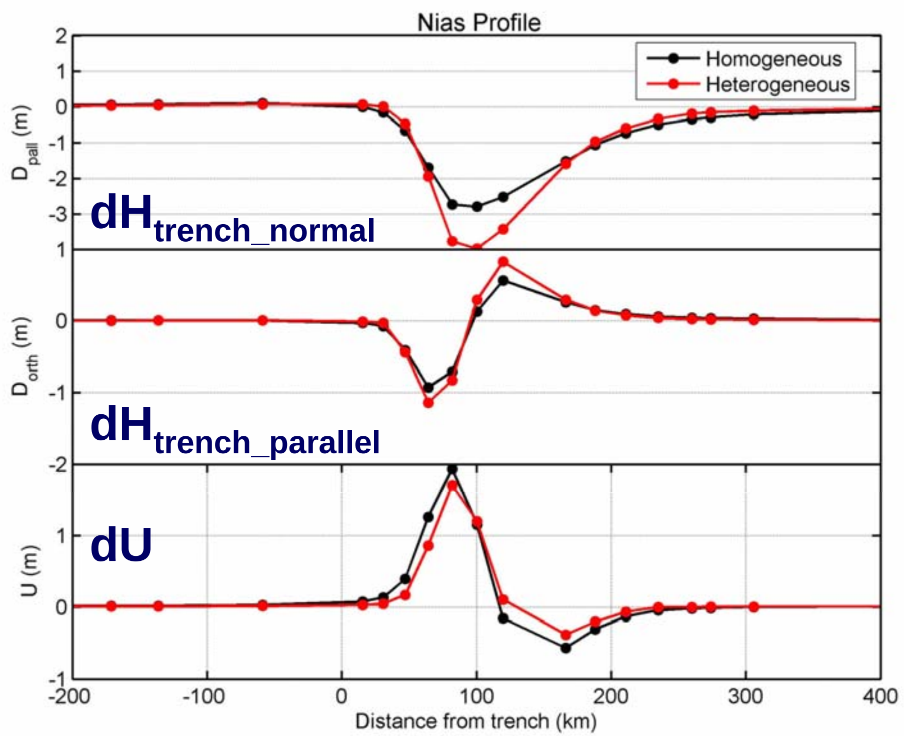
Vertical displacement

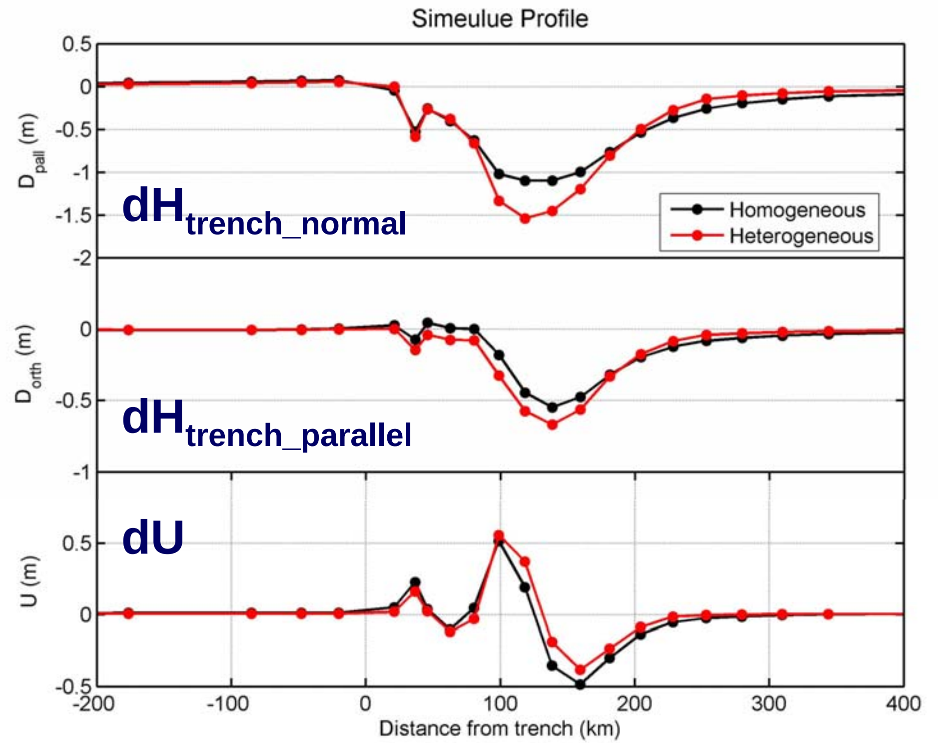


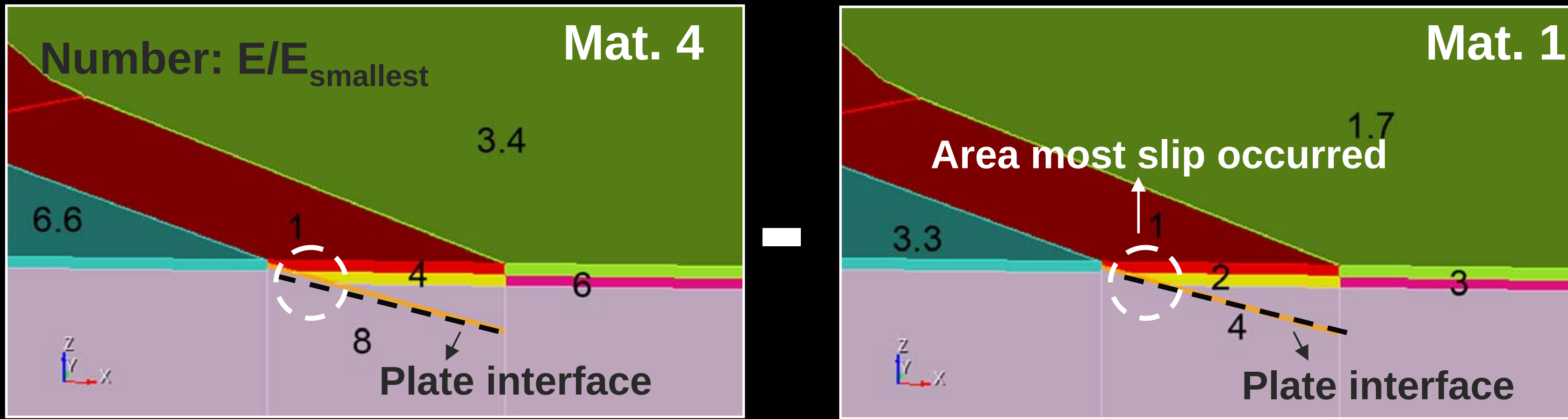
NE-SW cross section across Nias & Simeulue

Heterogeneous model has larger horizontal displacement and less vertical displacement comparing to those in elastic half-space model

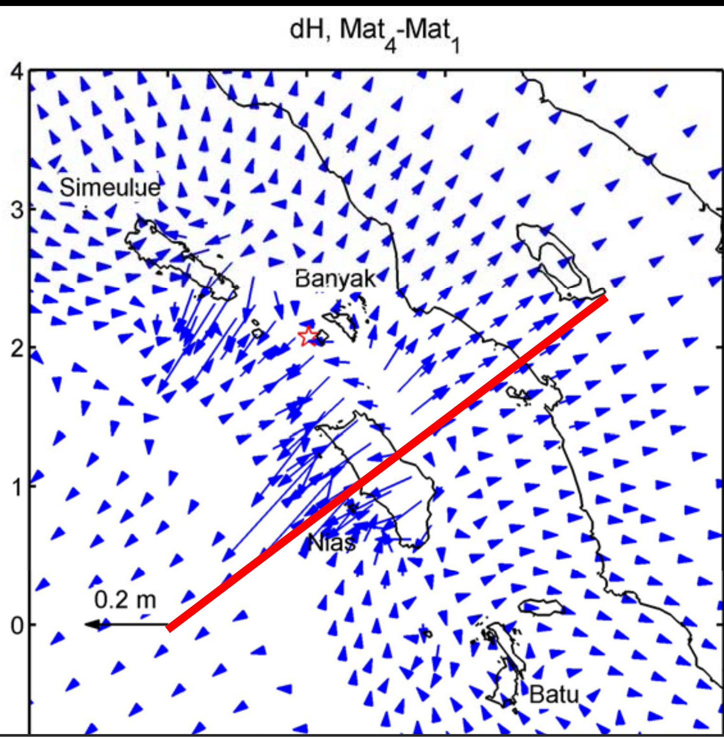


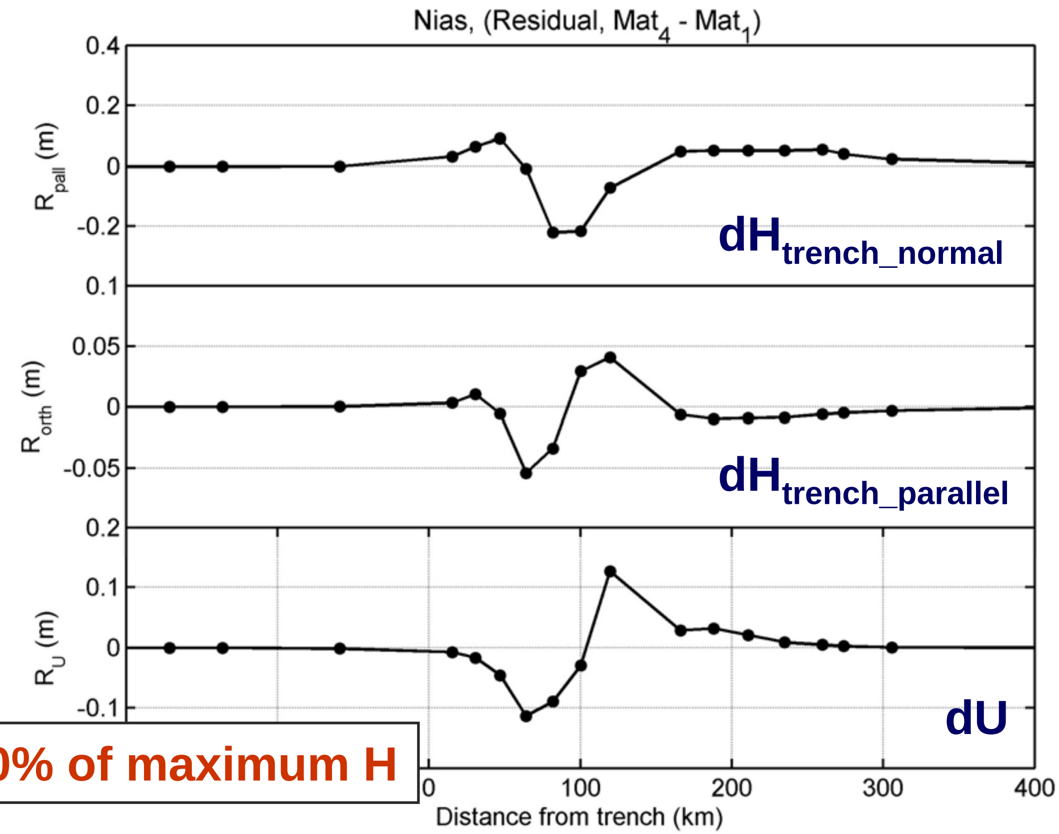




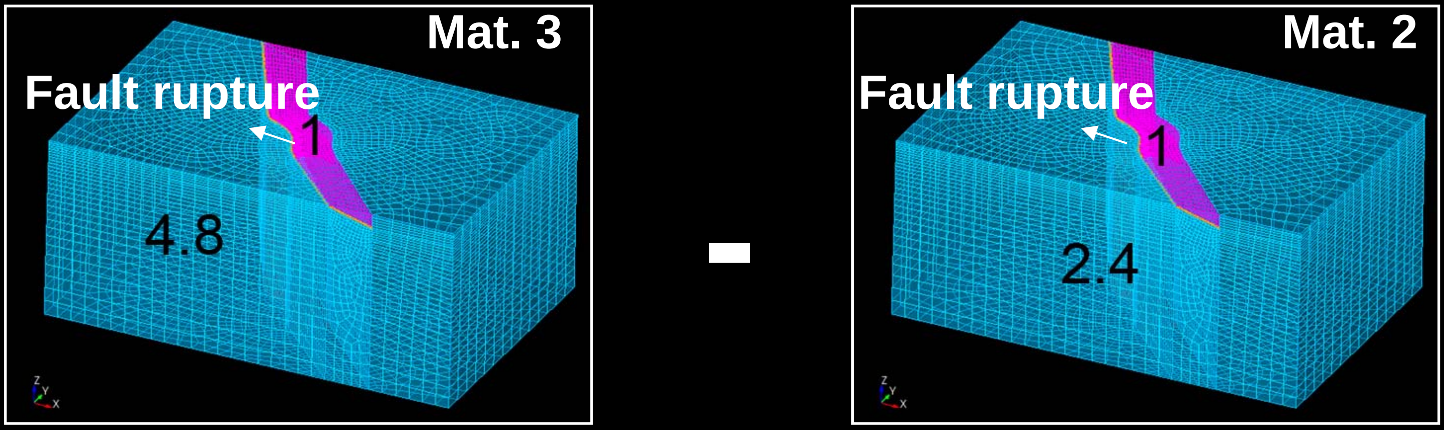


Surface Displacement (Mat_4)- Surface Displacement (Mat_1)

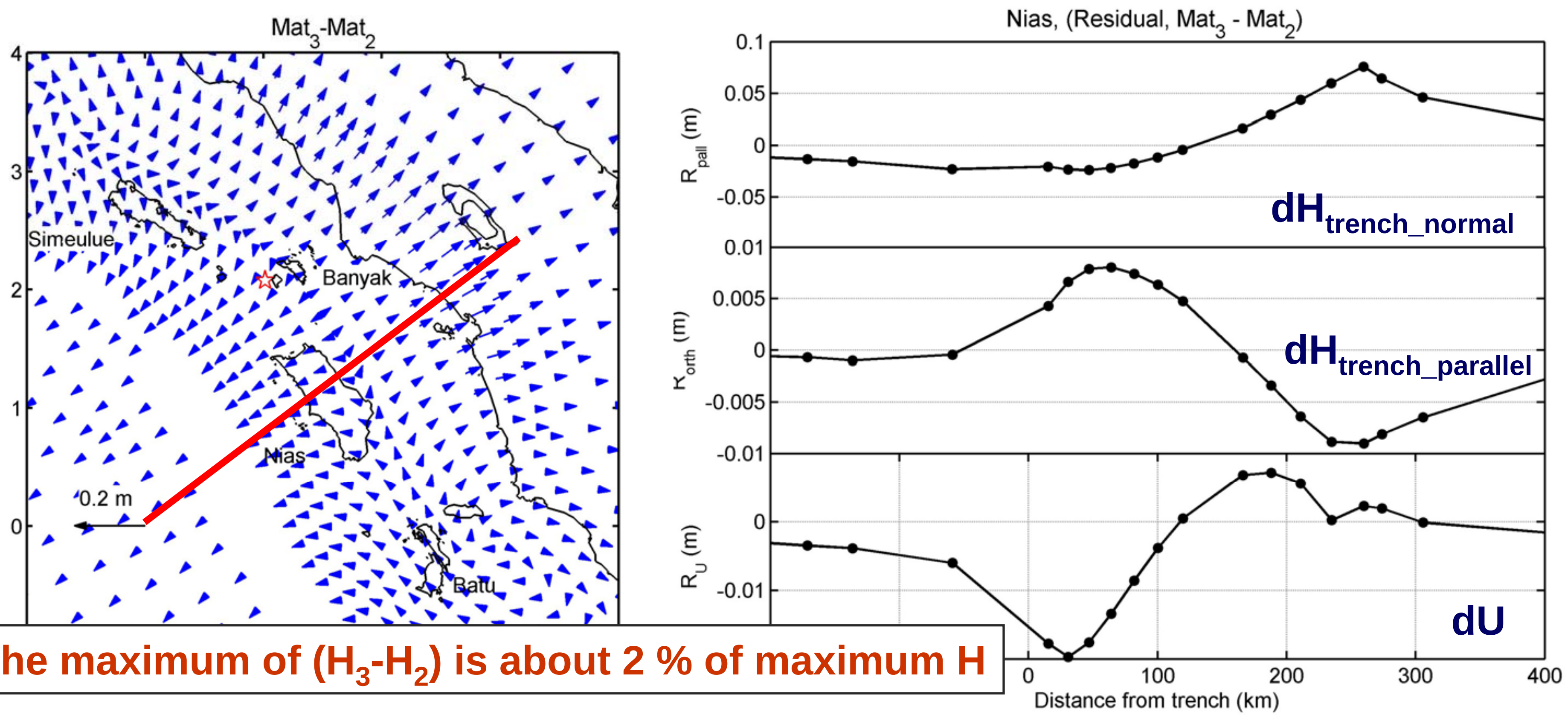




The maximum of (H_4-H_1) is about 10% of maximum H



Surface Displacement (Mat_3)- Surface Displacement (Mat_2)



The maximum of (H_3-H_2) is about 2 % of maximum H

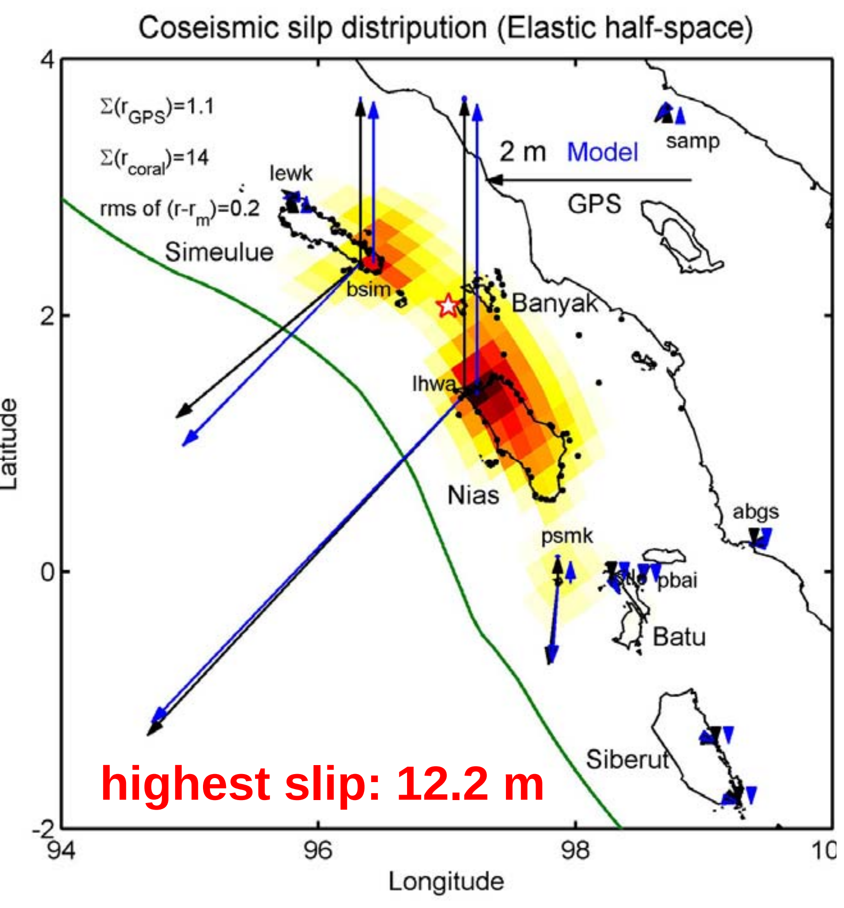
Invert coseismic slip of Nias-Simeulue EQ using 3D Green's Functions

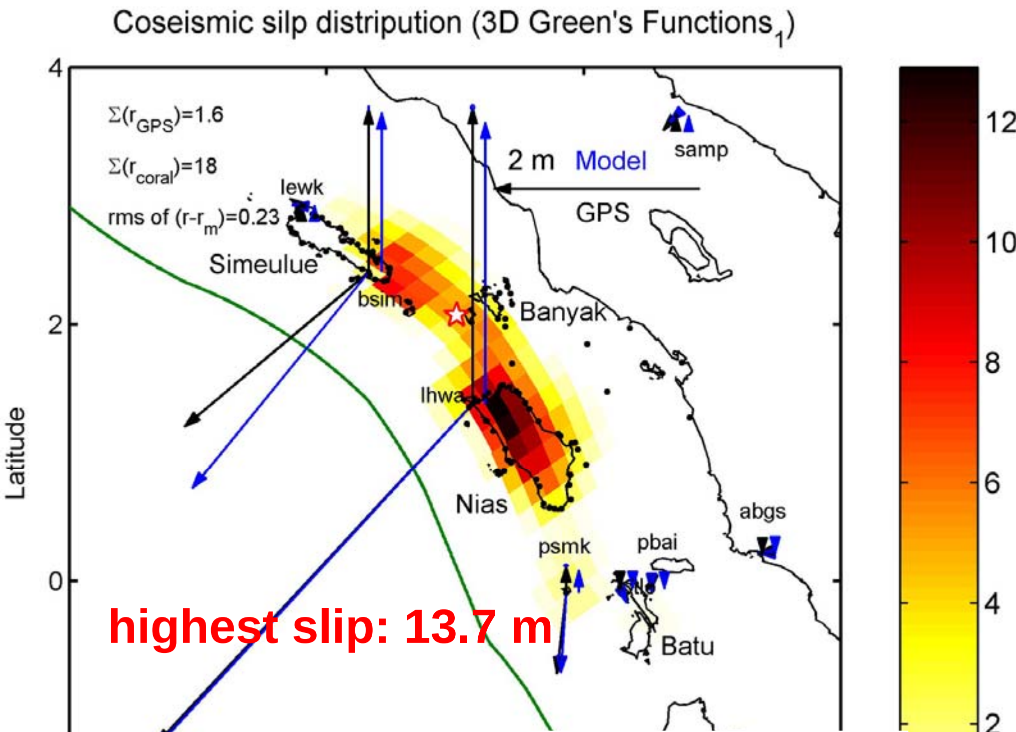
- Calculate 3D Green's functions at each fault node (including topography effect)
- Invert fault slip using 3D Green's functions

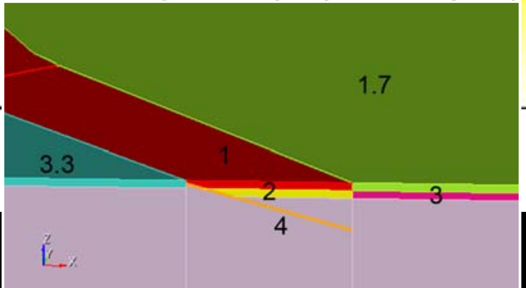
Coseismic slip distribution

(half-space vs. 3D elastic structure)

Elastic half-space model | **3D elastic structure (1)**

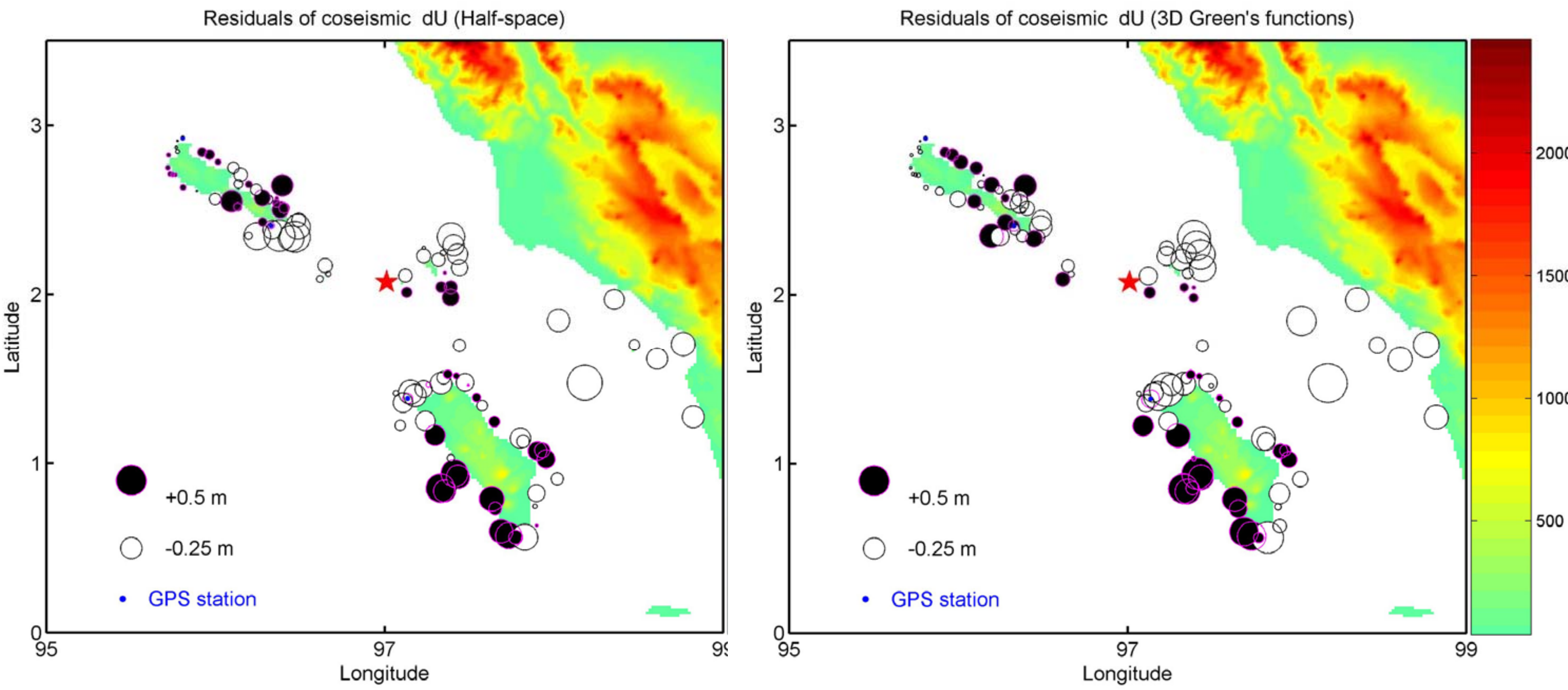




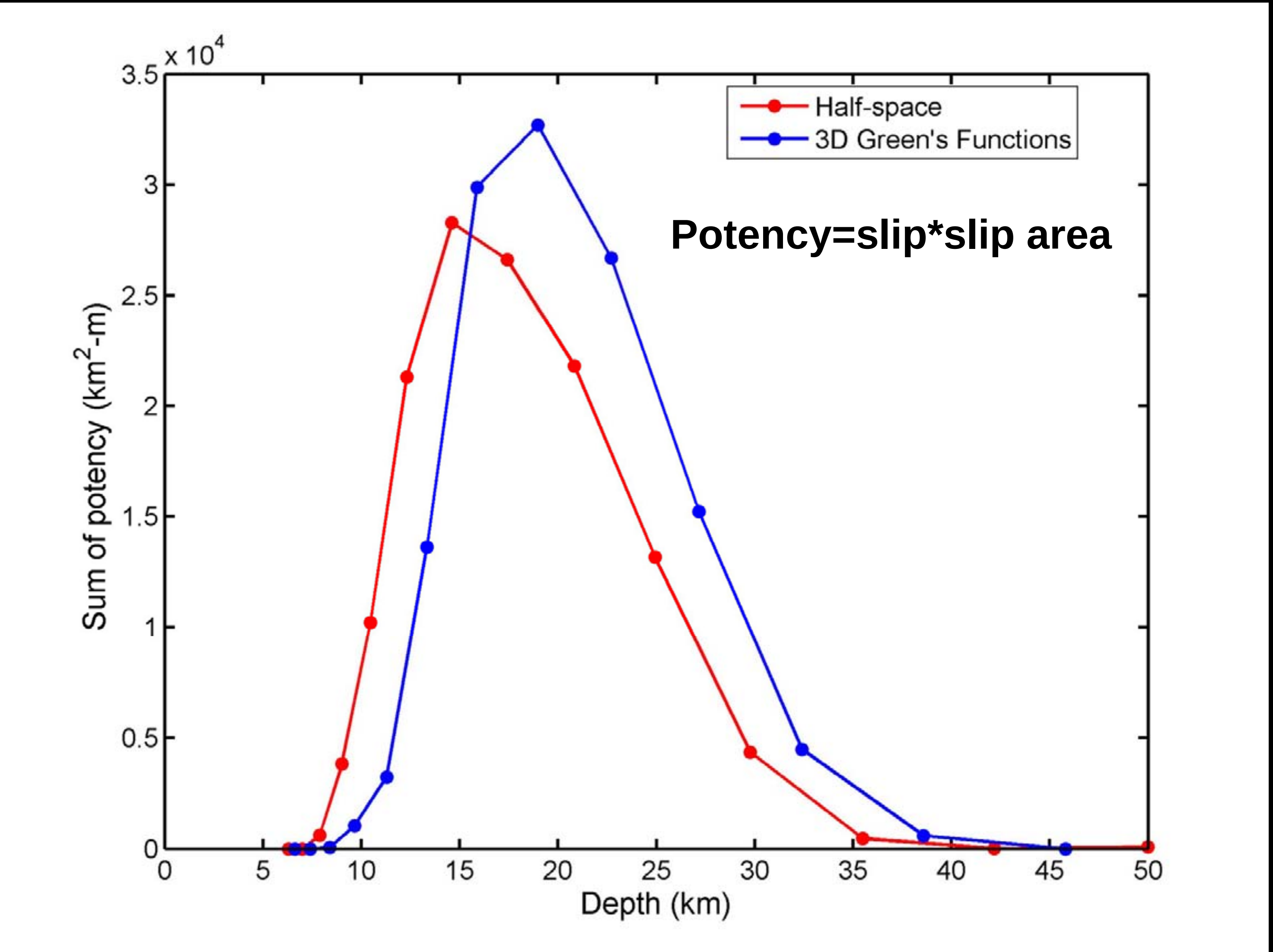


Residuals of dU in coral data

Elastic half-space model **3D elastic structure (1)**

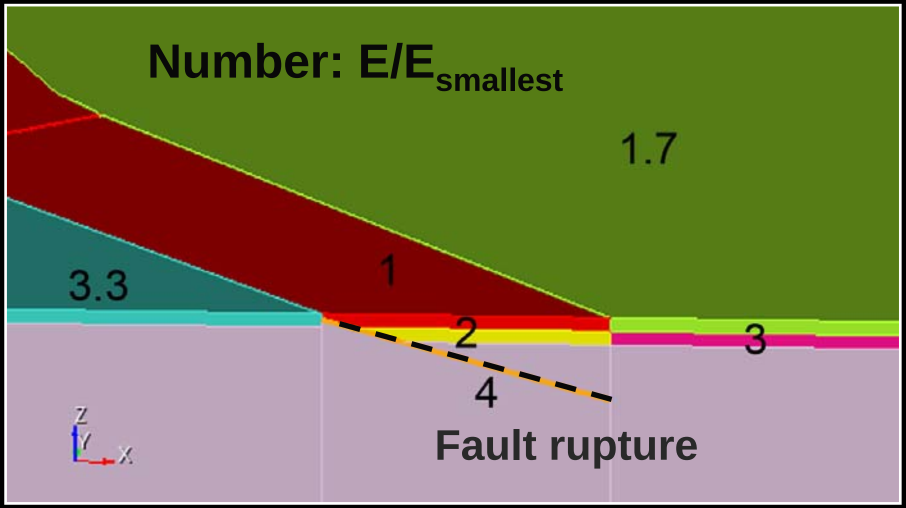


Integrated potency along depth

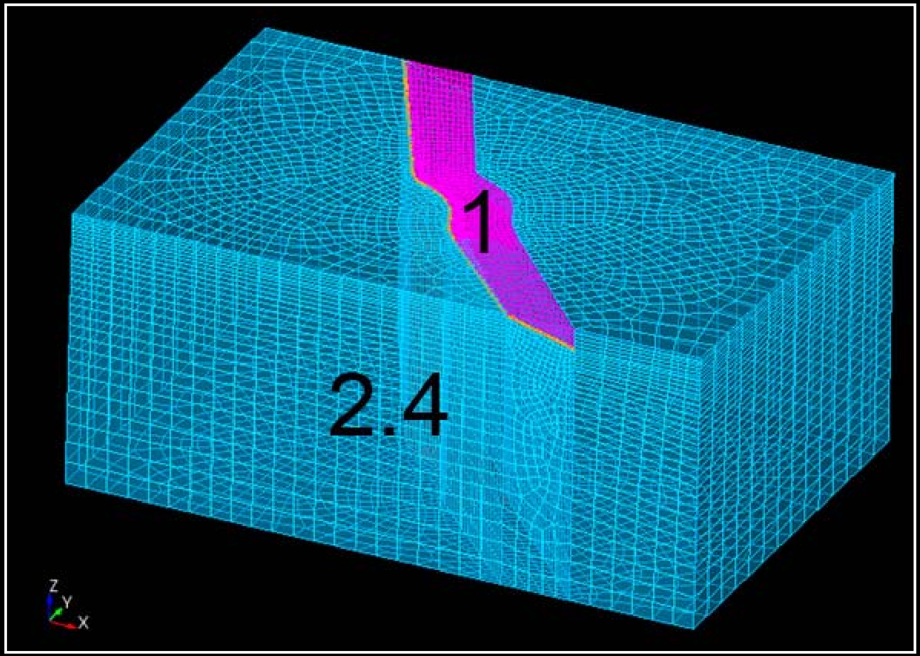


Various 3D elastic structures

3D elastic structure (1)



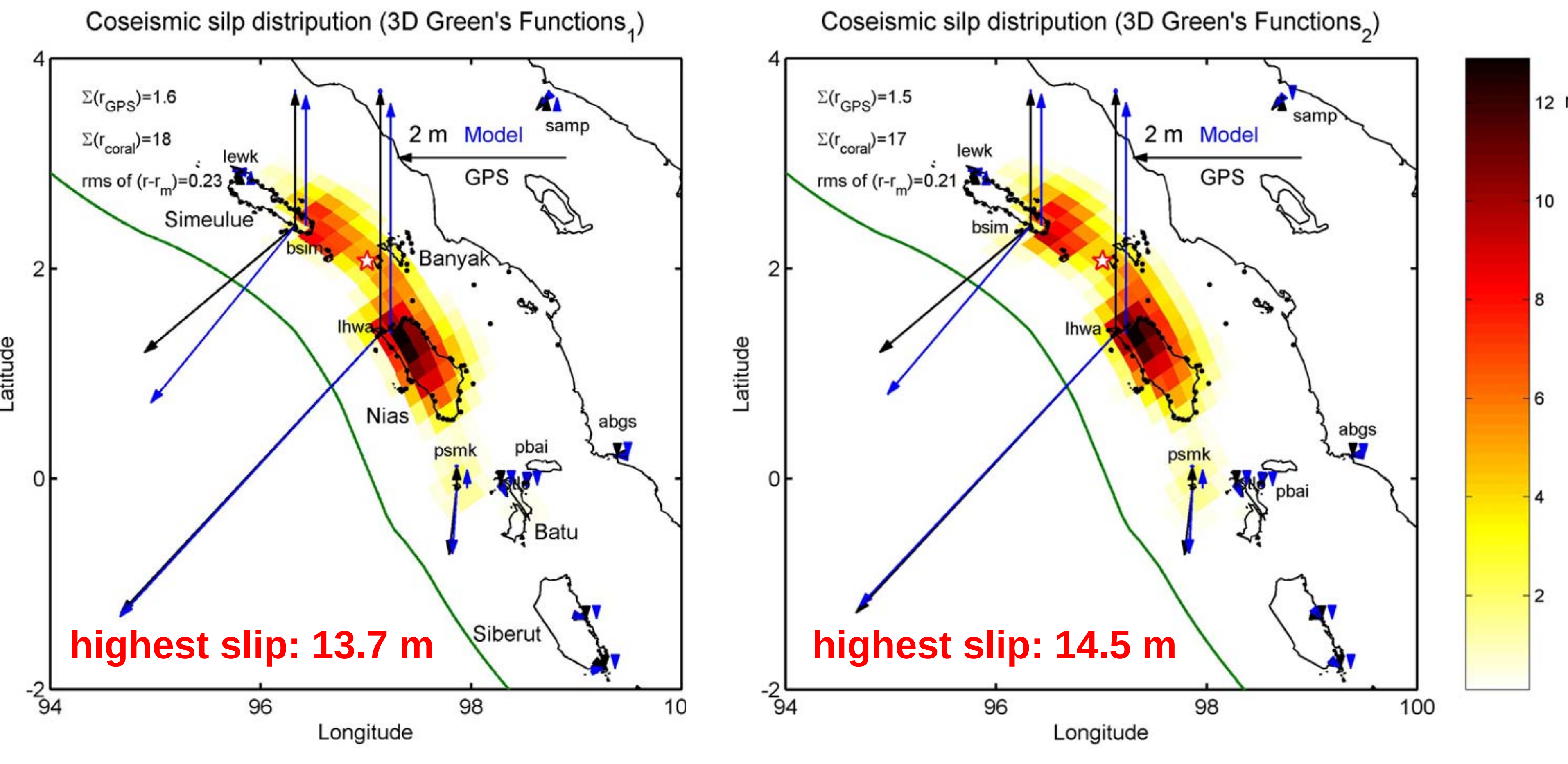
3D elastic structure (2)



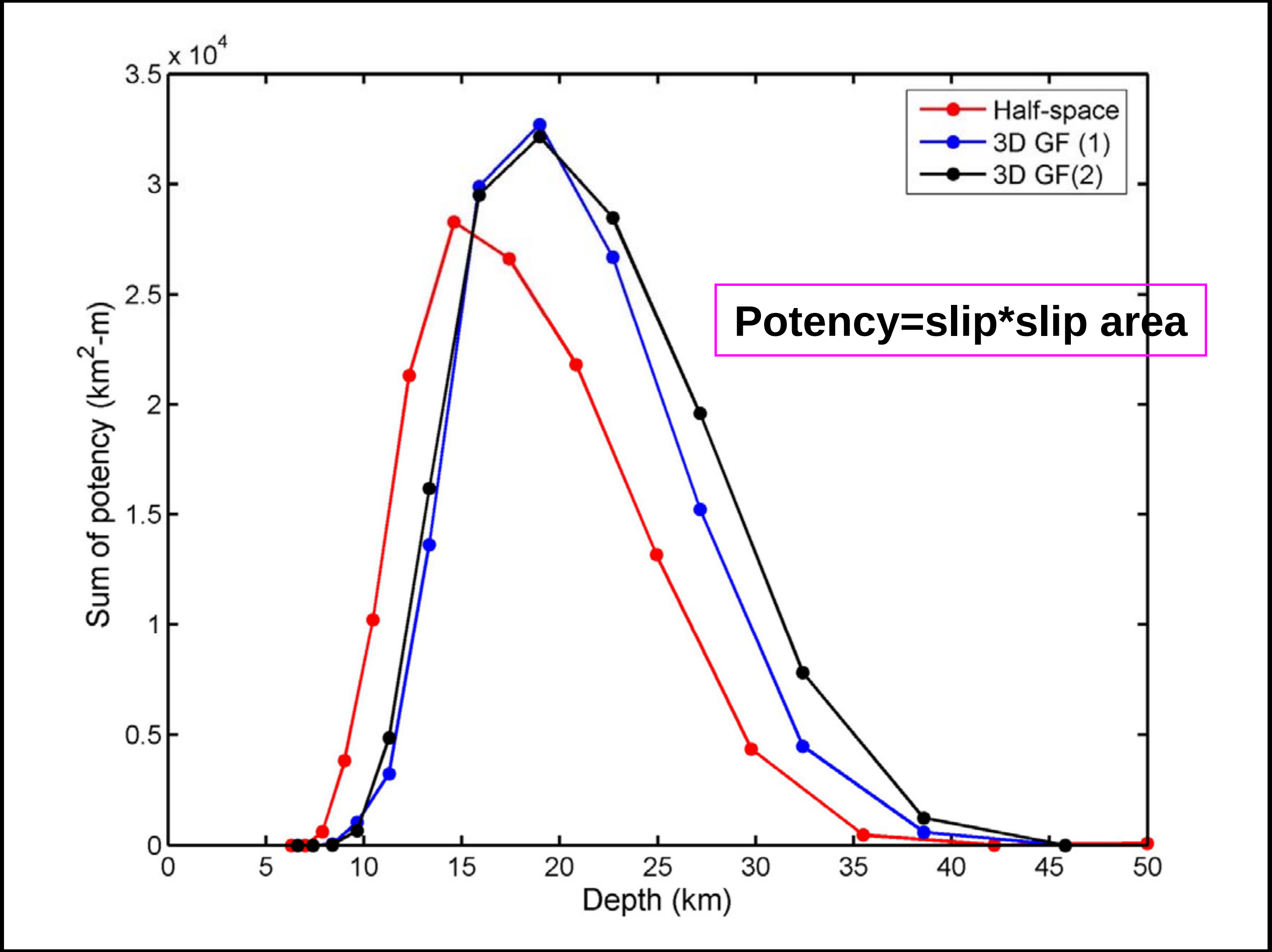
number: the ratio of Young’s modulus to the smallest Young’s modulus

Coseismic slip distribution
(various 3D elastic structures)

3D elastic structure (1) **3D elastic structure (2)**



Integrated coseismic potency along depth

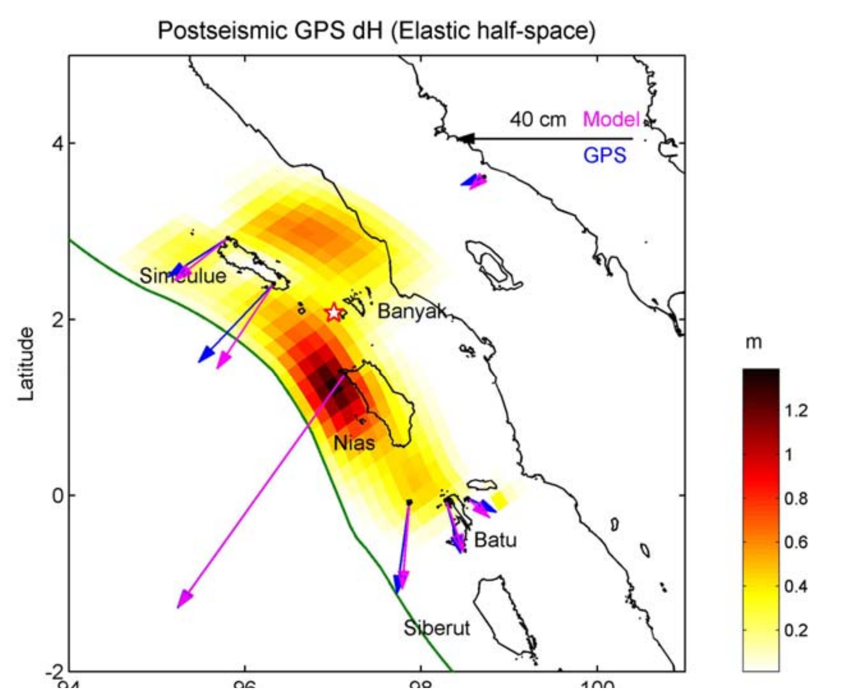


Postseismic slip distribution in 9 months

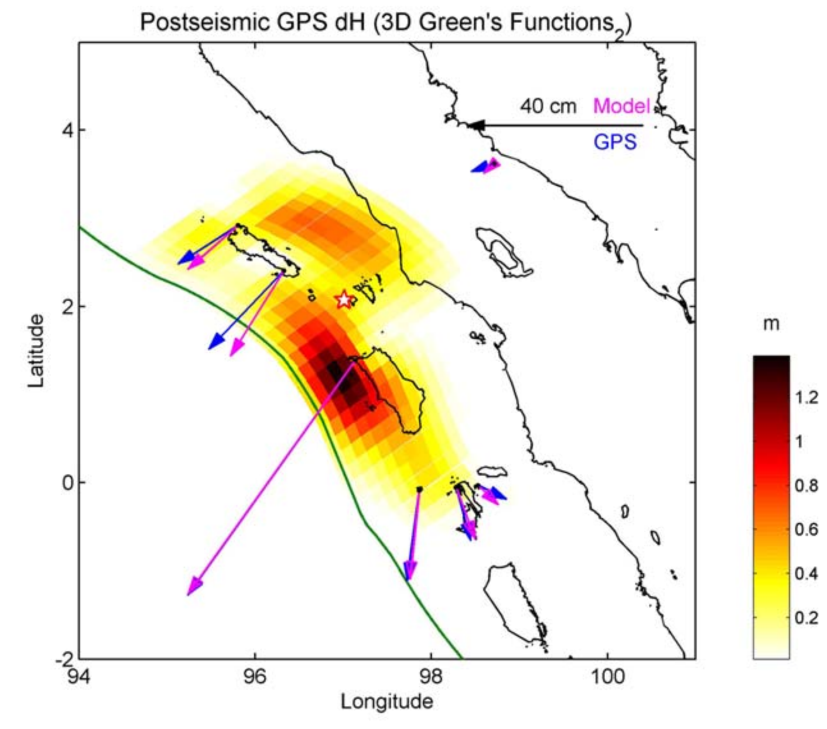
7 GPS sites, no coral measurements

Postseismic slip distribution (cumulative dH in 9 months)

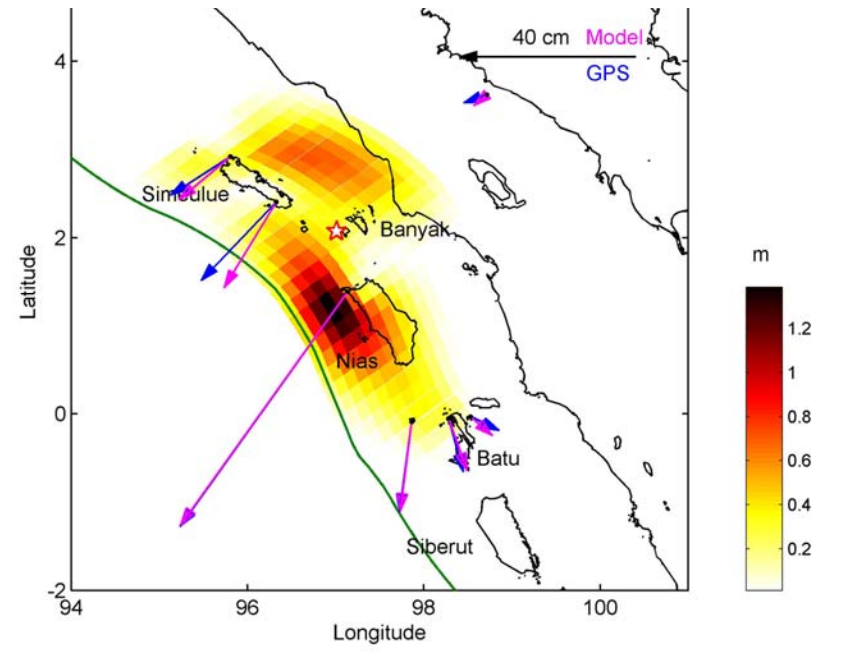
- Half-space



- 3D elastic structure (1)

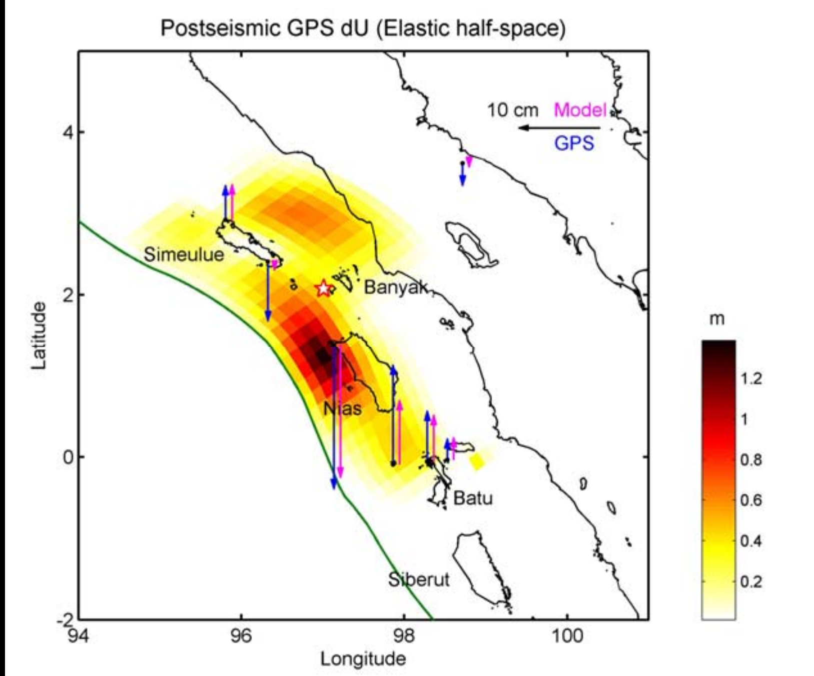


- 3D elastic structure (2)

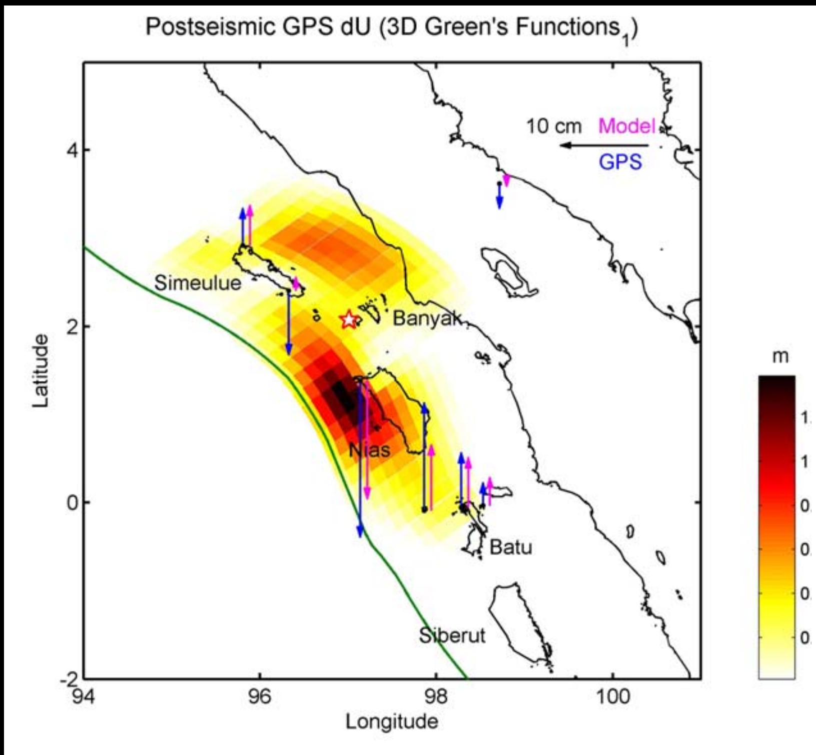


Postseismic slip distribution (cumulative dU in 9 months)

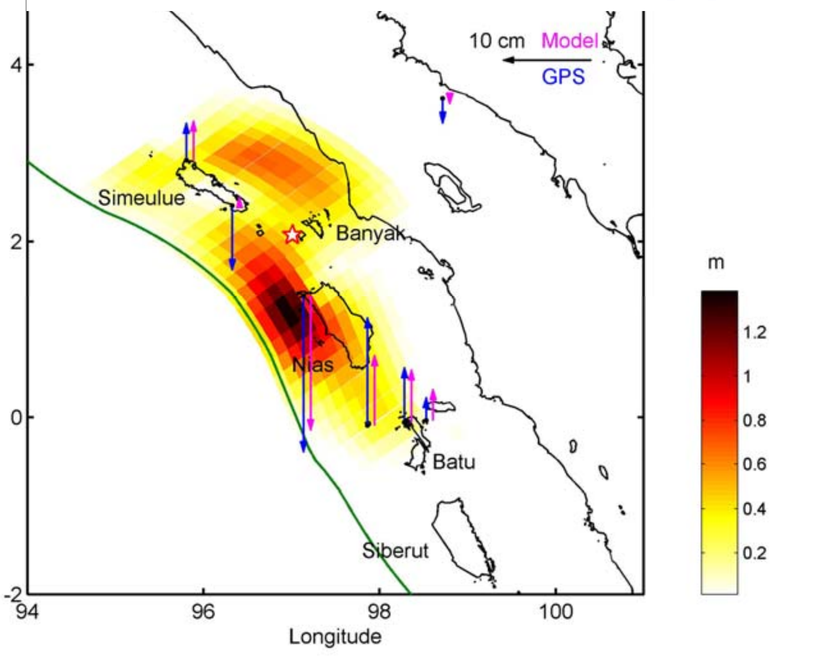
- Half-space



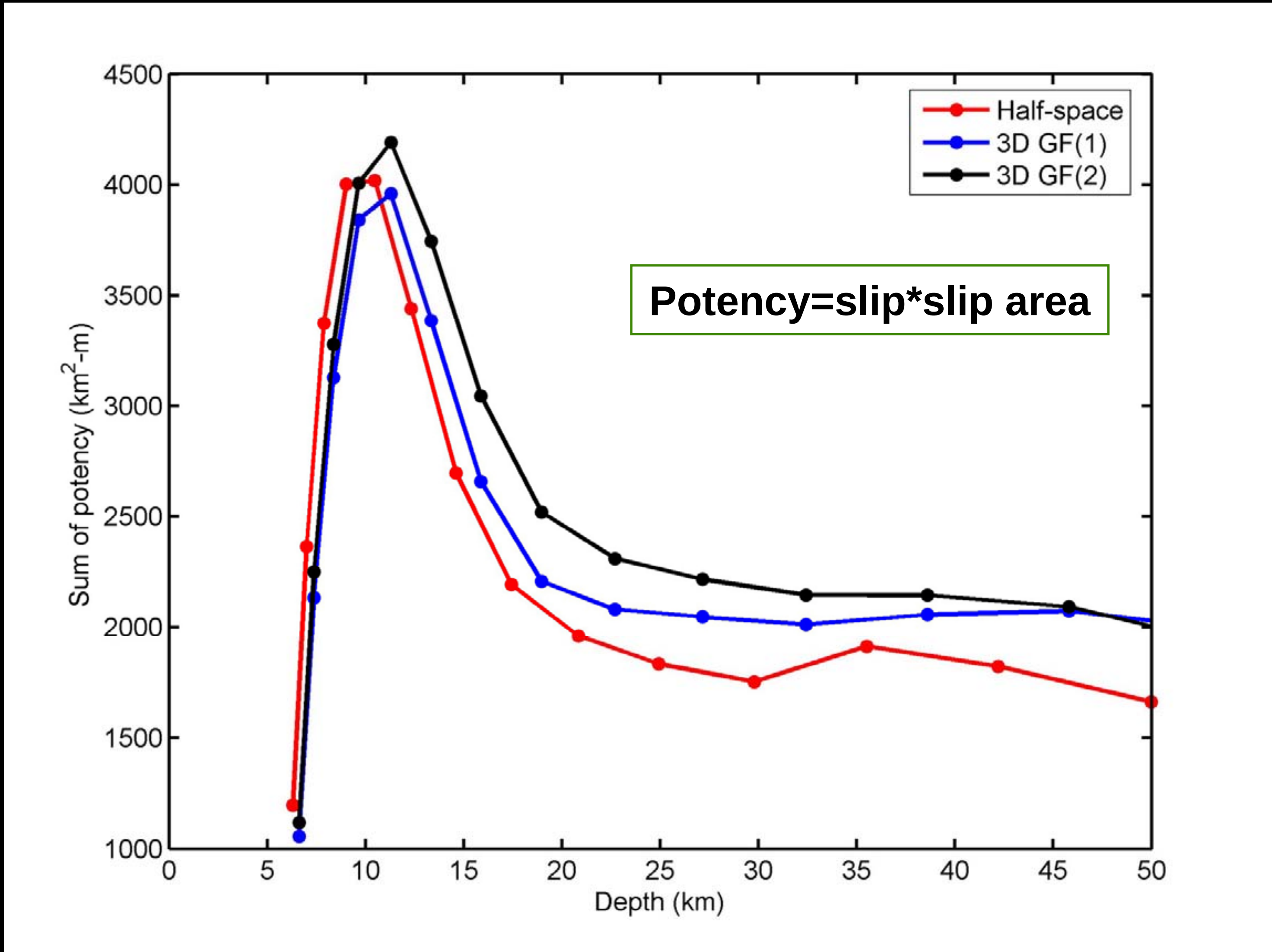
- 3D elastic structure (1)



- 3D elastic structure (2)



Integrated postseismic potency along depth



Summary of 3D modeling results

- While the fits to the data are comparable, we infer a model with less up-dip slip when using a more realistic 3D elastic structure.
- The spatial variation of coseismic/postseismic slip distribution in various models remains similar, while integrated potency along depth in 3D elastic models shift along the down-dip direction comparing with that in an elastic half-space model.
- The down-dip shift of maximum integrated potency along the depth depends on the material contrast in the fault zone.
- The fault geometry is important

Perspective

- Calculate fault slip distribution using a more realistic subduction zone model
- Include the variation of elastic structure along the fault strike if necessary
- Test different material contrasts near the fault zone