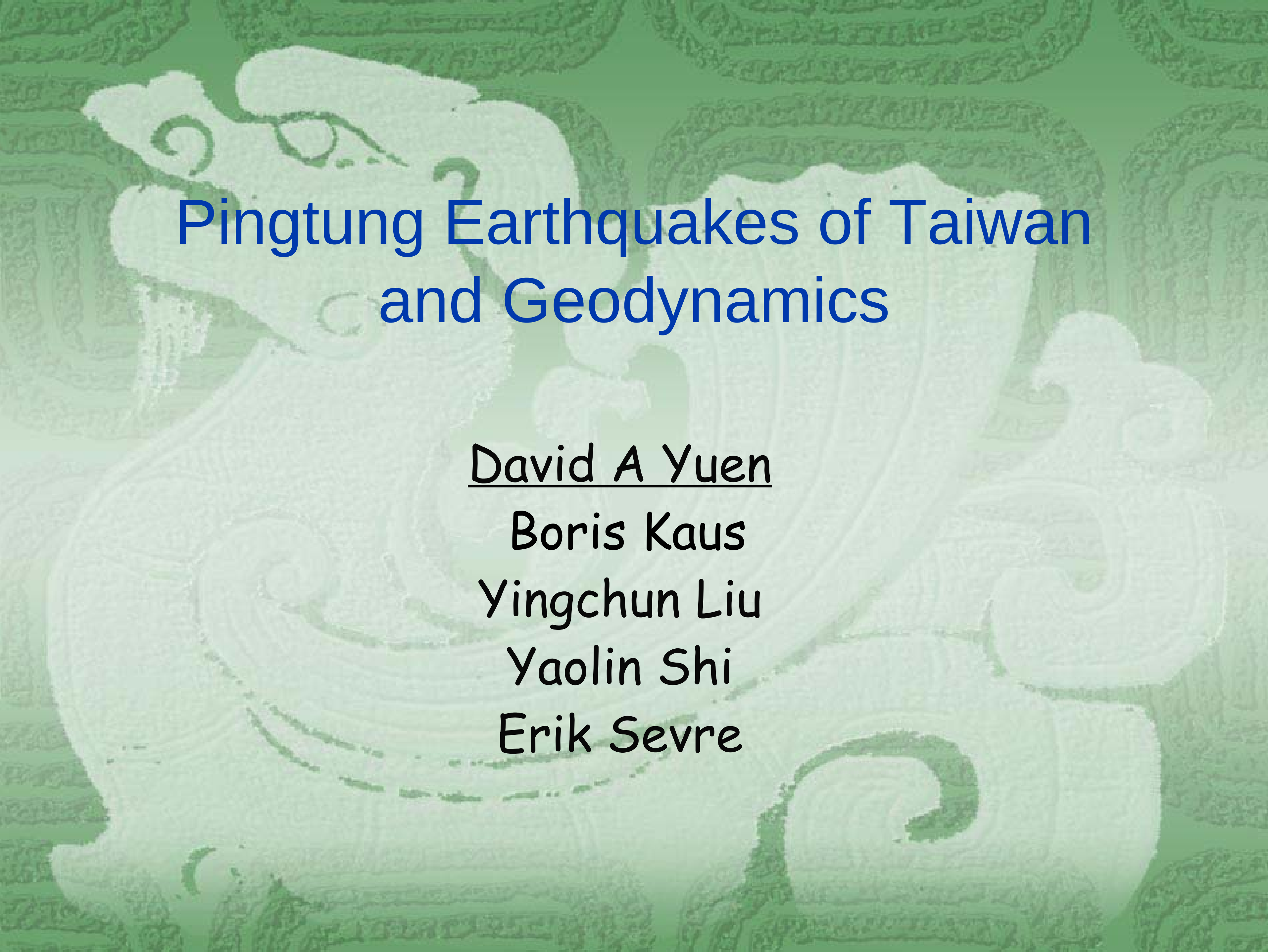


Pingtung Earthquakes of Taiwan and Geodynamics

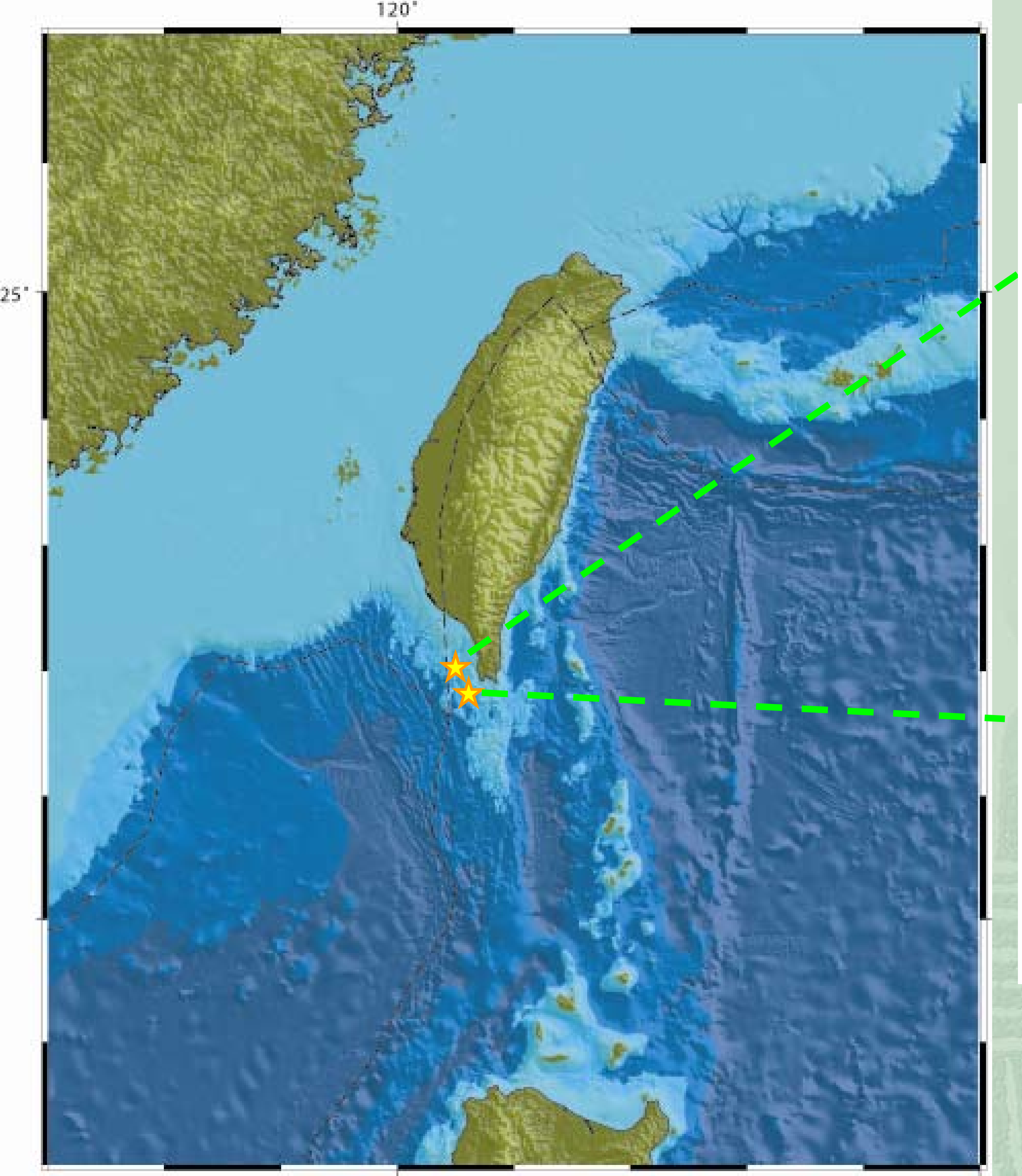
David A Yuen
Boris Kaus
Yingchun Liu
Yaolin Shi
Erik Sevre

Outline

- Pingtung Earthquake Event, Dec. 26, 2006
- The Depths of Epicentres and seismic constraints
- Geodynamical Modelling

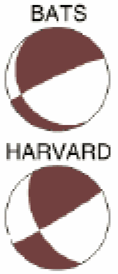
The Focal Mechanisms of Two Earthquakes

12:26:00 PM	FIRF						
	Lat	Long	Magnitude	Depth (Km)	Strike	Dip	Slip
Harvard	21.83N	120.39E	7.0	22.5	330	58	-93
USGS	21.813N	120.530E	7.1	5	334	83	-98
BATS	21.89 N	120.56 E	6.7	44.3	349	53	-54
12:34PM							
Havard	22.03N	120.41E	6.9	33.8	151	55	4
USGS							
BATS	21.95N	120.39E	6.5	30	144	26	-12



12:34 Dec 26 2006

depth : 34 km (HARVAR)
30 km (CWB)

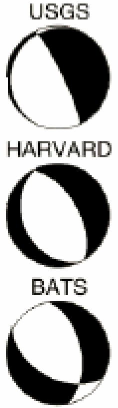


BATS (144, 26, -12)

HARVARD (151, 55, 4)

12:26 Dec 26 2006

depth : 23 km (HARVAR)
44 km (CWB)



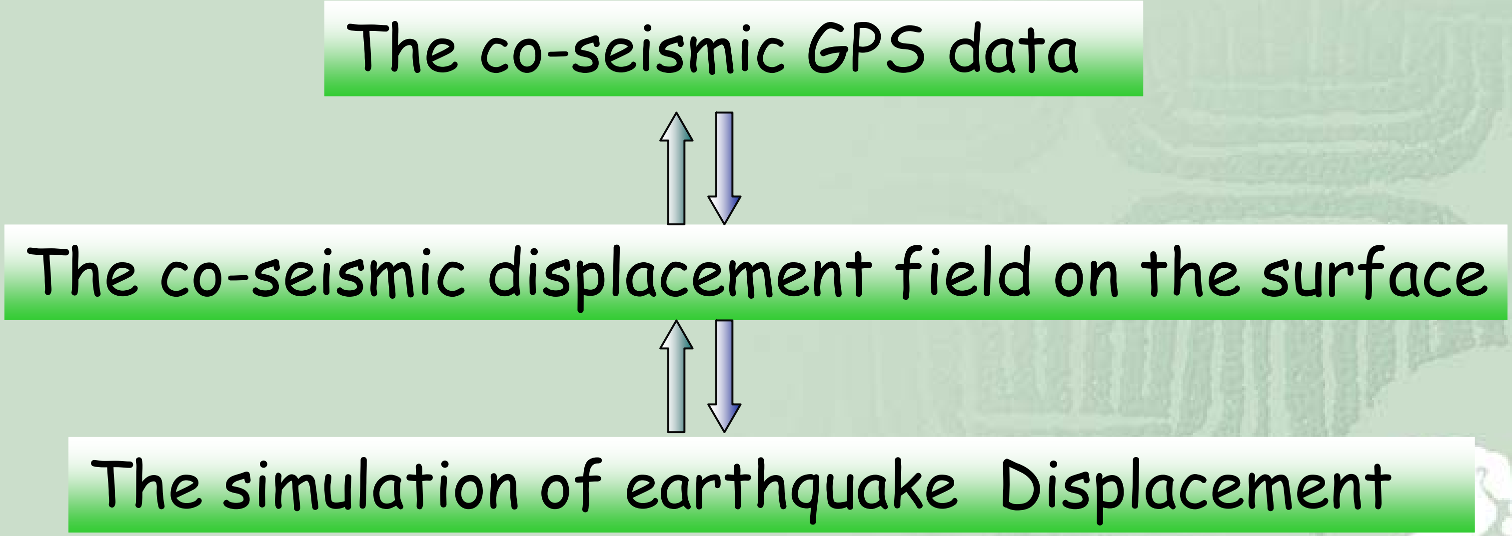
USGS (334, 83,-98)

HARVARD (330, 58,-93)

BATS (349, 53,-54)

Which epicentral depth is reasonable? Why ??

- Here we take one way to check it:

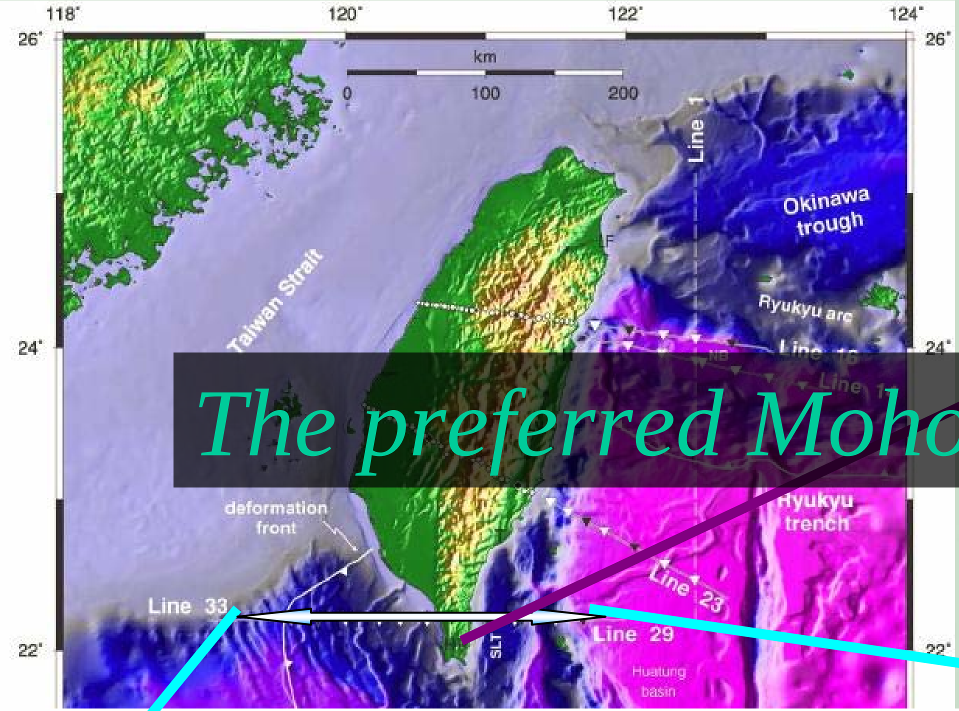


The co-seismic GPS data

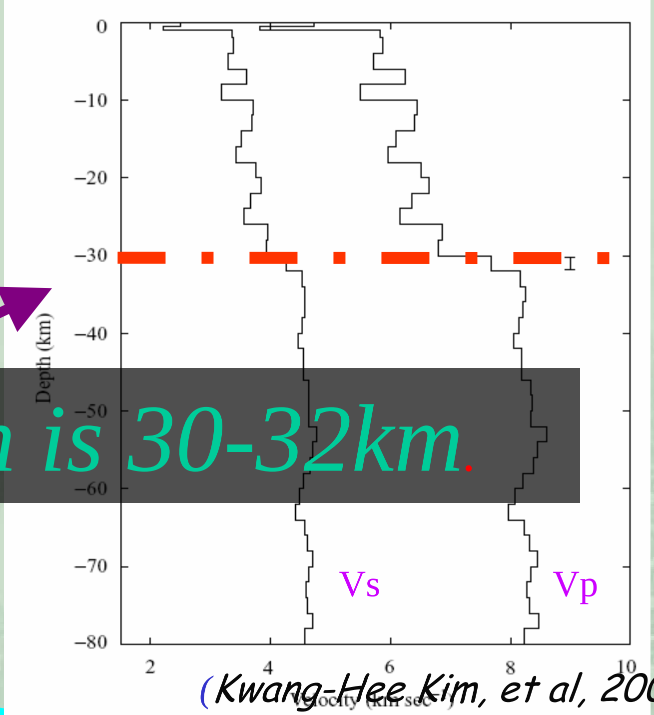
The co-seismic displacement field on the surface

The simulation of earthquake Displacement

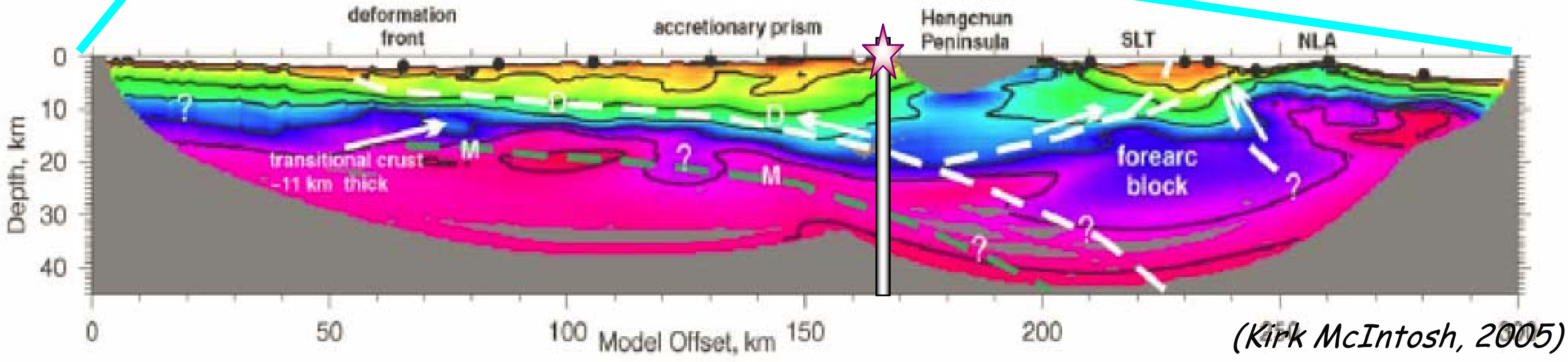
Seismic Profiles across Taiwan and the Western Philippine Sea



The preferred Moho depth is 30-32km.



(Kwang-Hee Kim, et al, 2004)

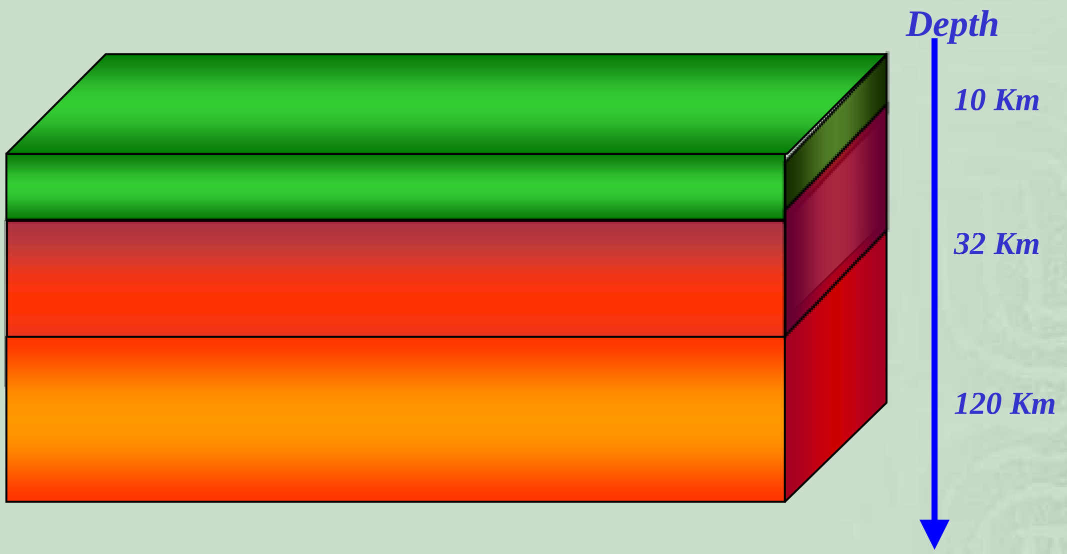


(Kirk McIntosh, 2005)

The Model of Crust

```
 4                             |int: no_model_lines;

# no  depth[km]  vp[km/s]  vs[km/s]  rho[kg/m^3]  eta[Pa*s]   relax
  0      0.000   5.8010    3.200     2700.0      1.0E+30     0.000
  1     10.000   6.458     3.500     2800.0      1.0E+20     0.000
  2     32.000   6.458     3.500     2800.0      1.0E+20     0.000
  3     120.000  7.958     4.600     2900.0      1.0E+25     0.000
  4     120.000  7.358     4.300     3000.0      1.0E+18     0.000
```



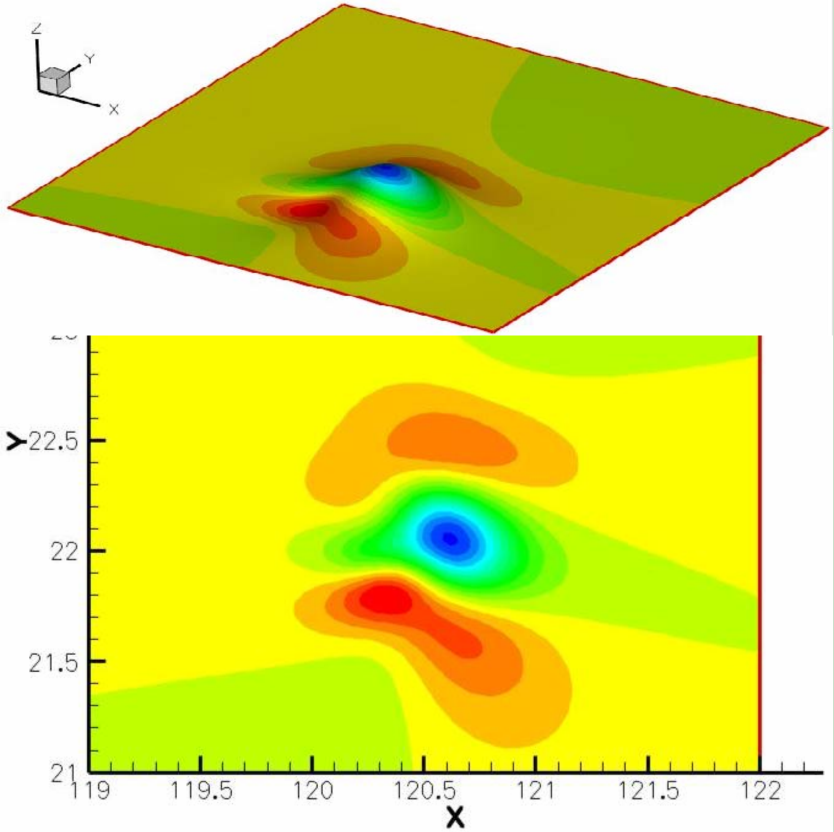
Half space

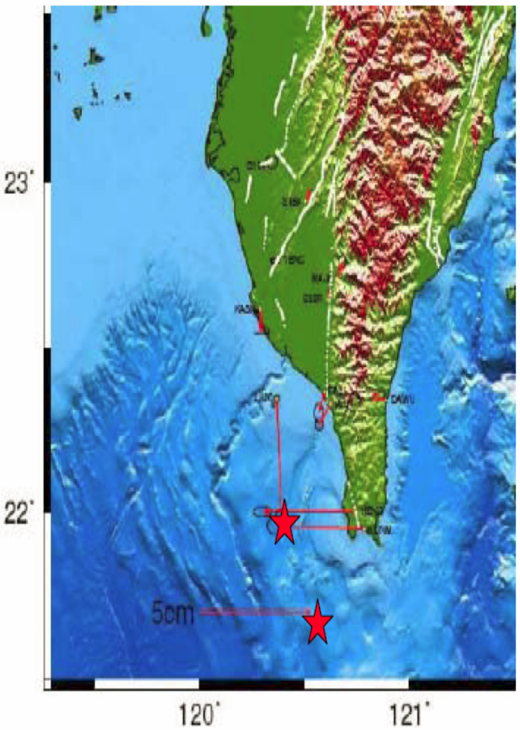
Maxwell model

Elastic Dislocation theory

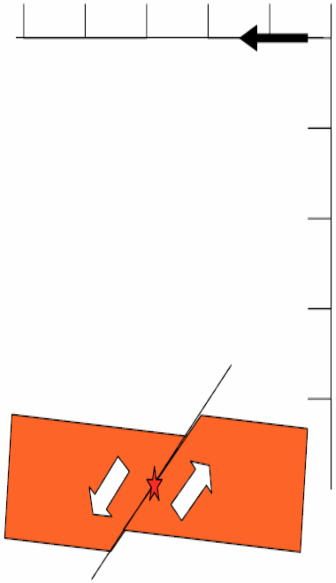
Rongjian Wang, ,
Potsdam,2004

The displacement field of Uz





Long-Cheng Kuo, 2006



(Wen-Tzong Liang, 2007)

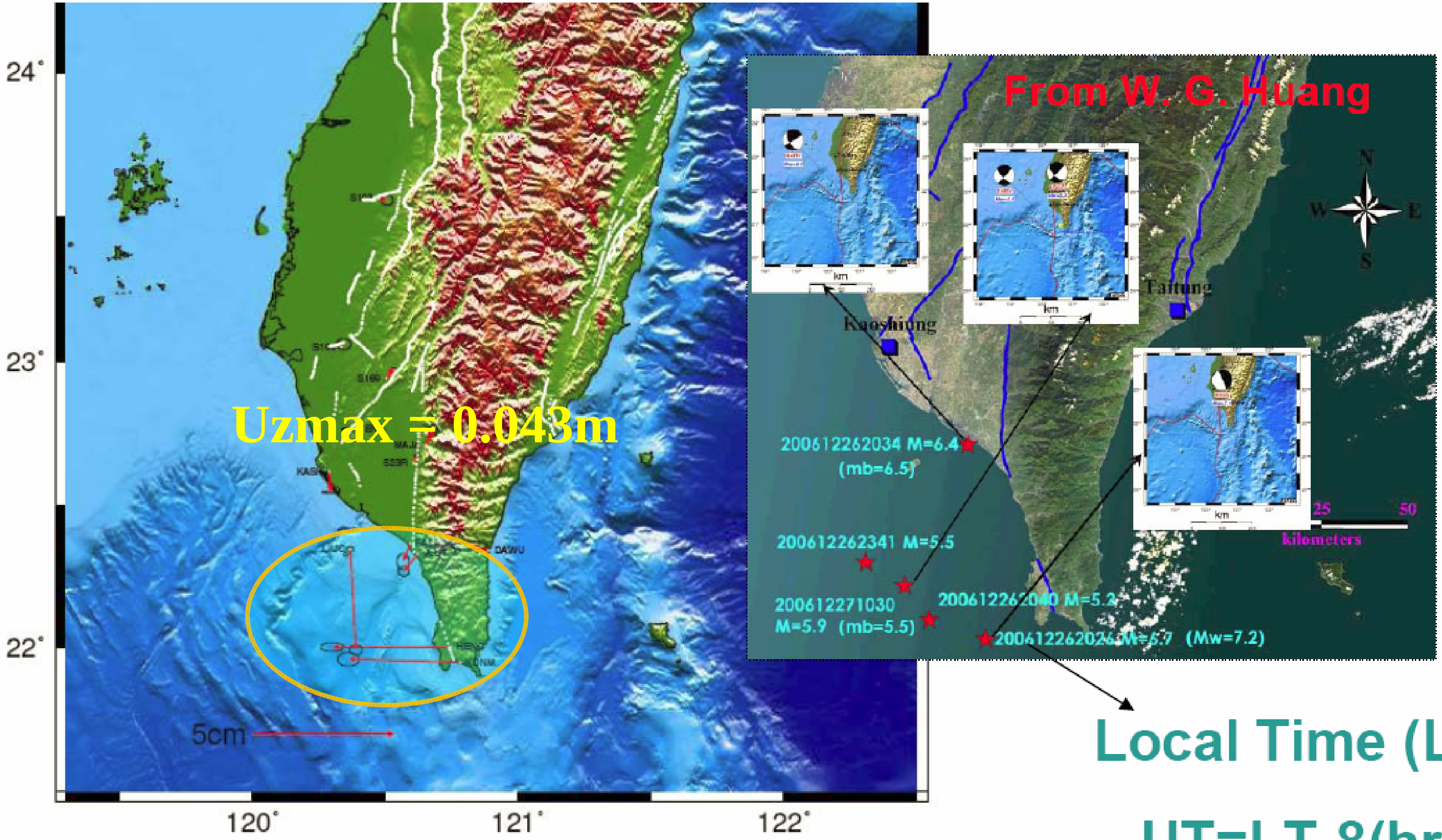
Maximum Displacement Uz in vertical direction from the focal mechanism of three official websites:

USGS : Uzmax = 1.12m Uzmin= -0.8798 m

HCMT: Uzmax = 0.616m Uzmin= -0.085m

BATS : Uzmax = 0.1541m Uzmin= -0.03611 m

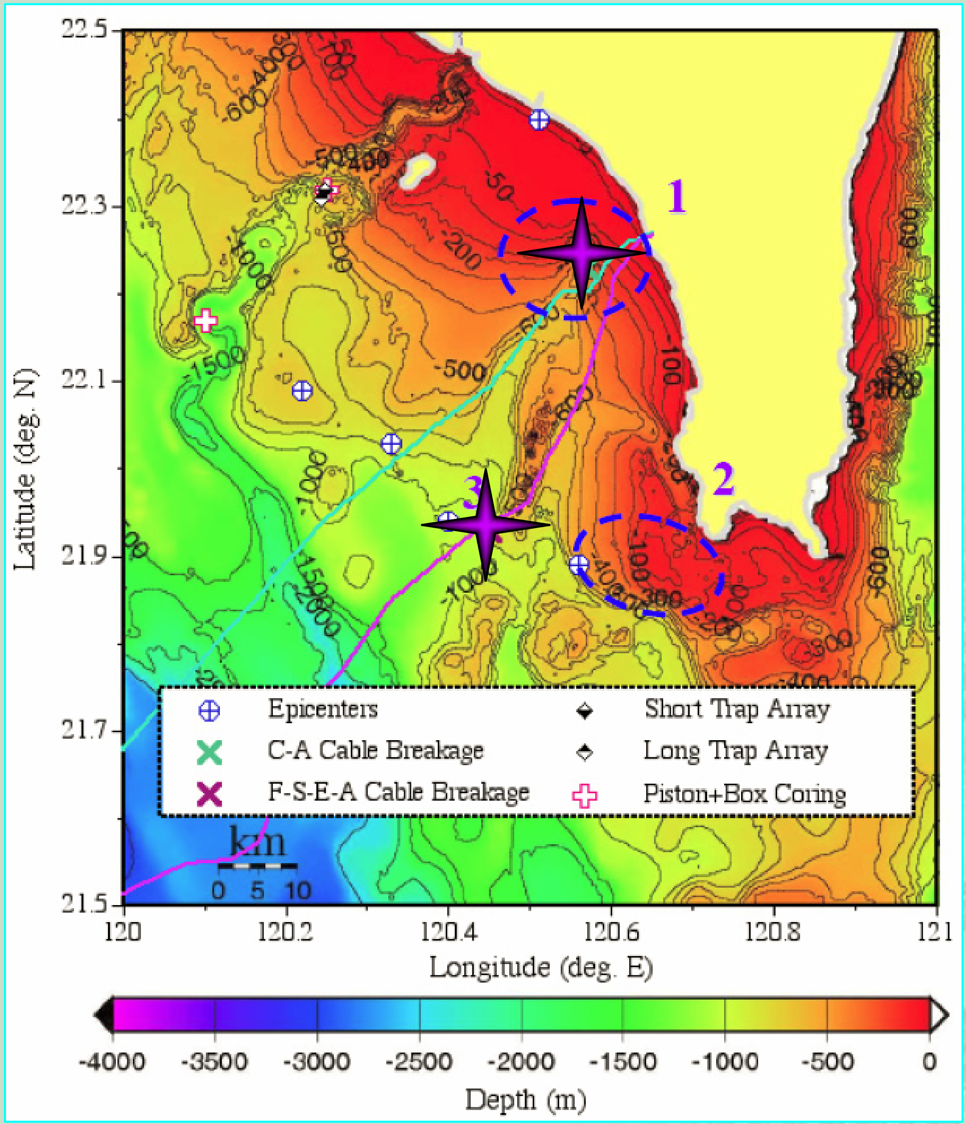
2006/12/26 Pingtung EQ Coseismic Displacement from GPS



Local Time (LT)

UT=LT-8(hr)

Broken Cable

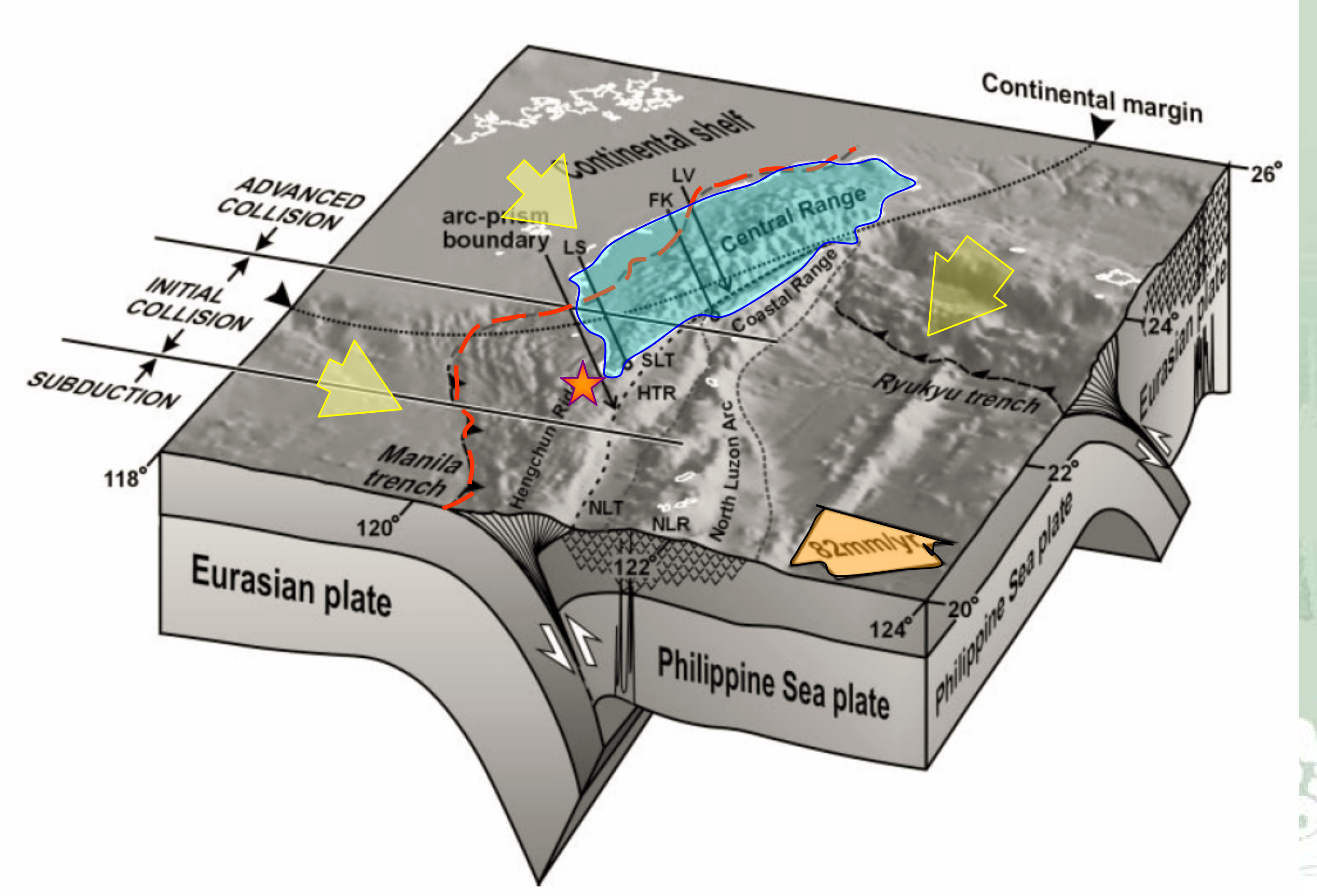


CS Lee, SK Hsu, HW Chen, F Wu, 2007

Conclusion(1)

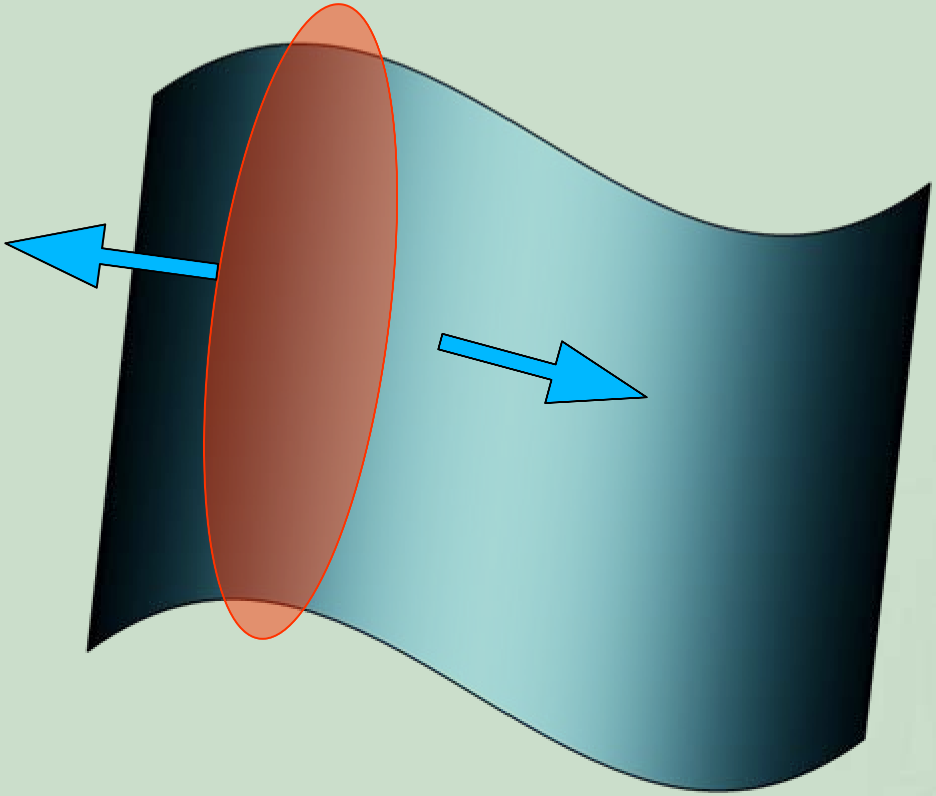
- The first earthquake is normal fault.
- From the report of website, only half a meter wave height was heading for Philippines. The earthquakes could have induced the landslide. Above all, the focal mechanism of BATS is more reasonable. The epicenter could be 40km deep.

Geophysical Background (1)



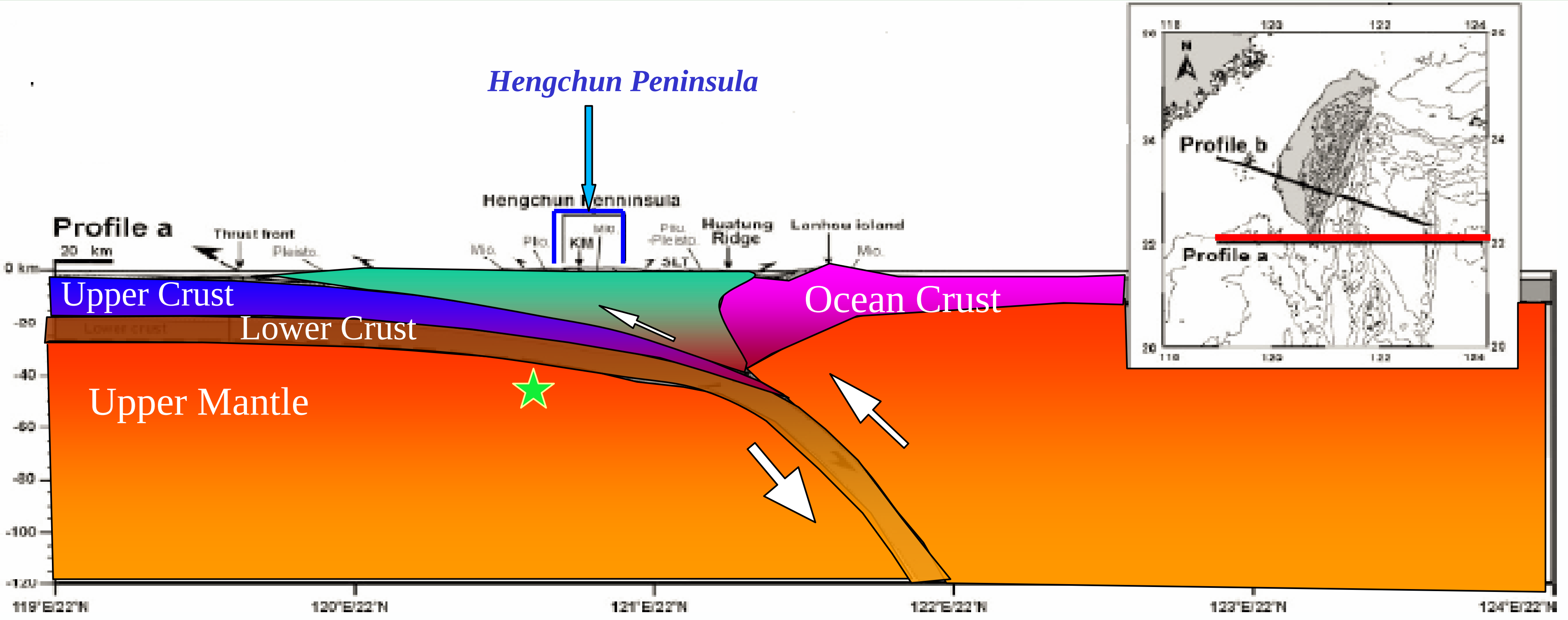
Chang, et al, 2001

The Geodynamic model



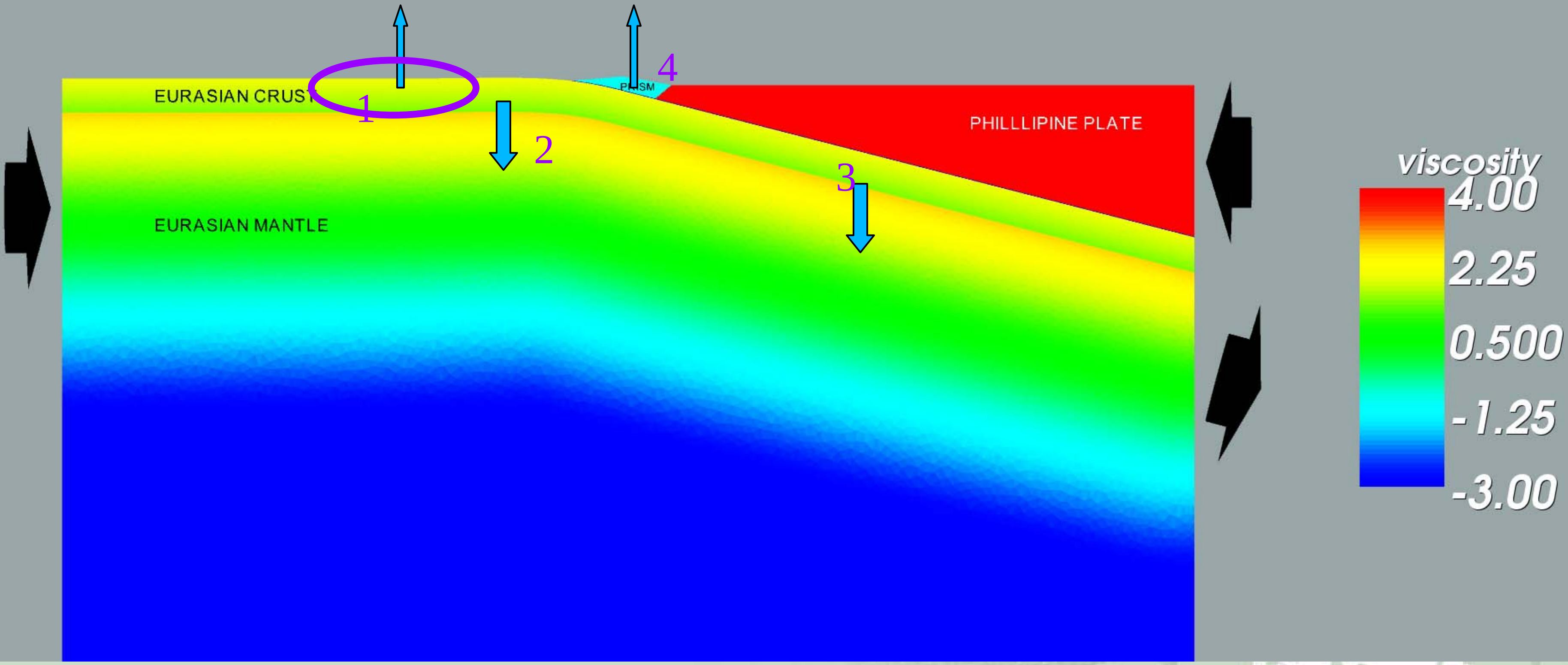
Why this earthquake occurred in the lower Moho, or upper mantle? Not the upper hard crust?

Seismic Profile
Geophysical Background (2)



Based on C. P. CHANG et al., 2005

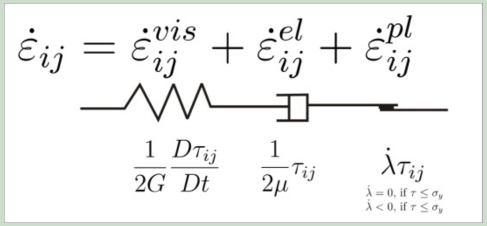
The Numerical Model



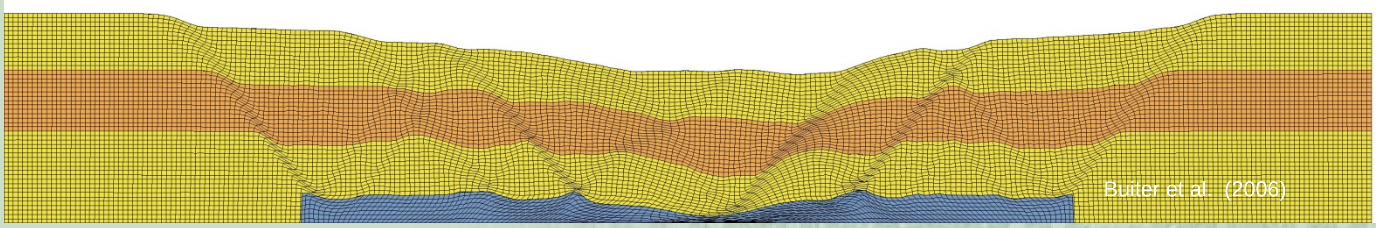
Numerical Method - SloMo

- 2D/3D Thermo-mechanical Lagrangian FEM.
- Rheology: Maxwell viscoelastic with Mohr Coulomb non-associated plasticity.
- Bulk deformation: compressible elastic/incompressible viscous
- Velocity-Pressure formulation ($Q_1P_0^+$ elements).
- Implicit plasticity.
- Markers to track material properties.
- Remeshing for large deformations.
- “True” free surface.

$$
\begin{aligned}
\dot{\varepsilon}_{ii} &= -\frac{1}{K}\frac{\partial P}{\partial t} \\
\frac{\partial \sigma_{ij}}{\partial x_j} &= \rho g_i \\
\rho c_p \frac{DT}{Dt} &= \frac{\partial}{\partial x_i}\left(k_T \frac{\partial T}{\partial x_i}\right) + \rho H + \chi \tau_{ij}\left(\dot{\varepsilon}_{ij} - \dot{\varepsilon}_{ij}^{el}\right) \\
\dot{\varepsilon}_{ij} = \dot{\varepsilon}_{ij}^{vis} + \dot{\varepsilon}_{ij}^{el} + \dot{\varepsilon}_{ij}^{pl} &= \frac{\tau_{ij}}{2\mu} + \frac{1}{2G}\frac{D\tau_{ij}}{Dt} + \dot{\lambda}\frac{\partial Q}{\partial \sigma_{ij}} \\
\mu &= B\dot{\varepsilon}_{II}^{\frac{1-n}{n}} e^{\frac{Q_a}{nRT}} \\
\rho &= \rho_0\left(1 - \alpha(T - T_0)\right) \\
Q &= \tau^* - \sigma^* \sin(\psi) \\
F &= \tau^* - \sigma^* \sin(\phi) - C\cos(\phi)
\end{aligned}
$$



$$\dot{\varepsilon}_{ij} = \dot{\varepsilon}_{ij}^{vis} + \dot{\varepsilon}_{ij}^{el} + \dot{\varepsilon}_{ij}^{pl}$$

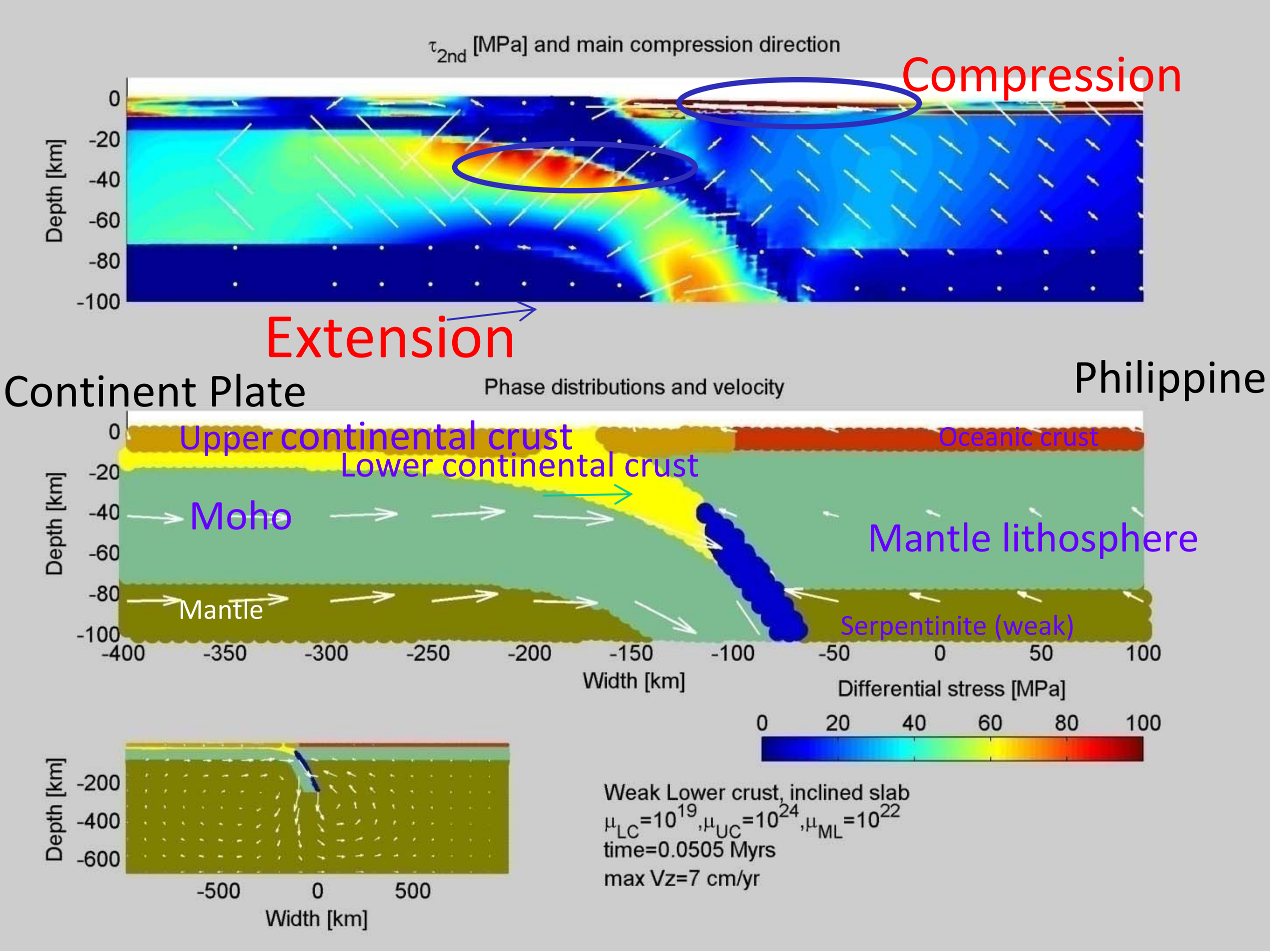


Buiter et al. (2006)

Model setup

- Interest:
  - Stress-field caused by mantle flow and mantle/lithosphere interaction (compressional/extensional)
  - Effect of rheological layering?
  - Slab break-off, weak lower crust?
- Therefore:
  - Models ran for very short timescale only (to ensure isostatic re-equilibrium).
  - Maxwell timescale artificially reduced (<30 years).
- Limitation:
  - Viscosity constant in each of the layers (T-dependent underway, not finished yet).

Horizontal Normal Stress Field



Eurasia Continent Plate

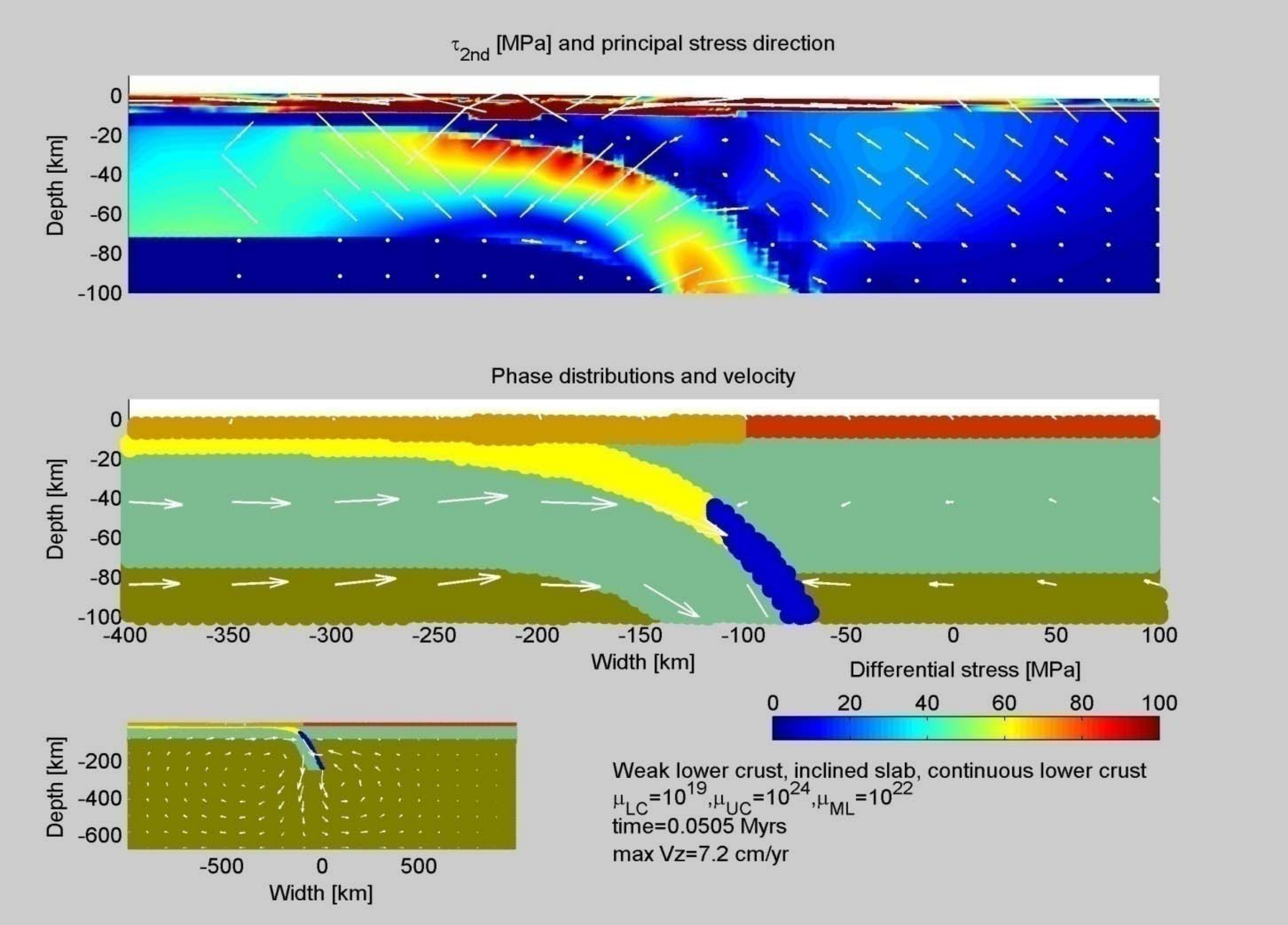
Philippine Sea Plate

Horizontal compression direction = thrust EQ

Vertical compression direction = normal EQ

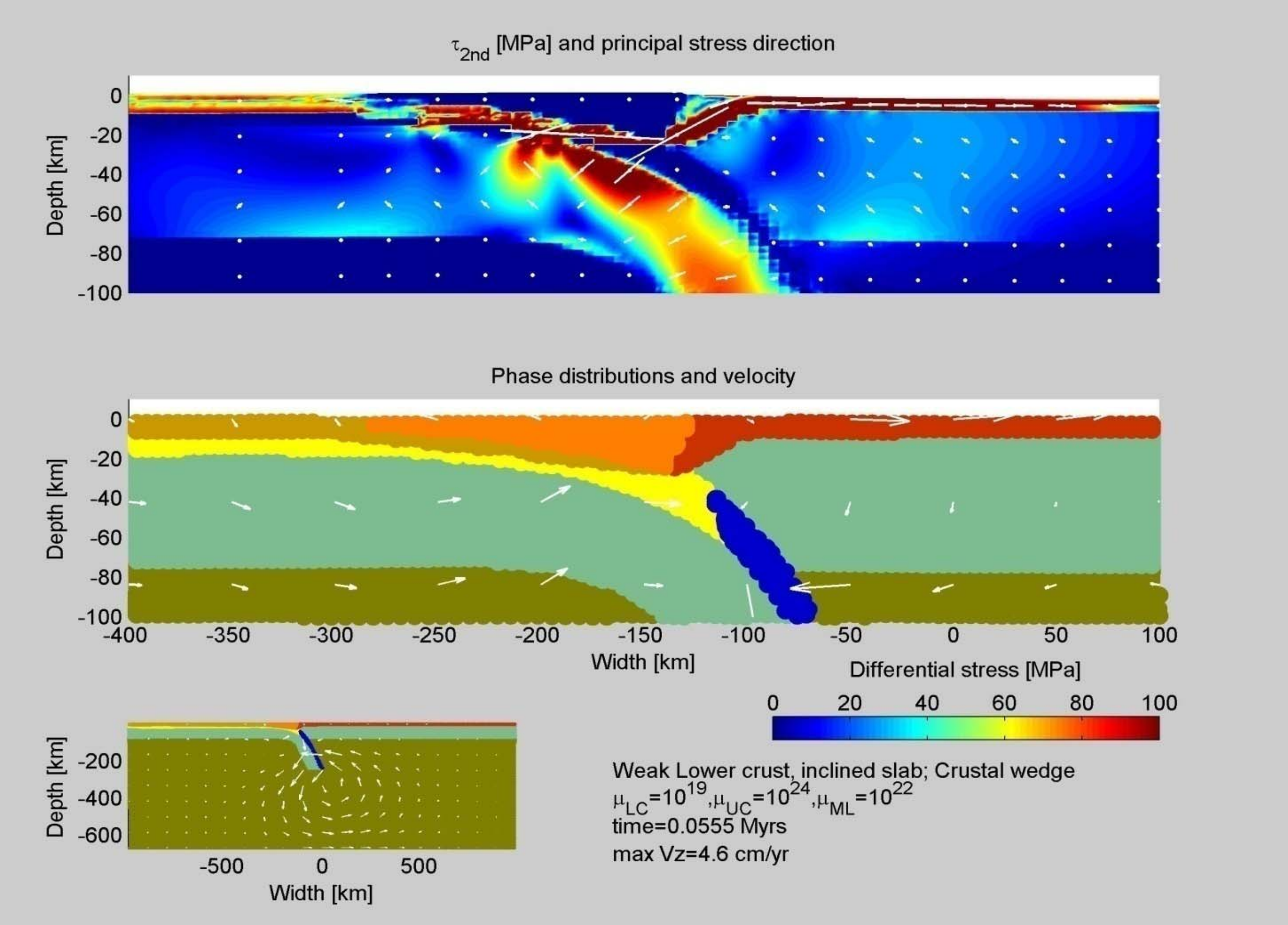
-> Extensional stresses below the Moho due to bending of subducting (oceanic) slab.

Continuous lower crust

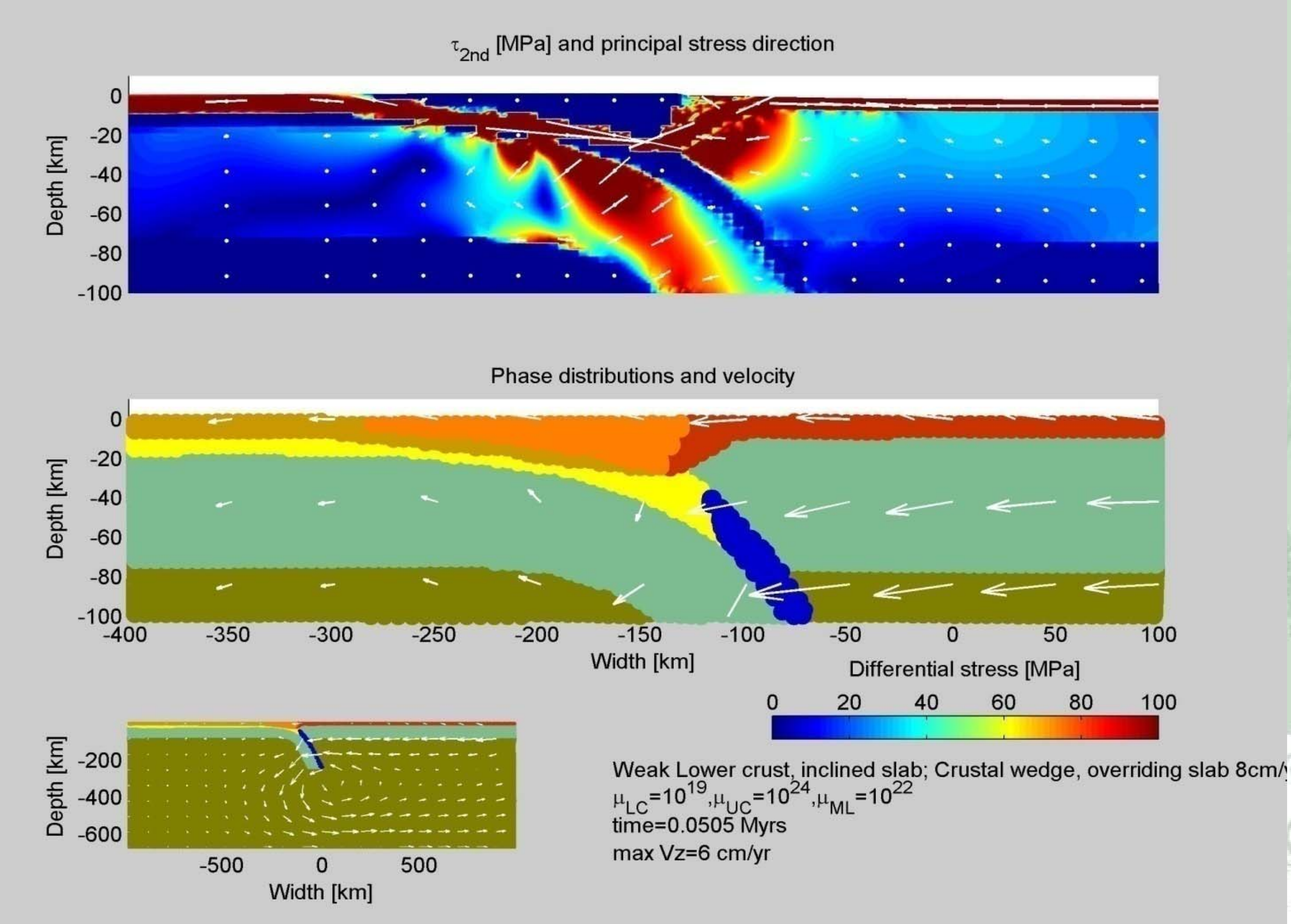


Weak lower crust, inclined slab, continuous lower crust
$\mu_{LC}=10^{19}, \mu_{UC}=10^{24}, \mu_{ML}=10^{22}$
time=0.0505 Myrs
max Vz=7.2 cm/yr

With weak crustal wedge



Weak crustal wedge & overriding PSP (8cm/yr)



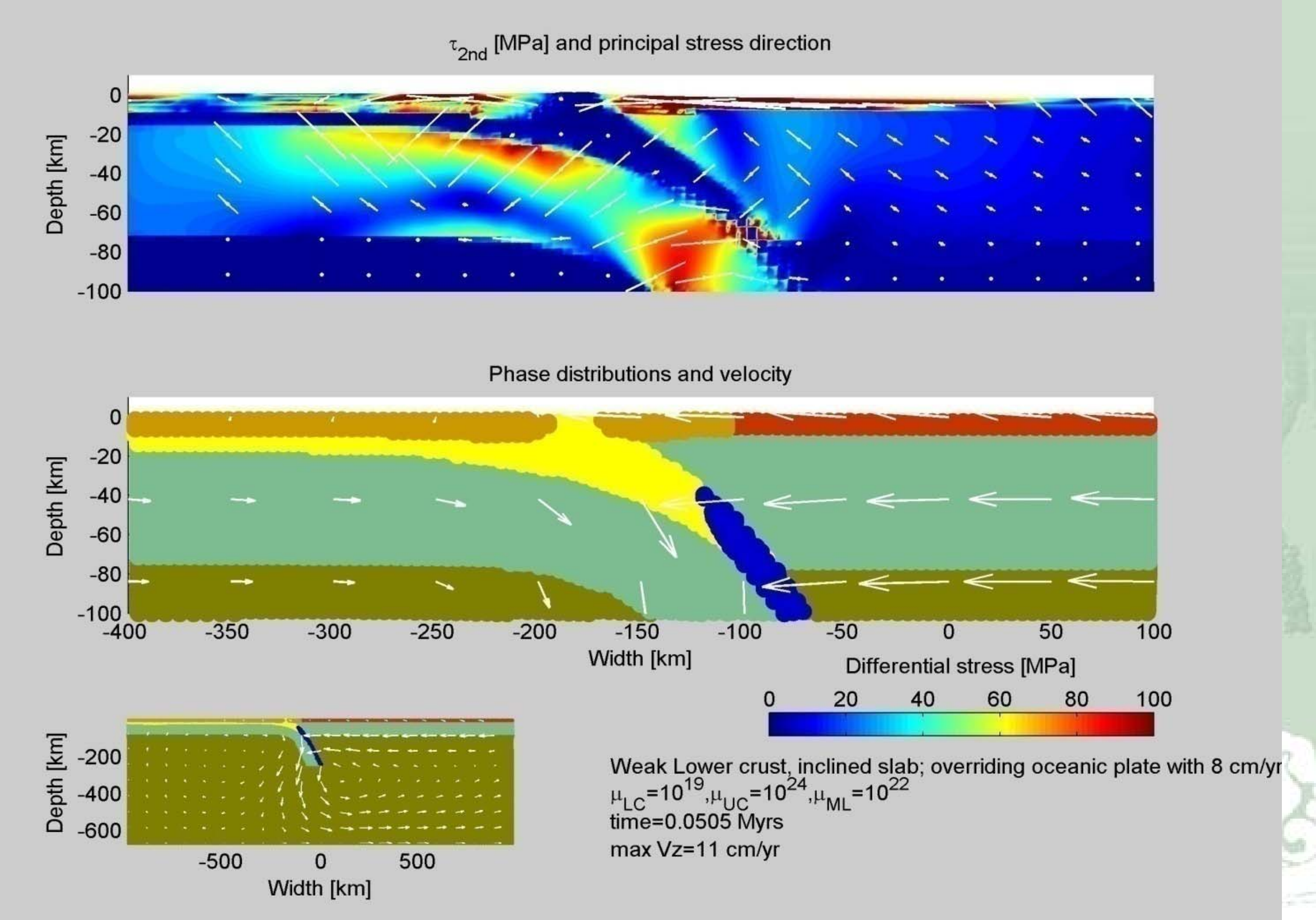
Weak Lower crust, inclined slab; Crustal wedge, overriding slab 8cm/

$\mu_{LC}=10^{19}, \mu_{UC}=10^{24}, \mu_{ML}=10^{22}$

time=0.0505 Myrs

max Vz=6 cm/yr

With overriding PSP (8 cm/yr)

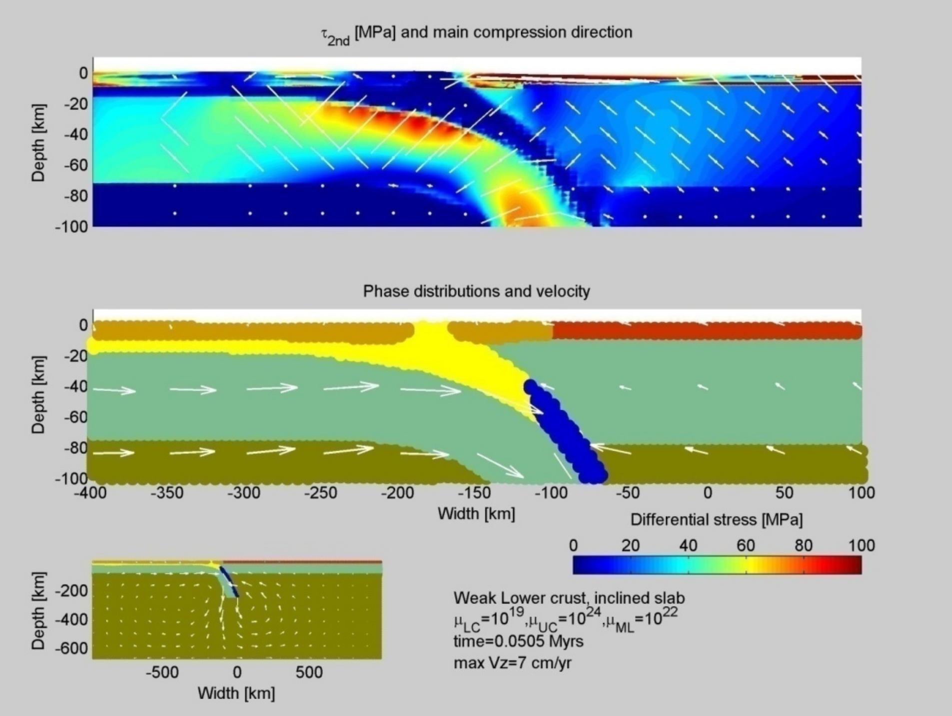


τ_{2nd} [MPa] and principal stress direction

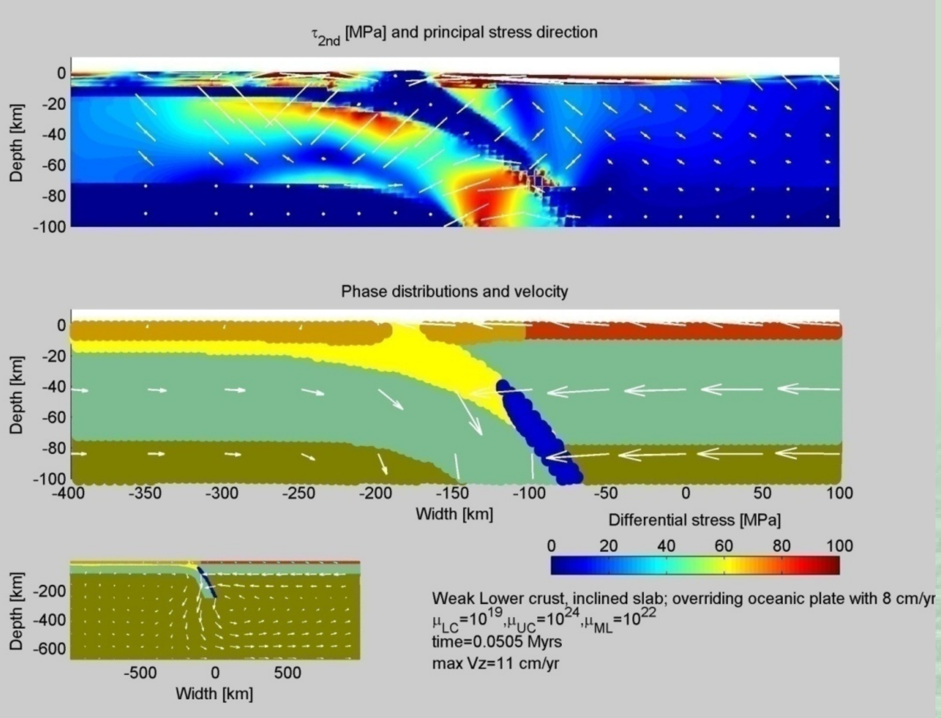
Phase distributions and velocity

Weak Lower crust, inclined slab; overriding oceanic plate with 8 cm/yr
$\mu_{LC}=10^{19}$, $\mu_{UC}=10^{24}$, $\mu_{ML}=10^{22}$
time=0.0505 Myrs
max Vz=11 cm/yr

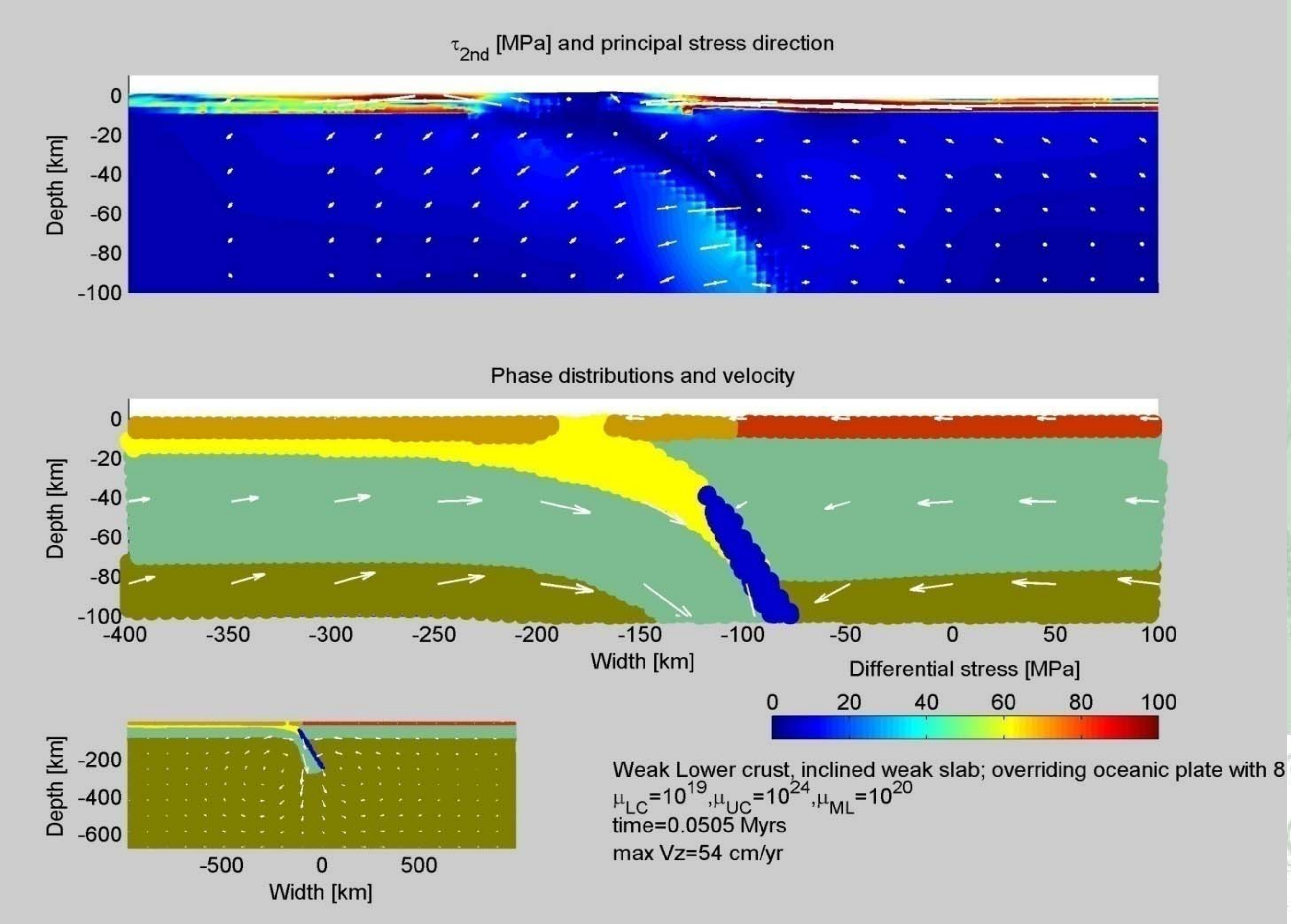
0 cm year



8 cm year



With overriding PSP & weak ML



τ_{2nd} [MPa] and principal stress direction

Phase distributions and velocity

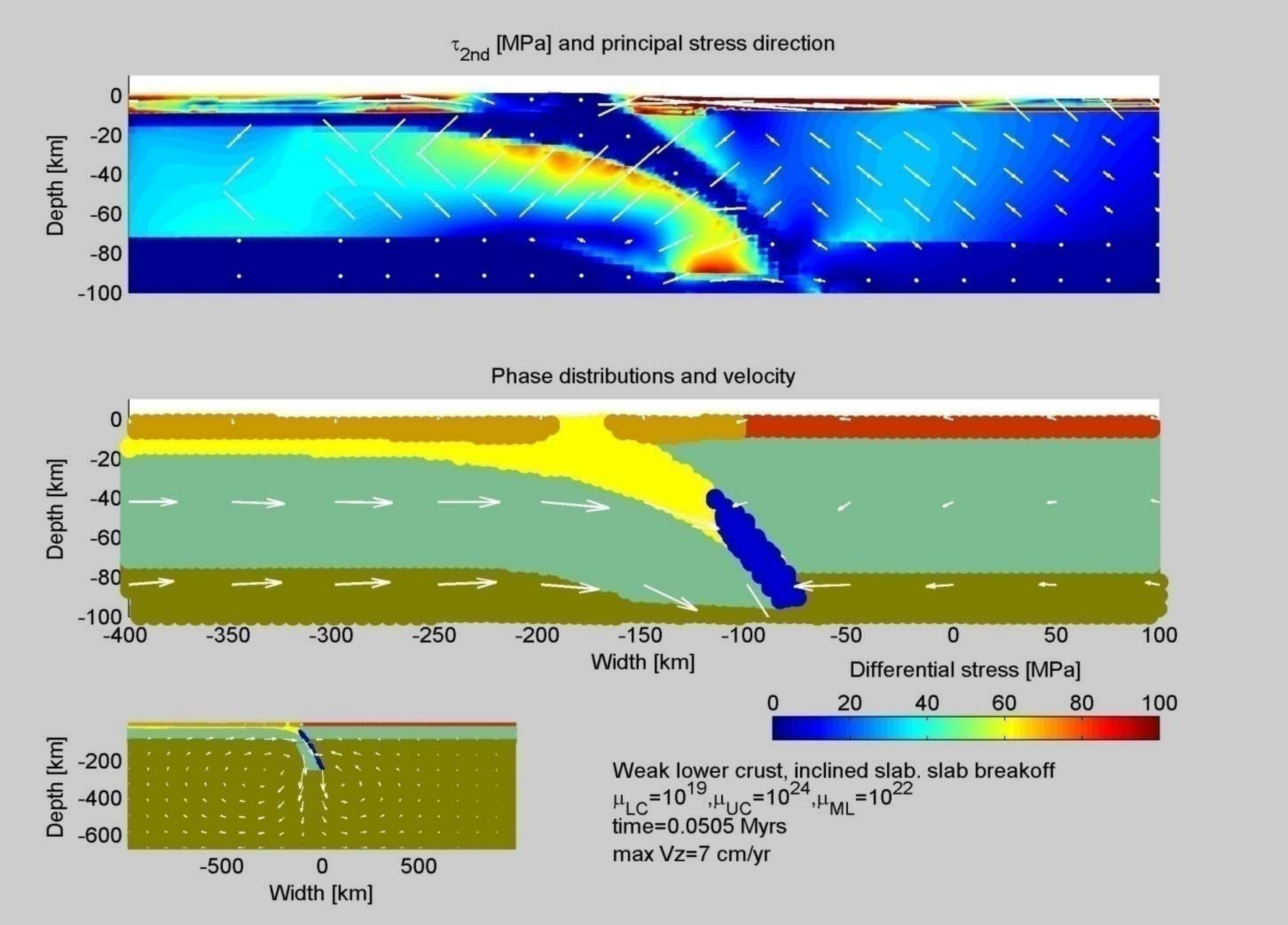
Weak Lower crust, inclined weak slab; overriding oceanic plate with 8

$\mu_{LC}=10^{19}$,$\mu_{UC}=10^{24}$,$\mu_{ML}=10^{20}$

time=0.0505 Myrs

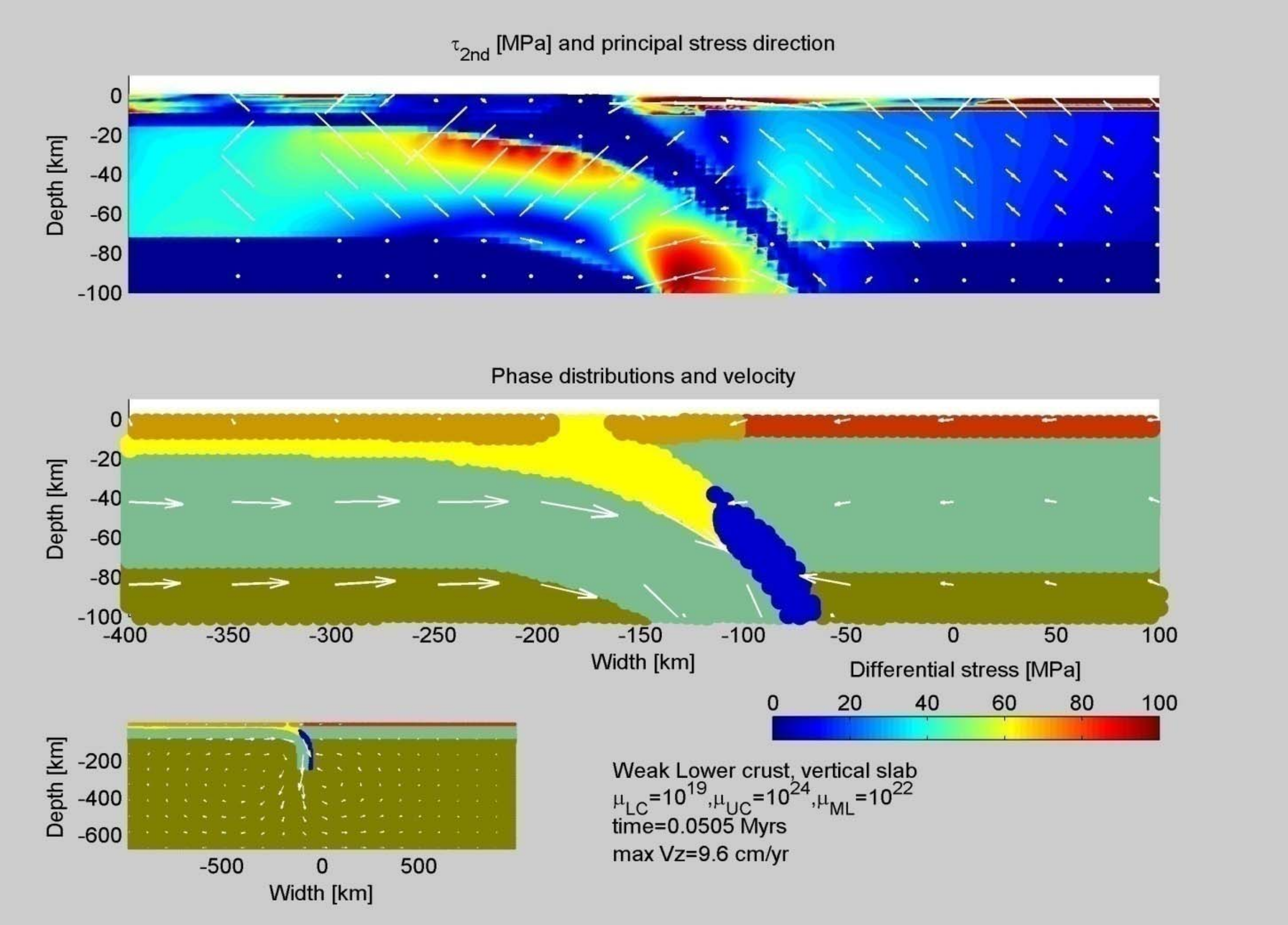
max Vz=54 cm/yr

Slab Breakoff (cut-off @ 100 km)

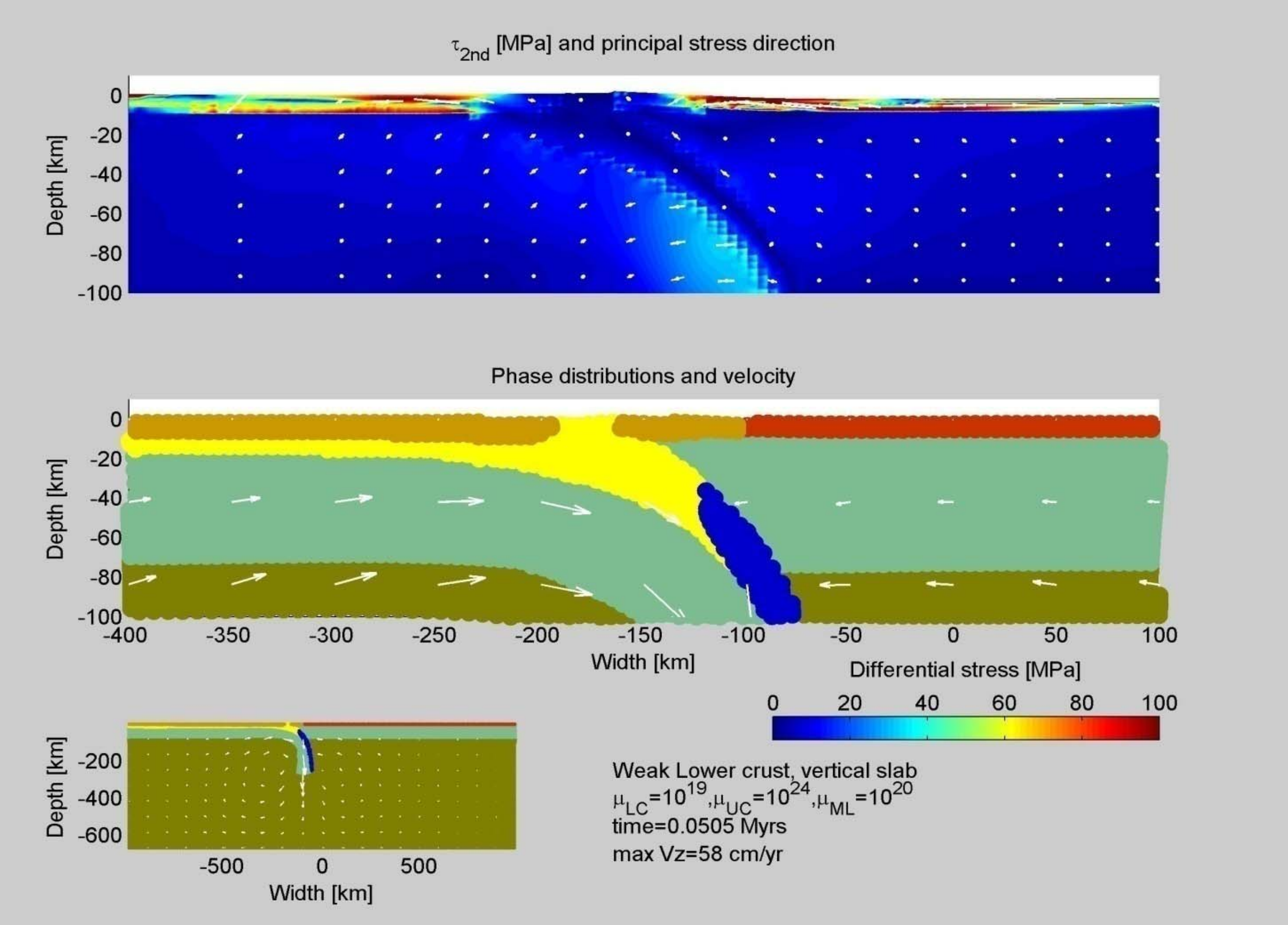


Weak lower crust, inclined slab. slab breakoff
$\mu_{LC}=10^{19}$,$\mu_{UC}=10^{24}$,$\mu_{ML}=10^{22}$
time=0.0505 Myrs
max Vz=7 cm/yr

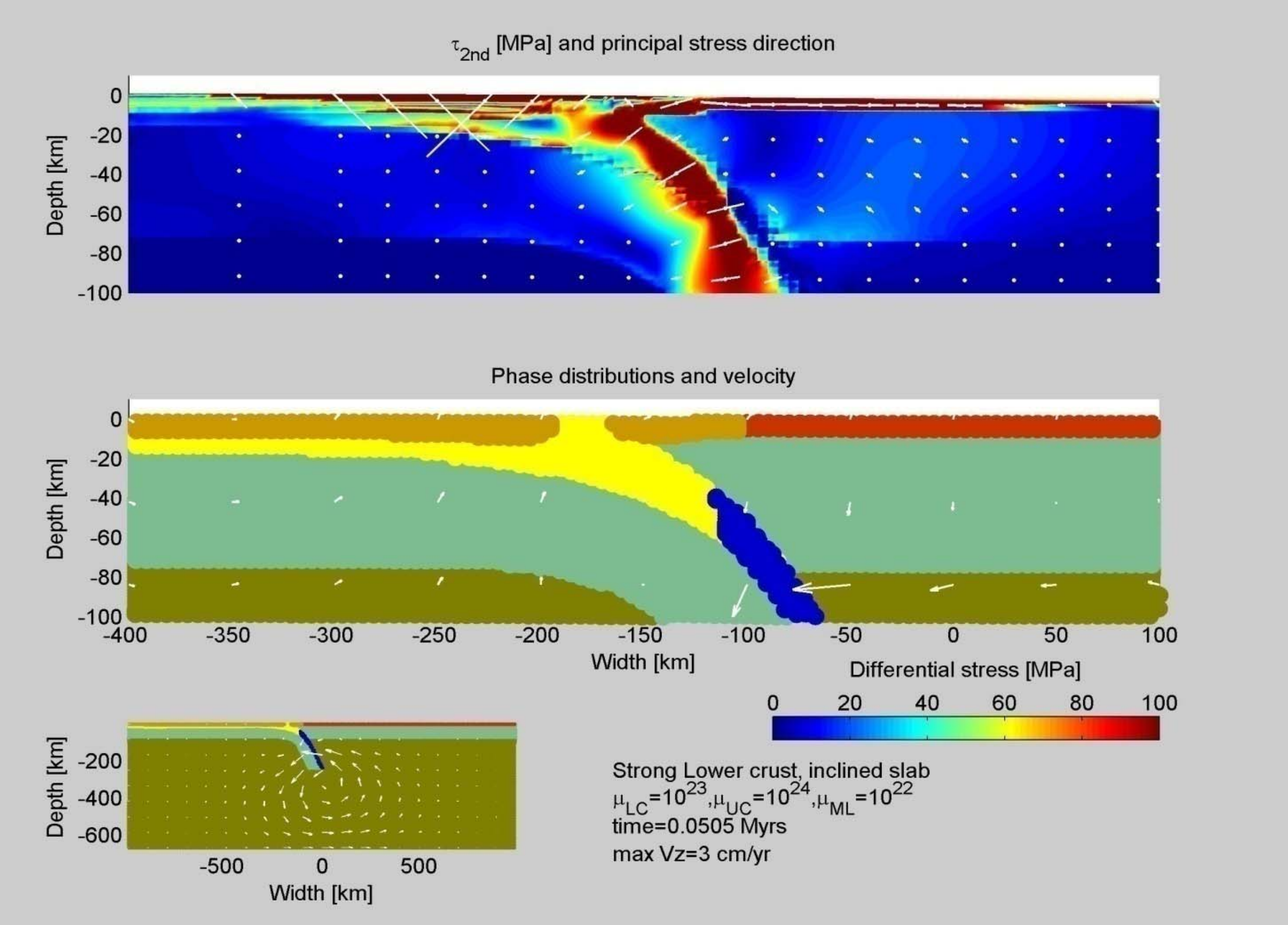
Vertical slab



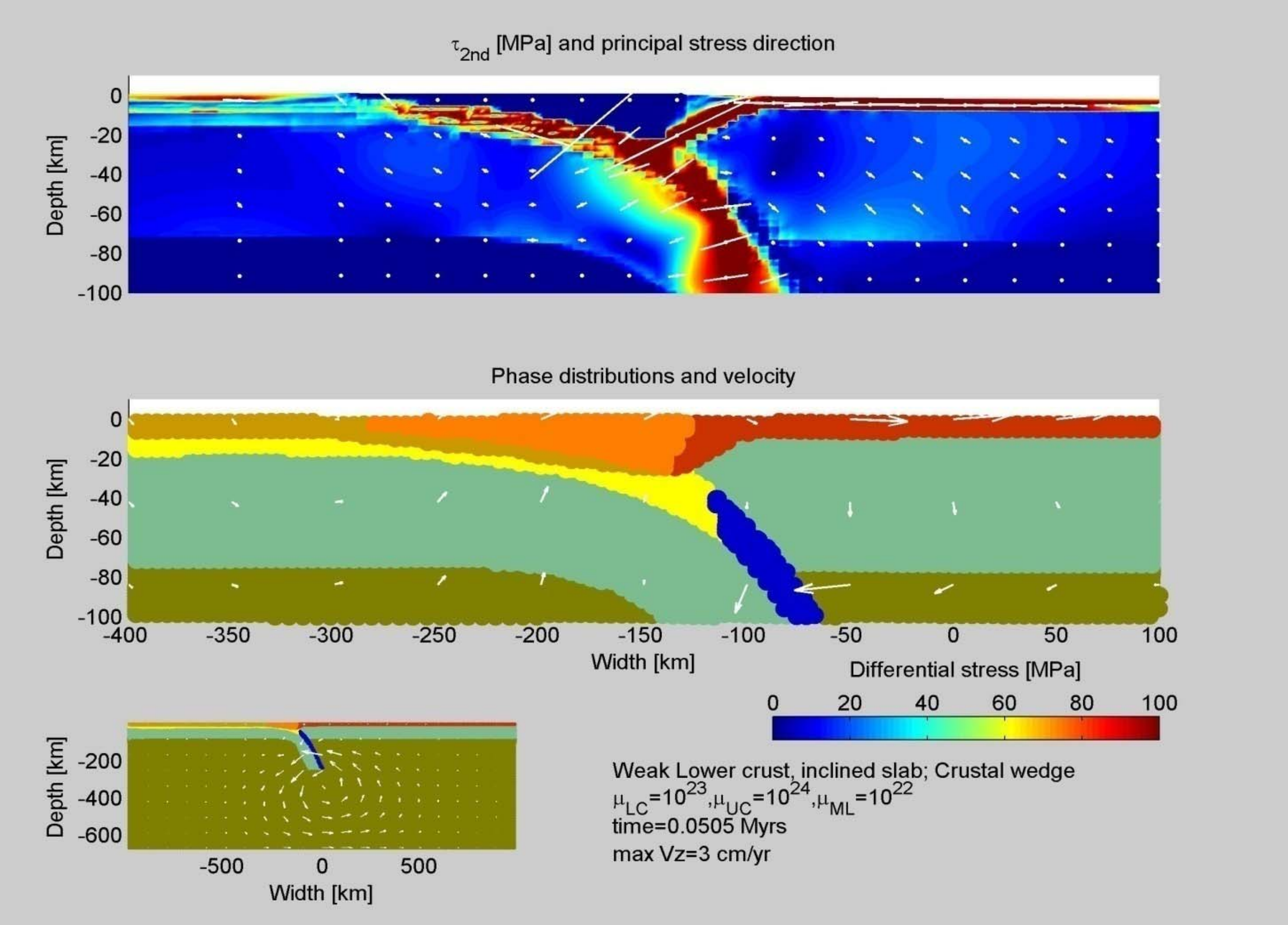
Vertical weak slab



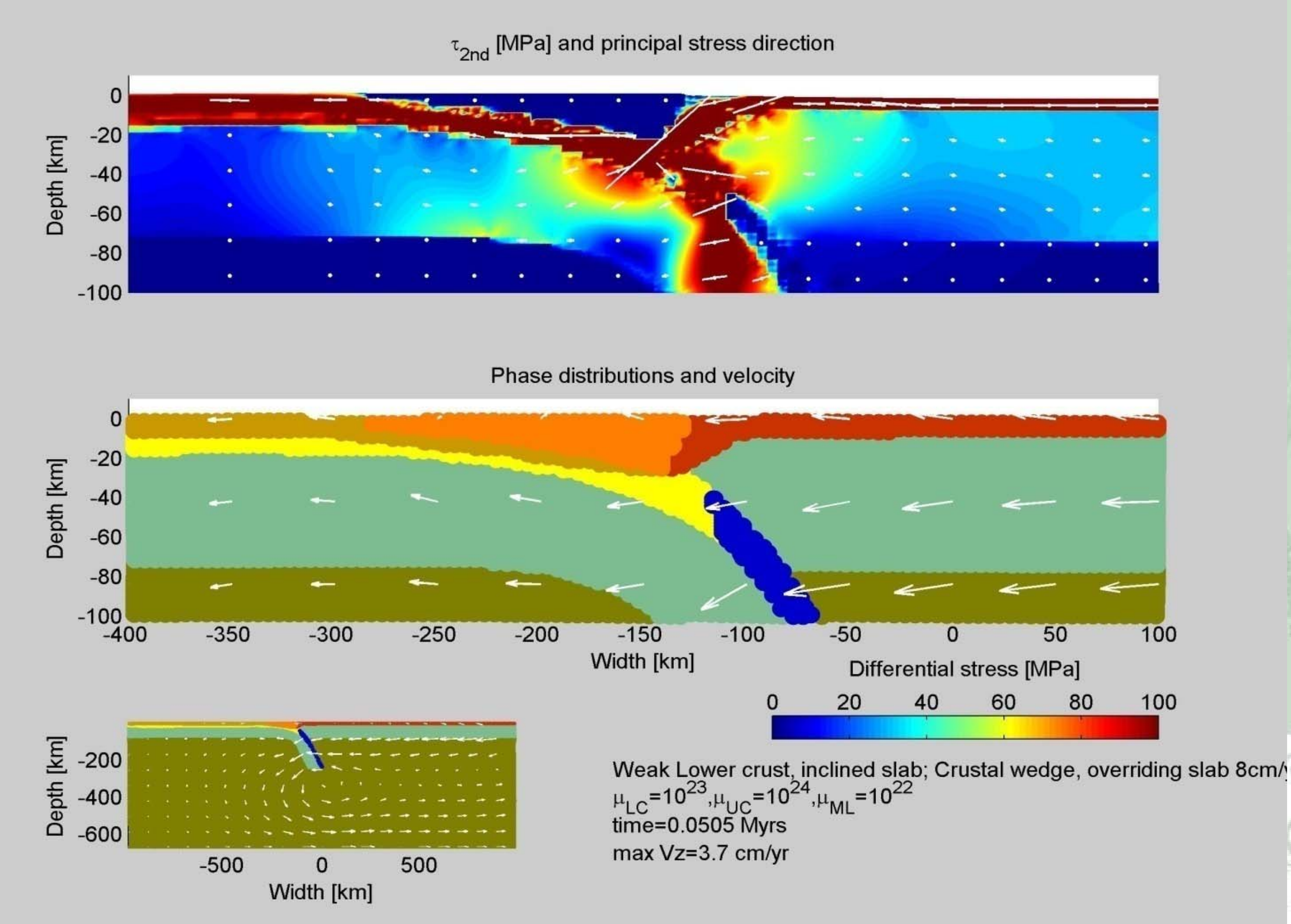
Strong lower crust



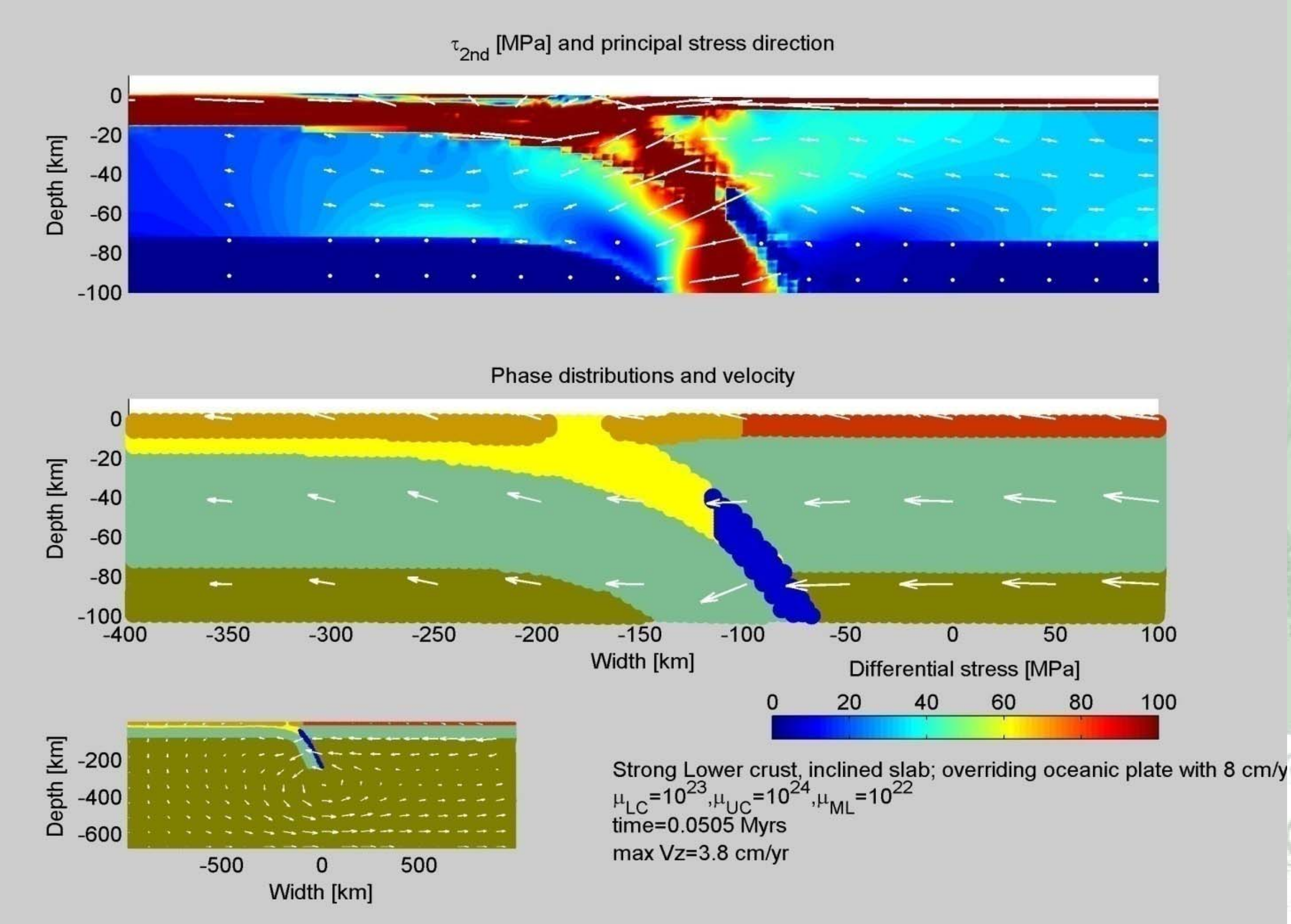
Strong LC & crustal wedge



Strong LC & crustal wedge & overriding PSP



Strong LC, overriding PSP (8cm/yr)

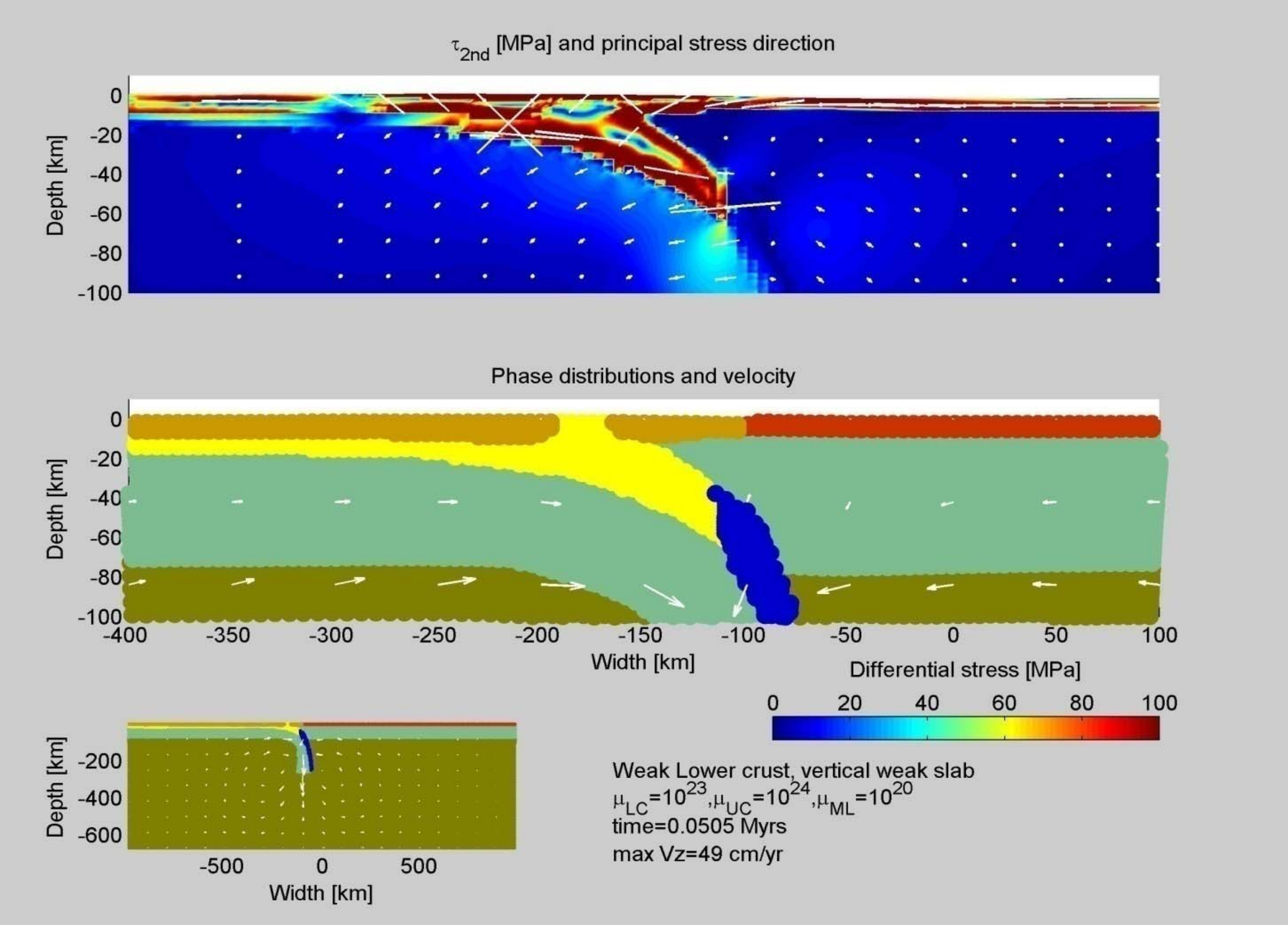


τ_{2nd} [MPa] and principal stress direction

Phase distributions and velocity

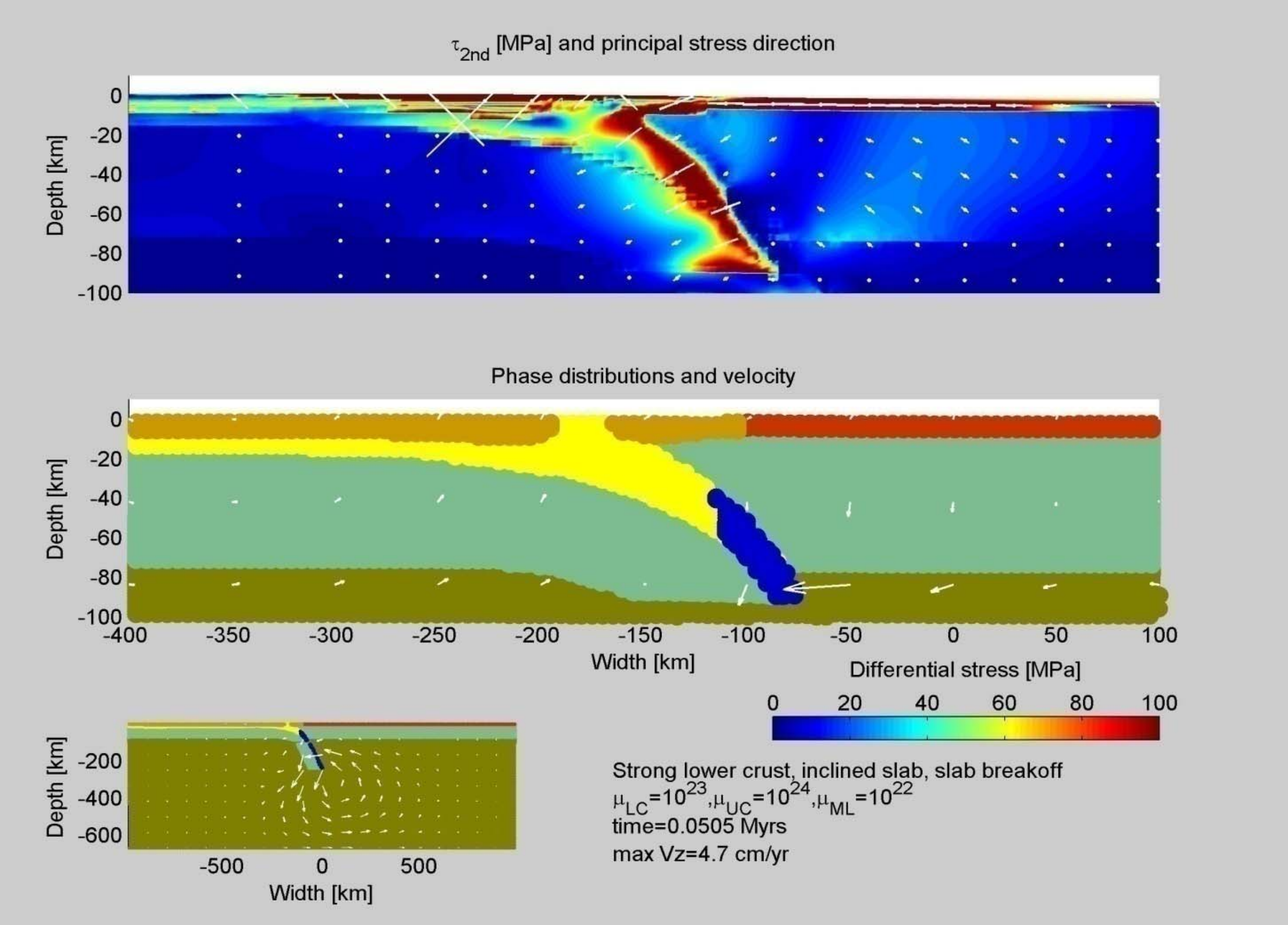
Strong Lower crust, inclined slab; overriding oceanic plate with 8 cm/y
$\mu_{LC}=10^{23}$,$\mu_{UC}=10^{24}$,$\mu_{ML}=10^{22}$
time=0.0505 Myrs
max Vz=3.8 cm/yr

Strong LC, overriding PSP (8cm/yr), weak slab



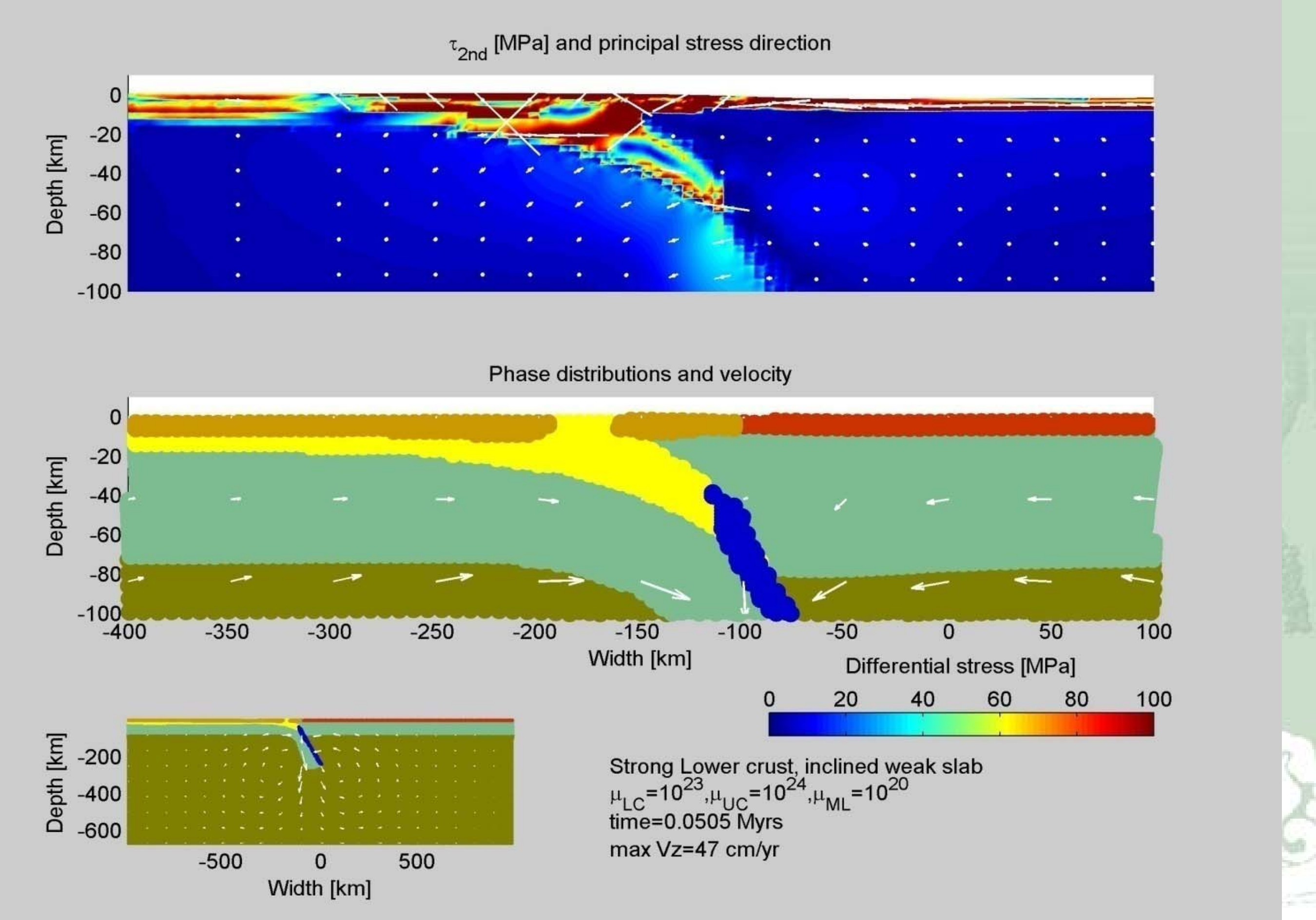
Weak Lower crust, vertical weak slab
$\mu_{LC}=10^{23}$, $\mu_{UC}=10^{24}$, $\mu_{ML}=10^{20}$
time=0.0505 Myrs
max Vz=49 cm/yr

Strong LC & slab breakoff



Strong lower crust, inclined slab, slab breakoff
$\mu_{LC}=10^{23}, \mu_{UC}=10^{24}, \mu_{ML}=10^{22}$
time=0.0505 Myrs
max Vz=4.7 cm/yr

Strong LC, weak slab (Crème Brulee)



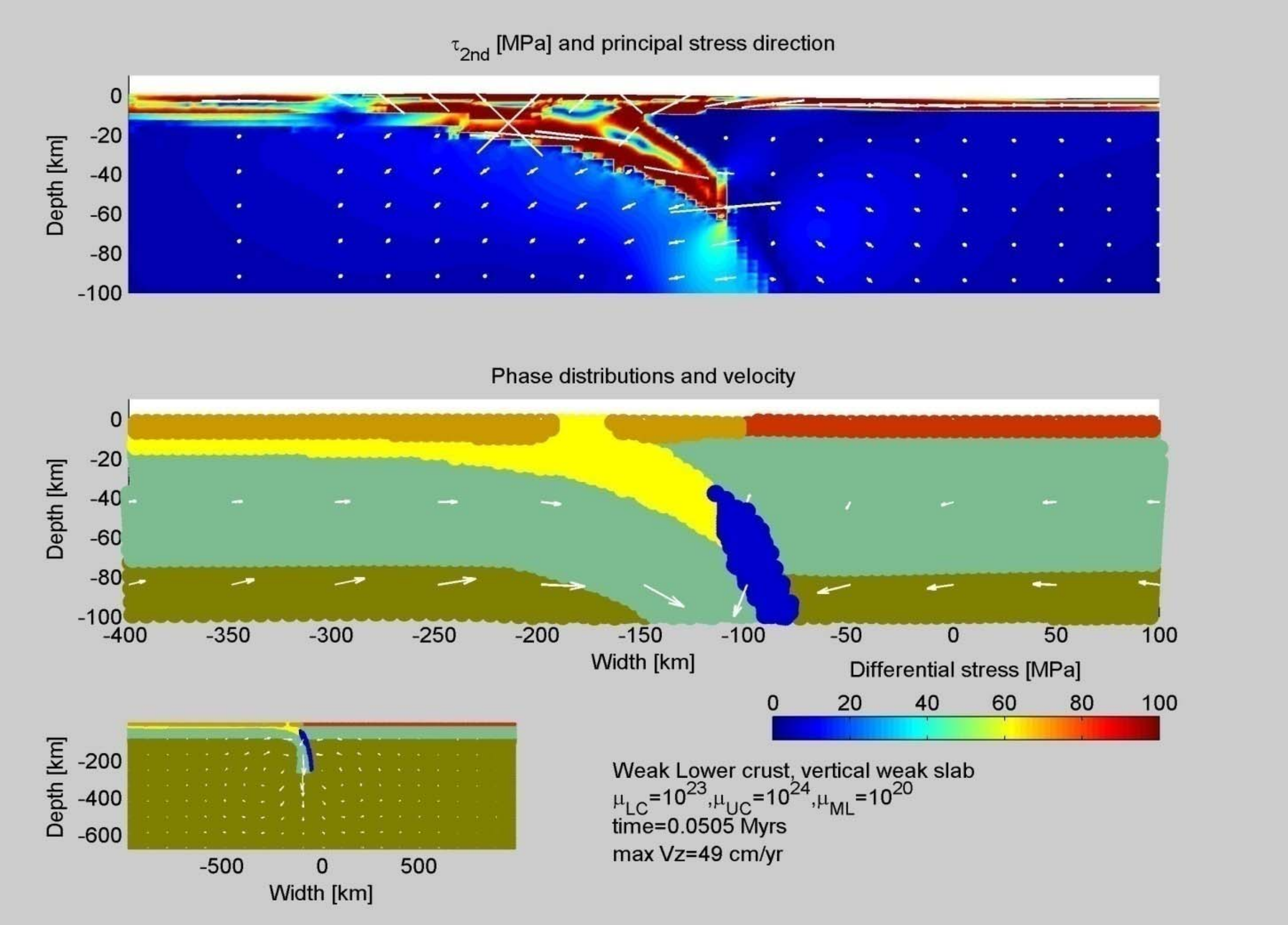
Strong Lower crust, inclined weak slab

$\mu_{LC}=10^{23}, \mu_{UC}=10^{24}, \mu_{ML}=10^{20}$

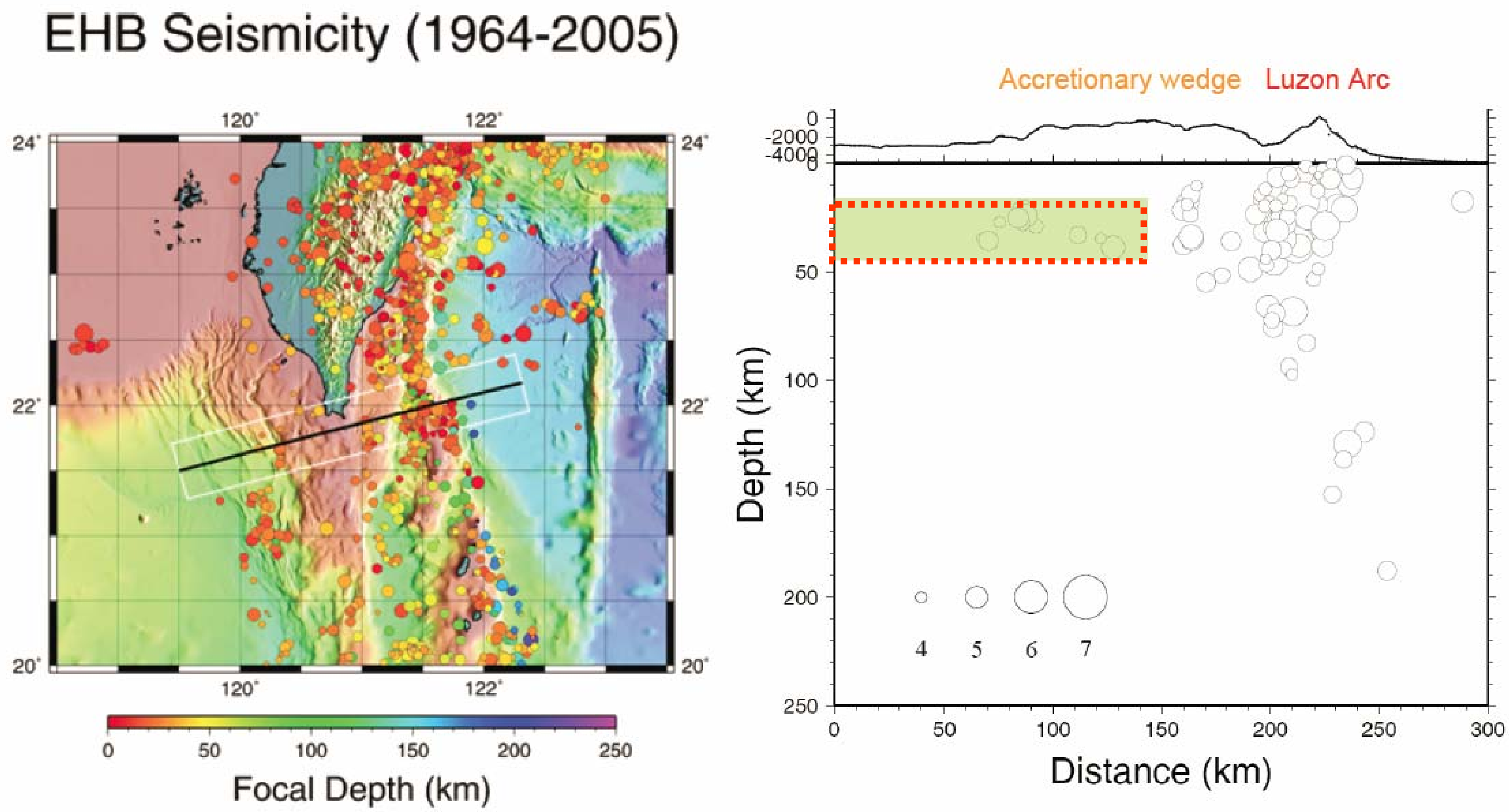
time=0.0505 Myrs

max Vz=47 cm/yr

Strong LC, weak vertical slab

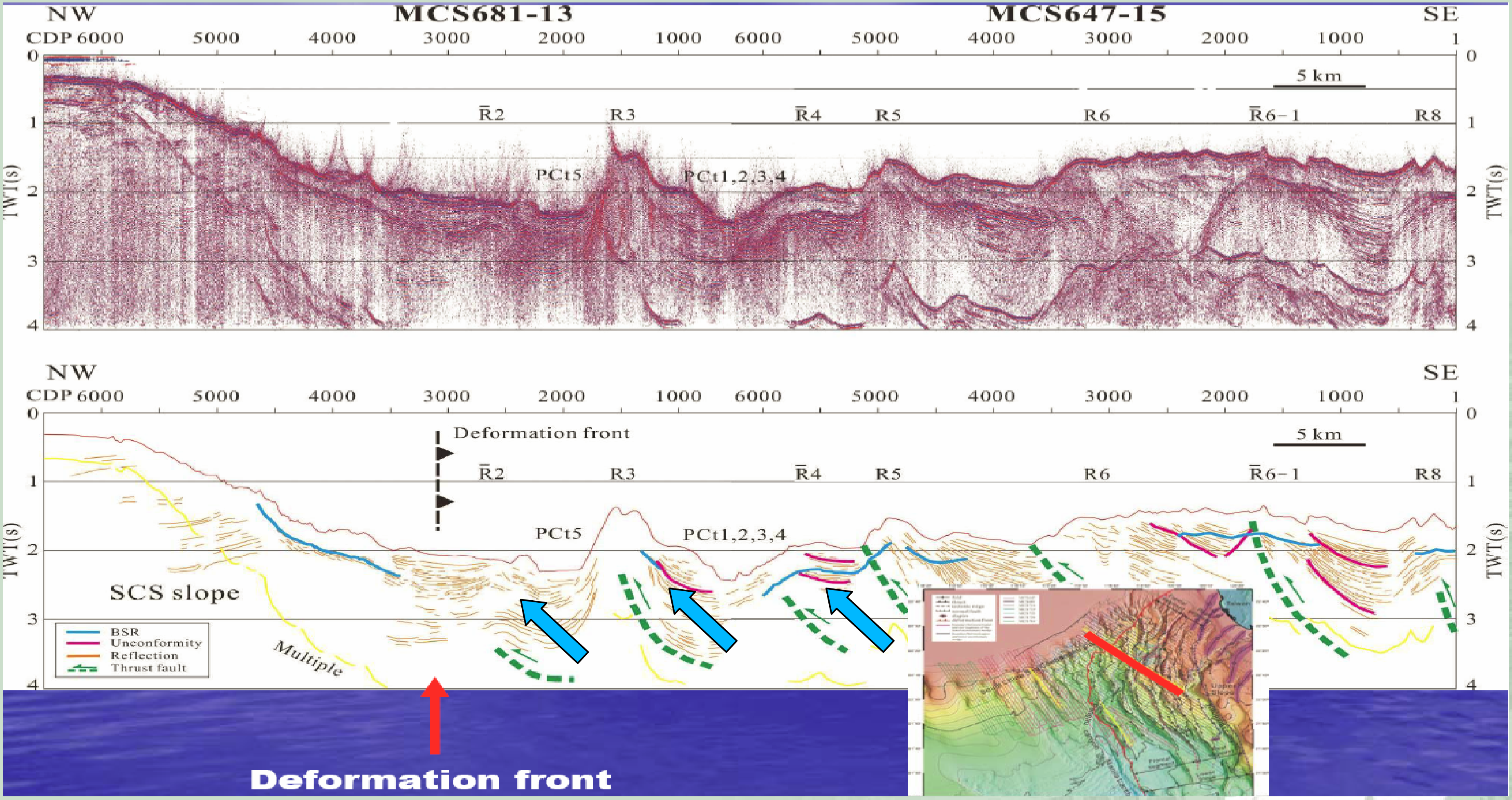


Historical Earthquakes Distribution

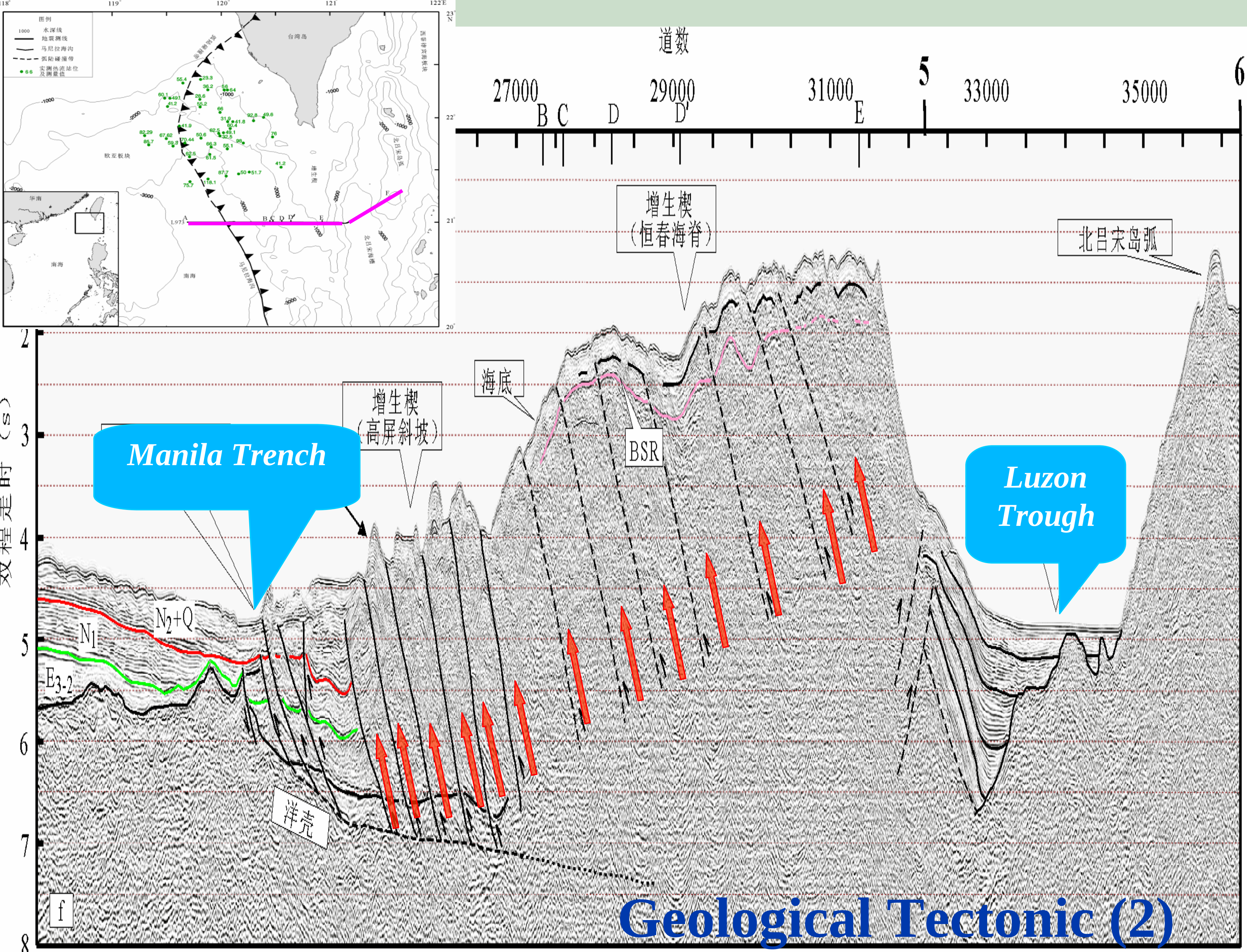


Engdahl, E.R., Van der Hilst, R.D. & Buland, R.P., 1998. Global teleseismic earthquake relocation with improved travel times and procedures for depth determination, *Bull. seism. Soc. Am.*, **88,** 722–743.

Geological Tectonics (1)



Deformation front



Geological Tectonic (2)

Conclusion 1

- In this case, the lower mantle layer must be decoupled from the upper crust by a very soft layer (lower crust). The upper crust is in compressional environment.
- The upper mantle lithosphere is extensional because of bending due to subducted slab, and because decoupled with upper crust compression

Conclusion 2

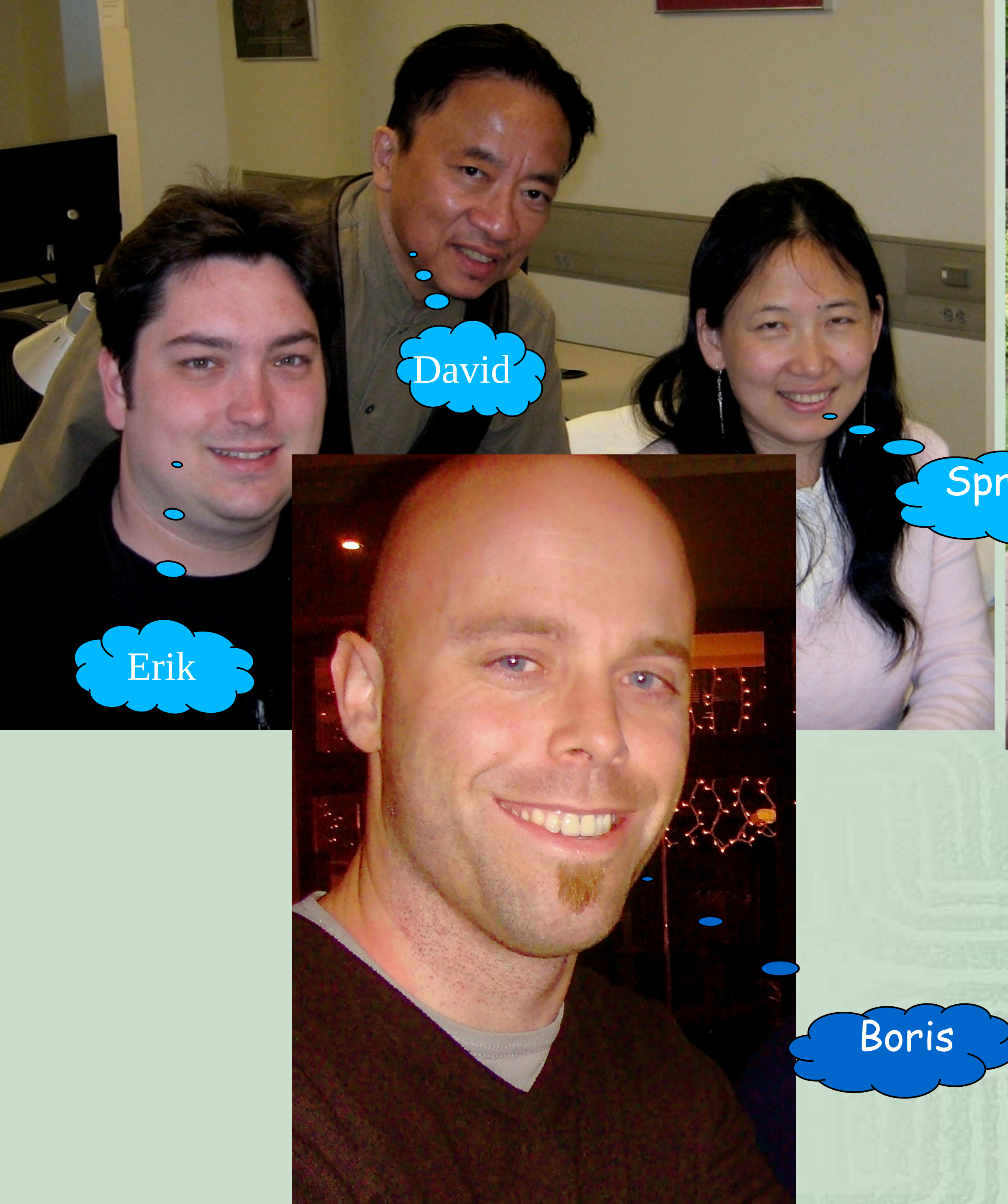
- Normal faulting EQs below Moho below southern Taiwan can be explained by slab subduction of the oceanic slab attached to the China plate.

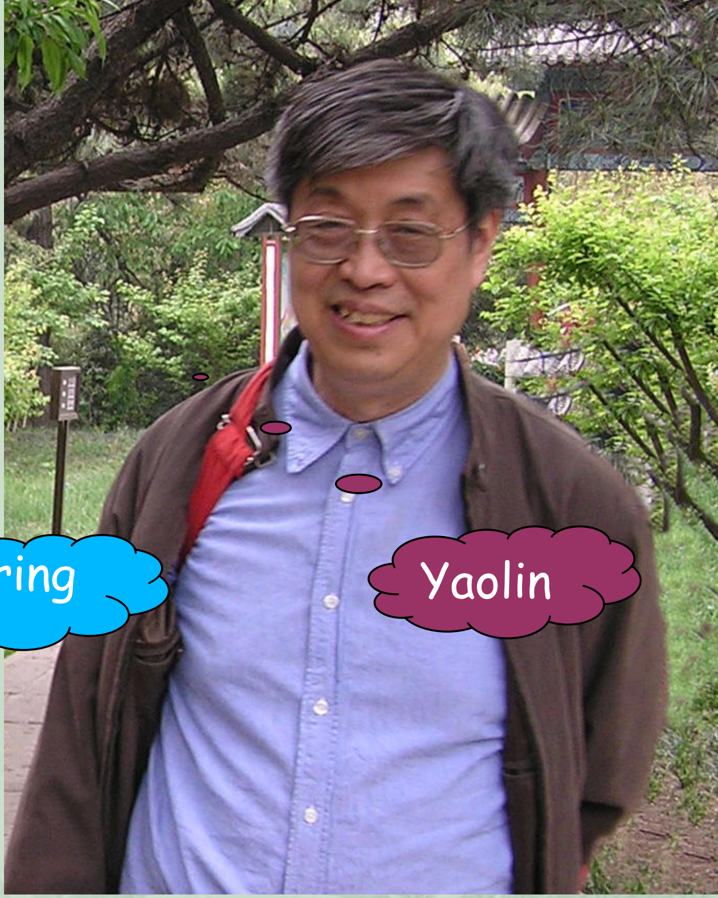
- A weak lower crust & sufficiently strong mantle lithosphere are required

To be done

- Include thermal effects (modifies the result but is unlikely to change the main conclusions).

Thanks for your attention!


David
Spring
Erik
Boris


Yaolin