The Abdus Salam
International Centre
for Theoretical Physics

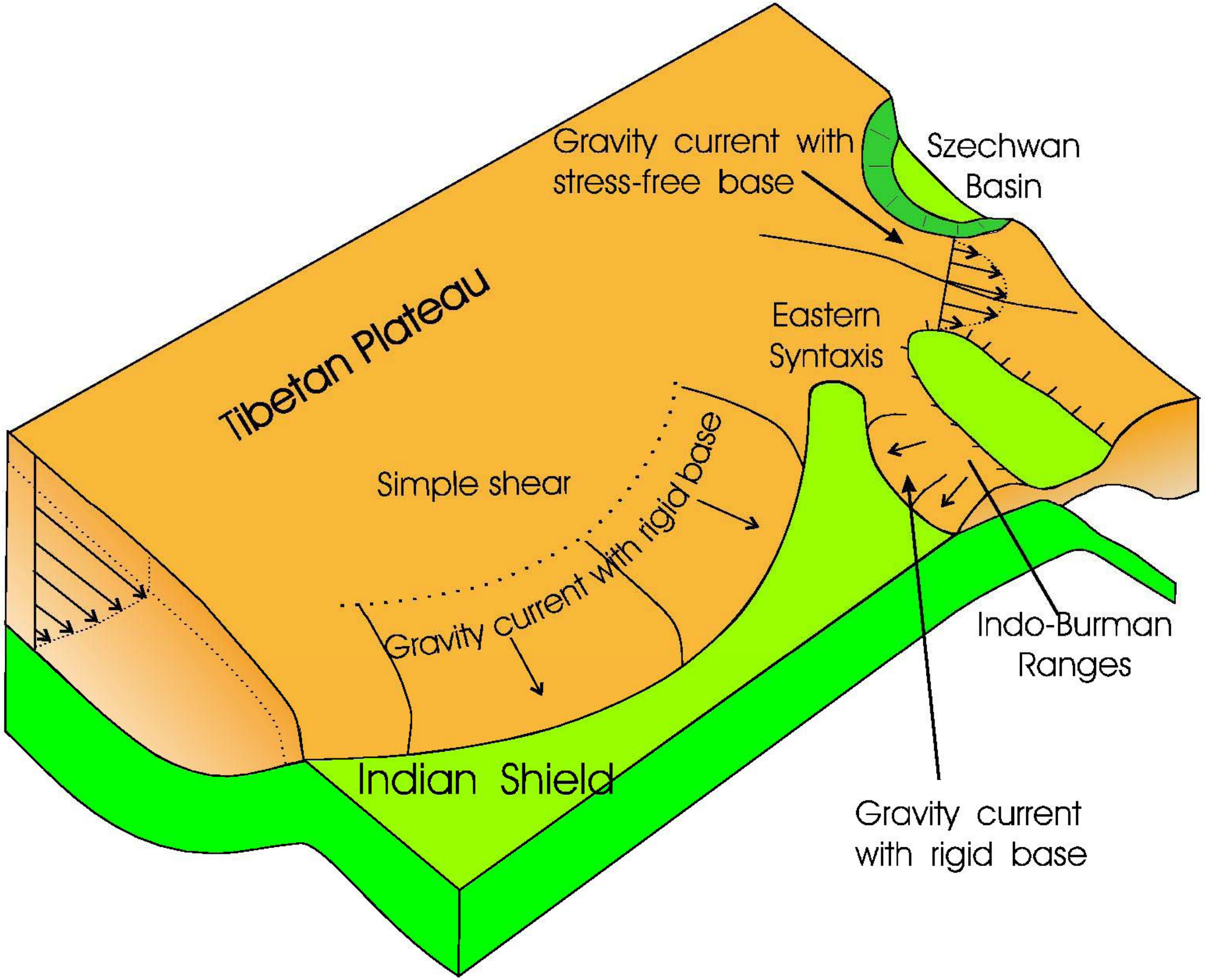
2464-10

Earthquake Tectonics and Hazards on the Continents

17 - 28 June 2013

The Mechanics of Continental Deformation: Examples from Southern Asia

A. Copley
University of Cambridge
UK

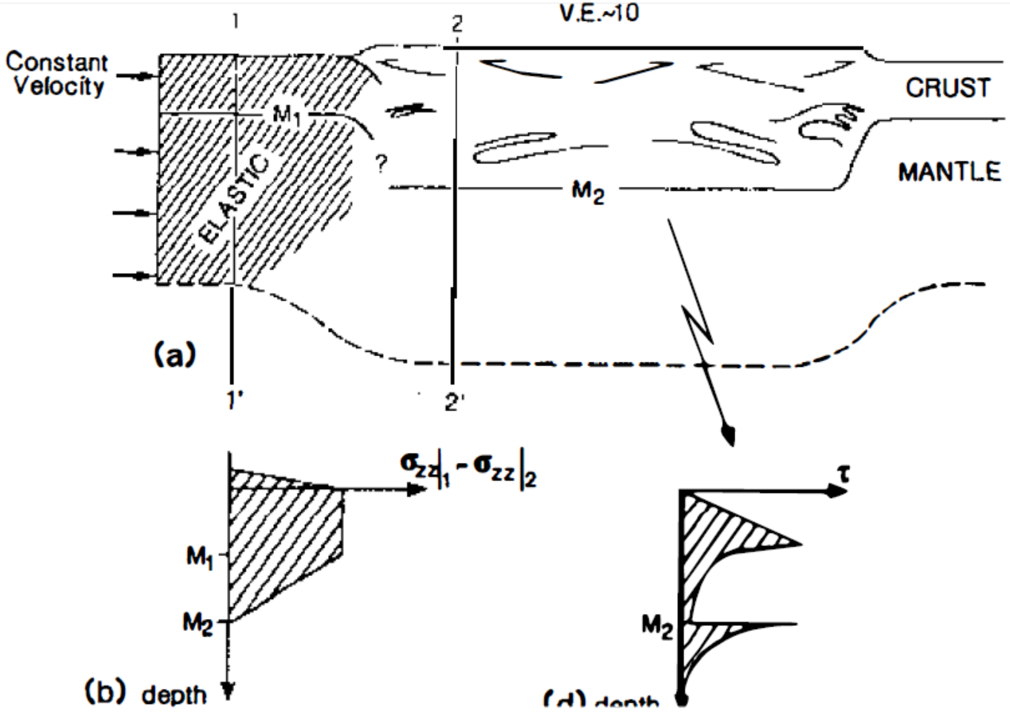


The dynamics of Tibet: the importance of lowland strength

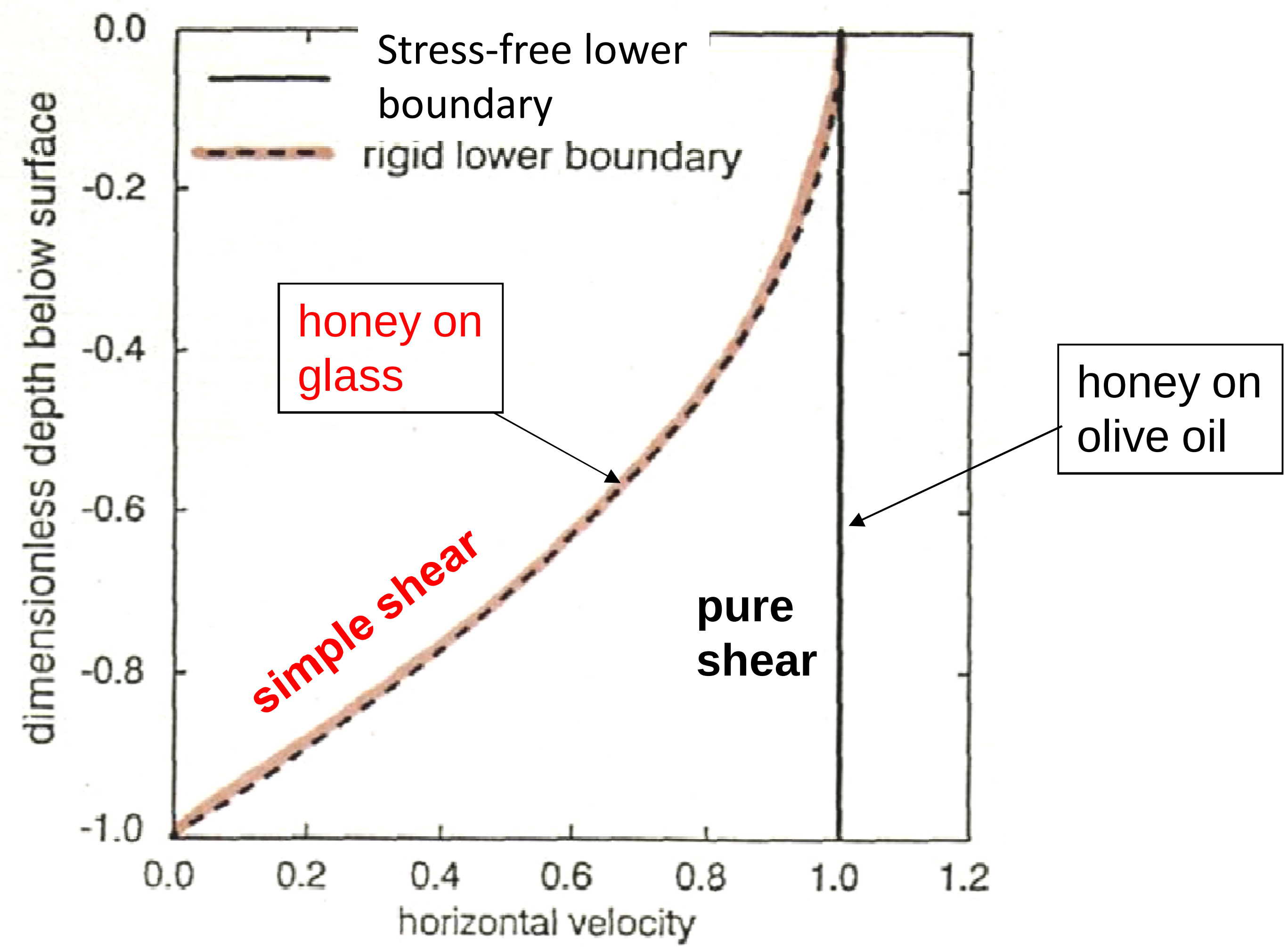
Some assumptions Philip was using:

1. The lithosphere can be treated as a **fluid**
2. The lithosphere is **hot** because of thickening and radiogenic heating -> **significant flow**
3. The base of the flowing layer (the lithosphere) is **'stress-free'** (which means vertical planes deform by **pure shear**)

The 'Thin-Viscous-Sheet' model



Viscous Gravity Currents



honey on glass

honey on olive oil

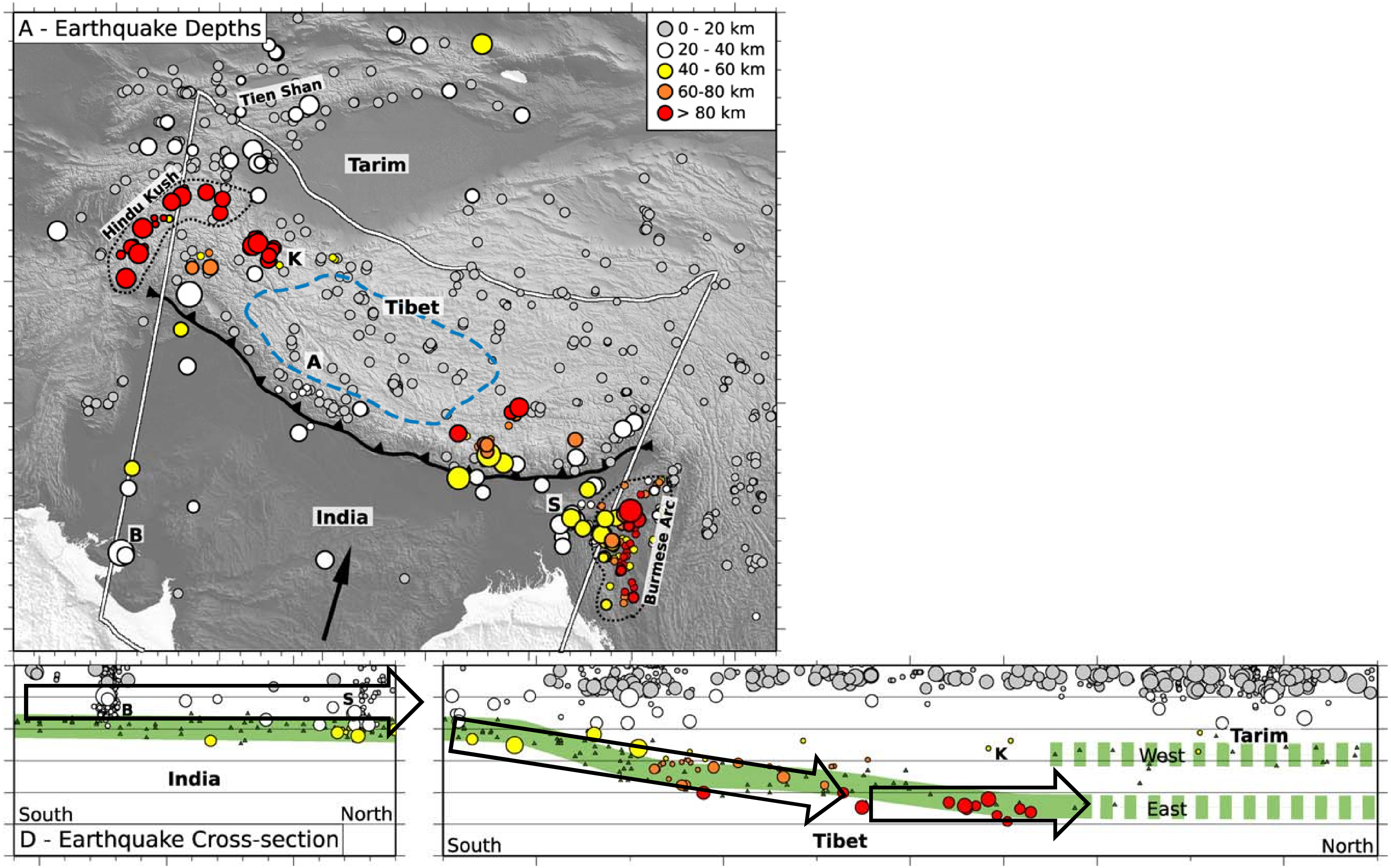
simple shear

pure shear

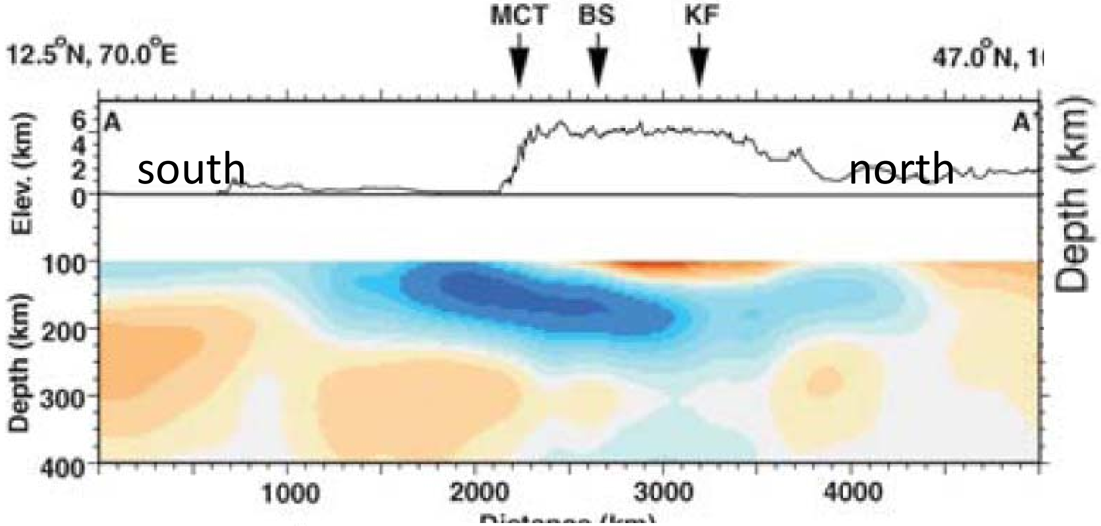
McKenzie et al (2000)

Tibetan seismicity

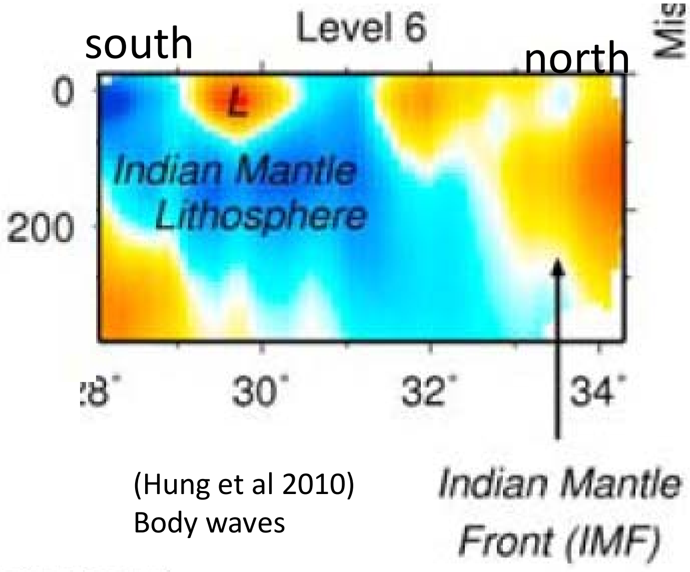
(Craig et al 2012)



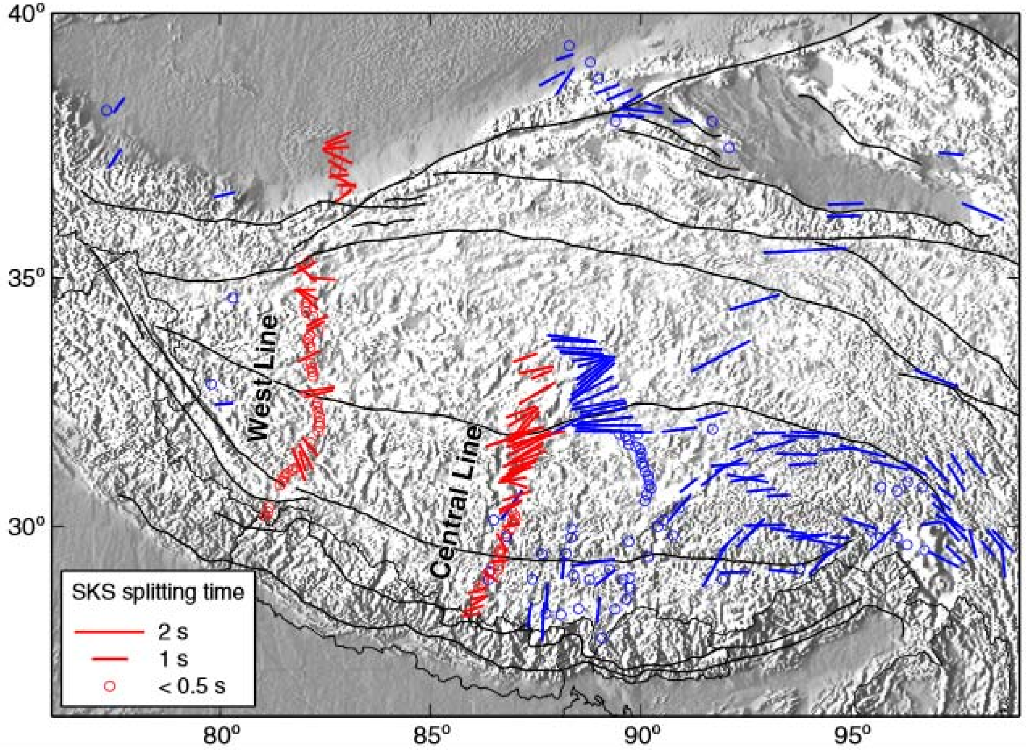
The seismic structure of the Tibetan Plateau



(Priestley et al 200
Surface waves



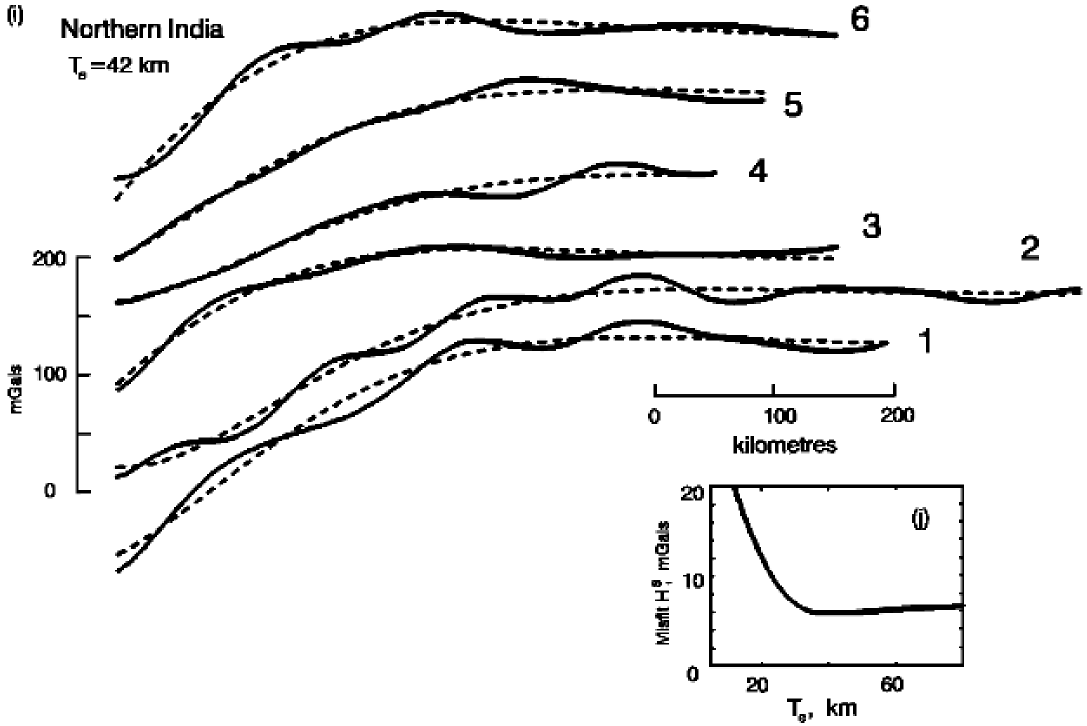
(Hung et al 2010)
Body waves

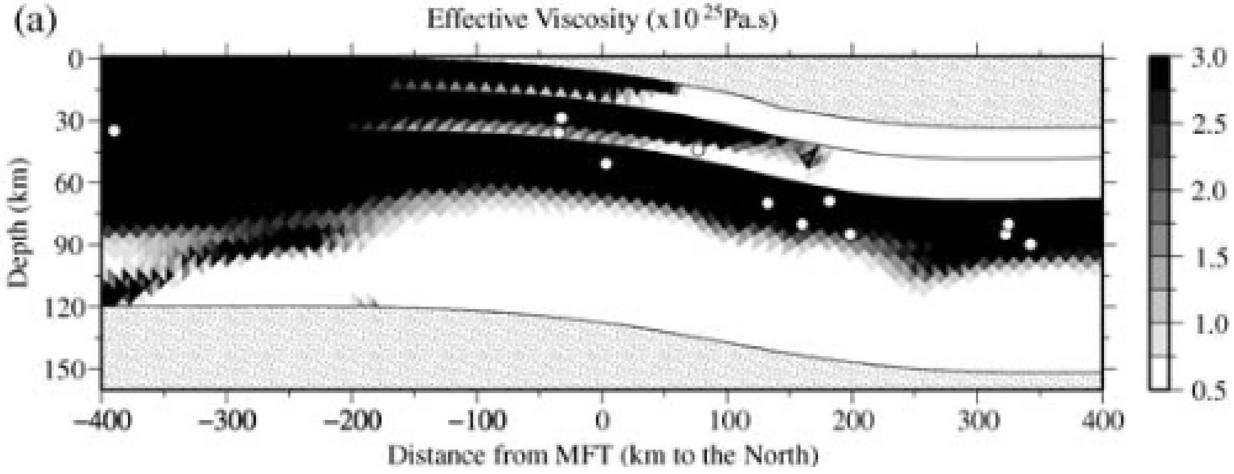


Anisotropy, Zhao et al 2010

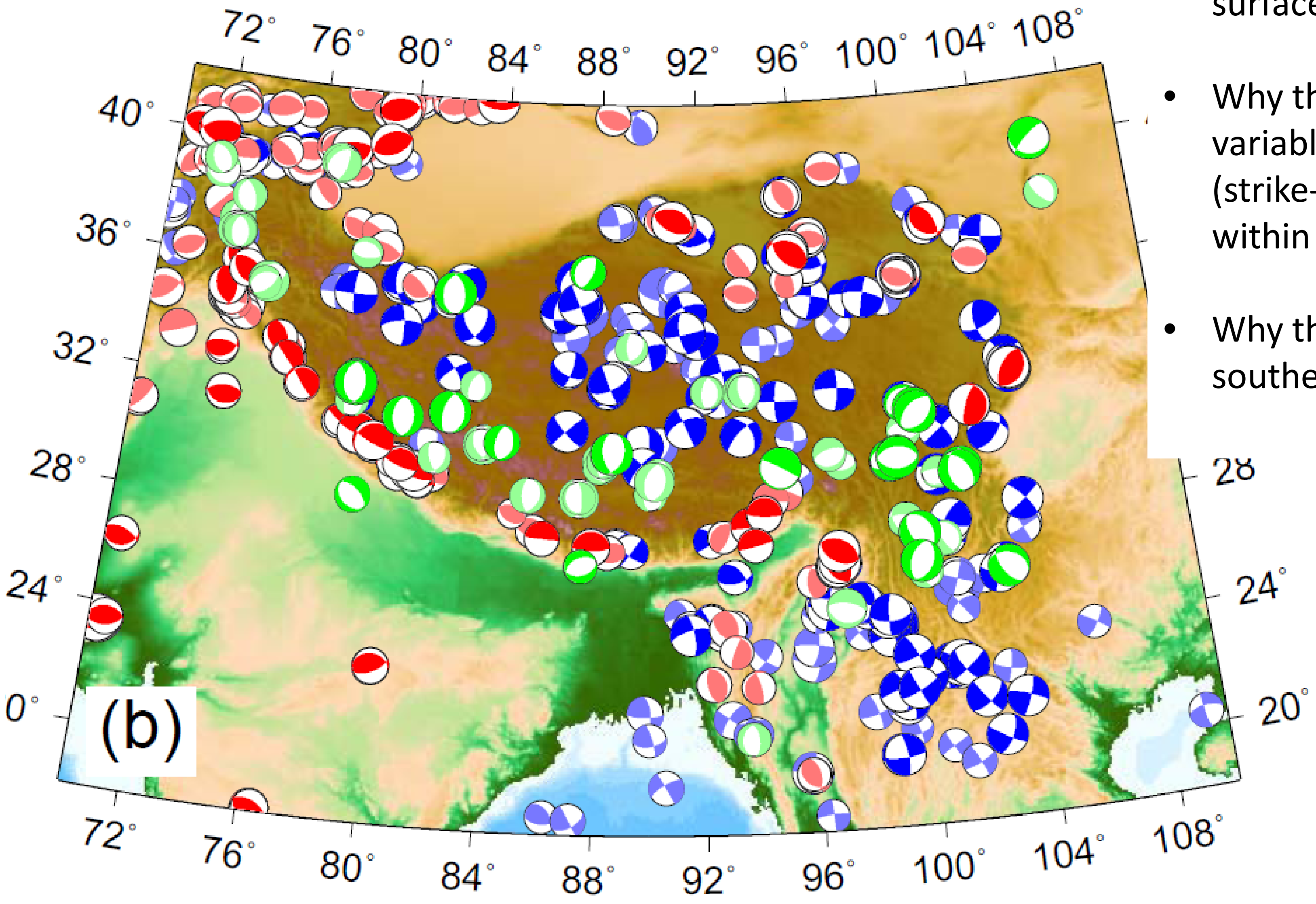
The strength of India

McKenzie and Fairhead (1997)



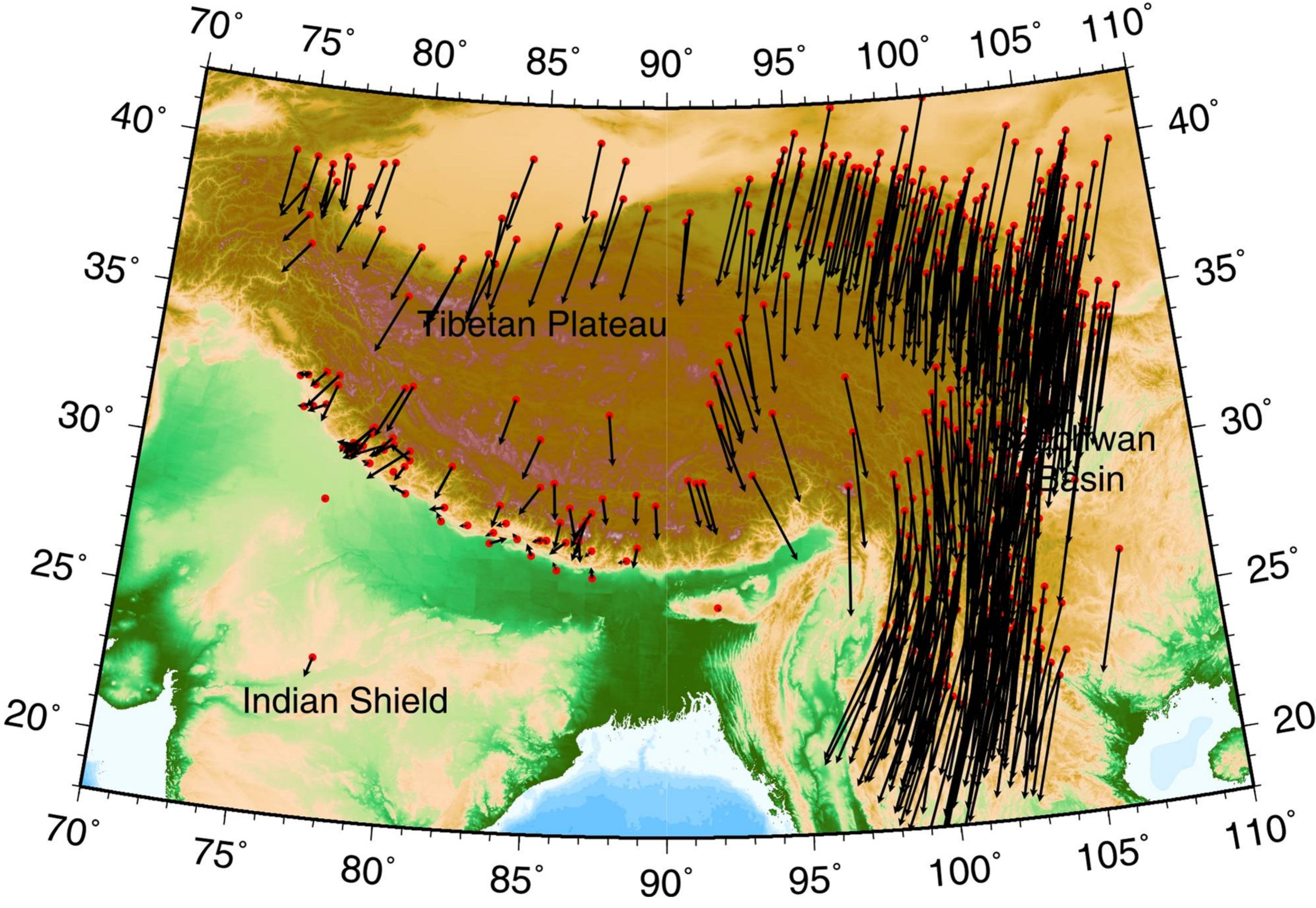


Hetenyi et al 2006

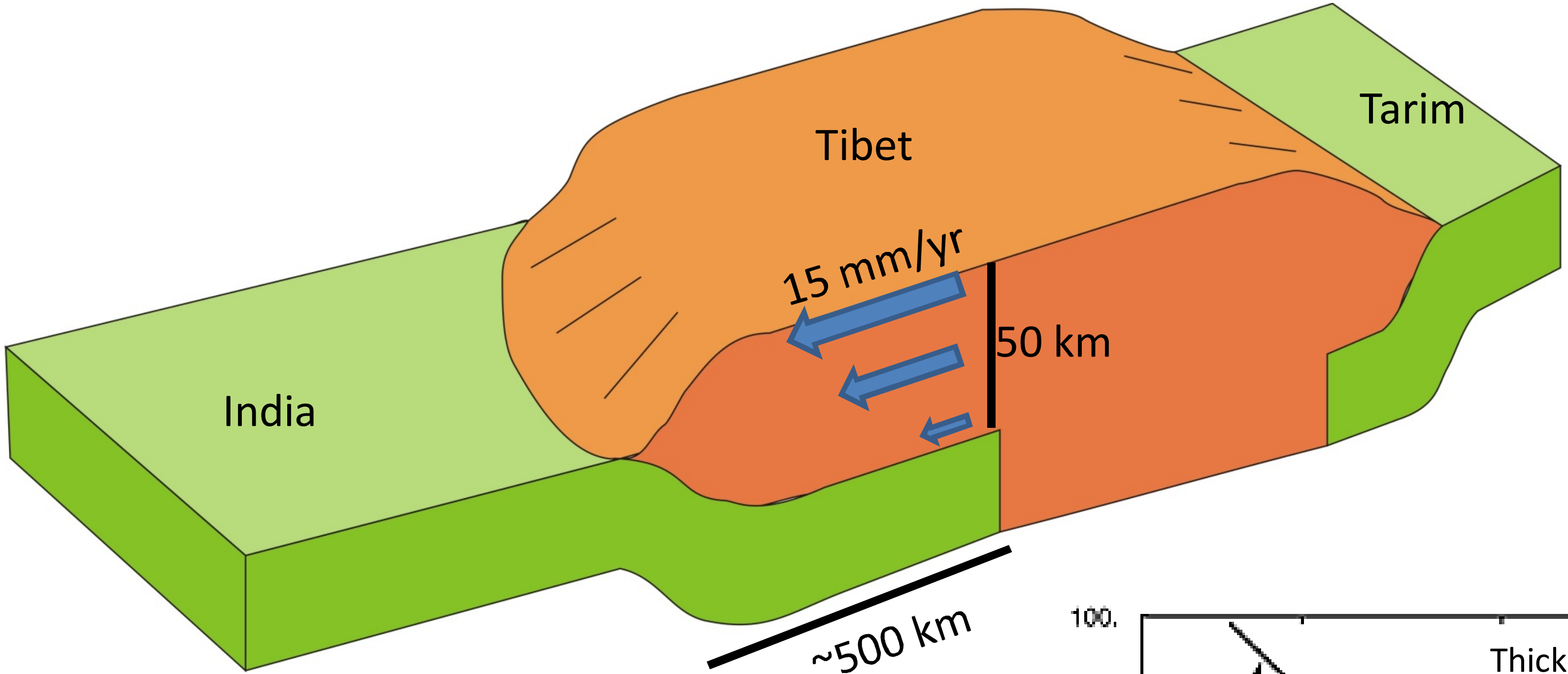


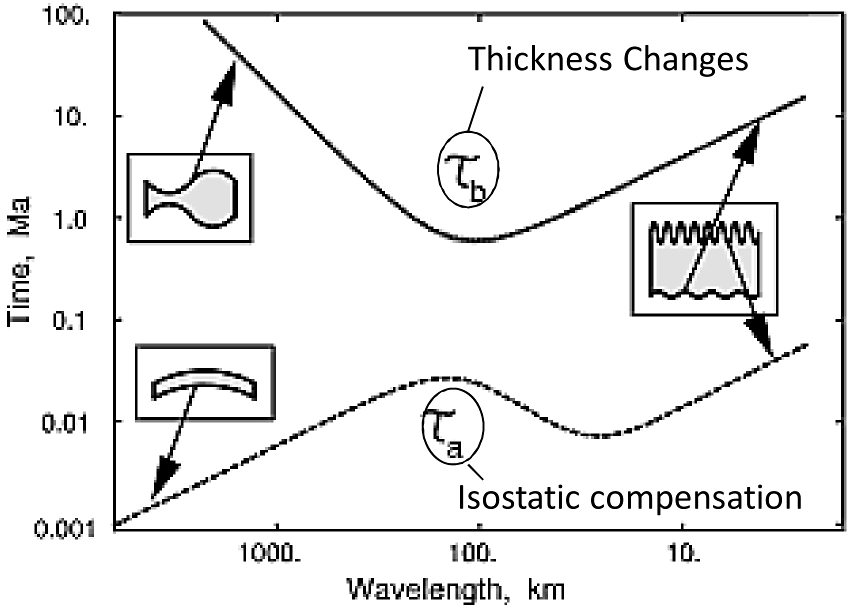
Questions:

- Why the variations in surface gradients?
- Why the spatially variable faulting (strike-slip/normal) within the plateau?
- Why the curved southern margin?


70°
75°
80°
85°
90°
95°
100°
105°
110°
40°
35°
30°
25°
20°
Tibetan Plateau
Sichuan Basin
Indian Shield

Schematic cross-section through Tibet

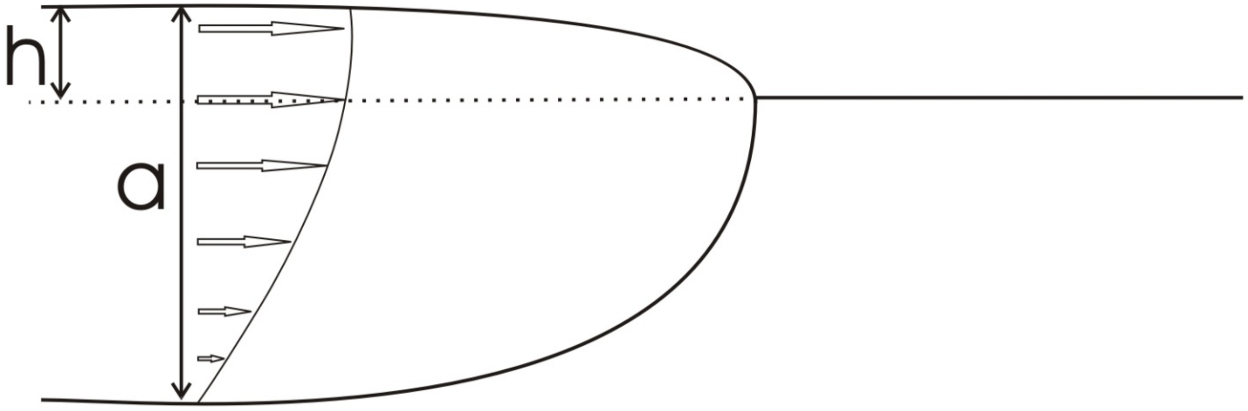




(McKenzie et al 2000)

Low-Reynolds-number gravity current with a rigid base

(Huppert 1982)



$$\frac{\rho g}{\eta}\frac{\partial h}{\partial x} = \frac{\partial^2 u}{\partial z^2}$$

Boundary conditions are

$$\left(\frac{\partial u}{\partial z}\right)_{z=h} = 0, \qquad (u)_{z=h-a} = 0$$

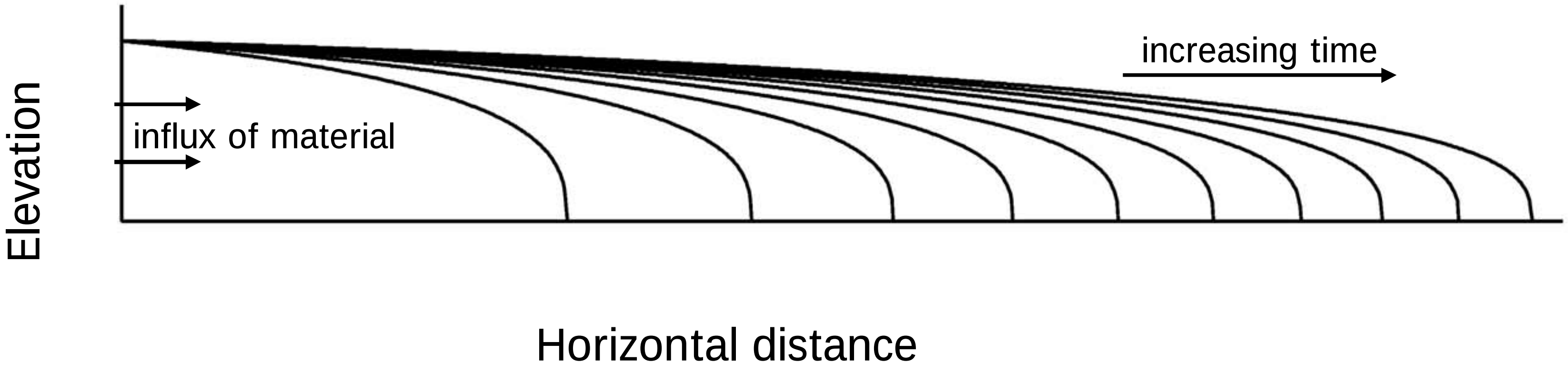
Which gives velocity of

$$u = \frac{\rho g}{2\eta}\left(z^2 - 2hz - \left(f^2 + 2f\right)h^2\right)\frac{\partial h}{\partial x}$$

At z=h, $\mathbf{u} = -\frac{\rho_1 g(f+1)^2}{2\eta}h^2\nabla h$

Flow in a thin layer with a rigid base

produces distinctive topography – a gently sloping top and a steep front (Huppert 1982)

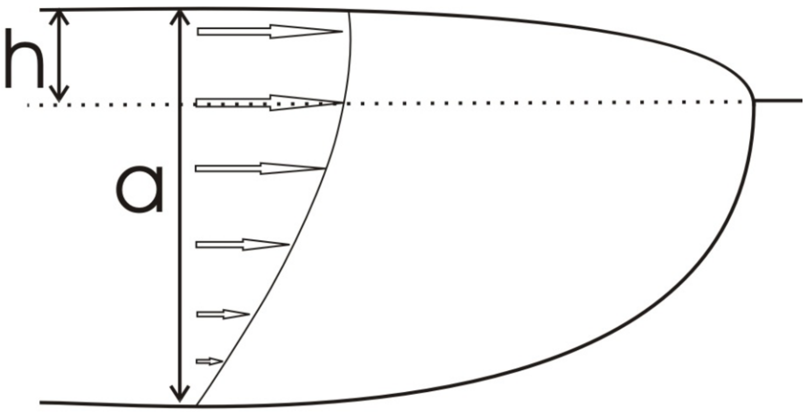


Surface velocity depends on viscosity, surface slope, and flow thickness:

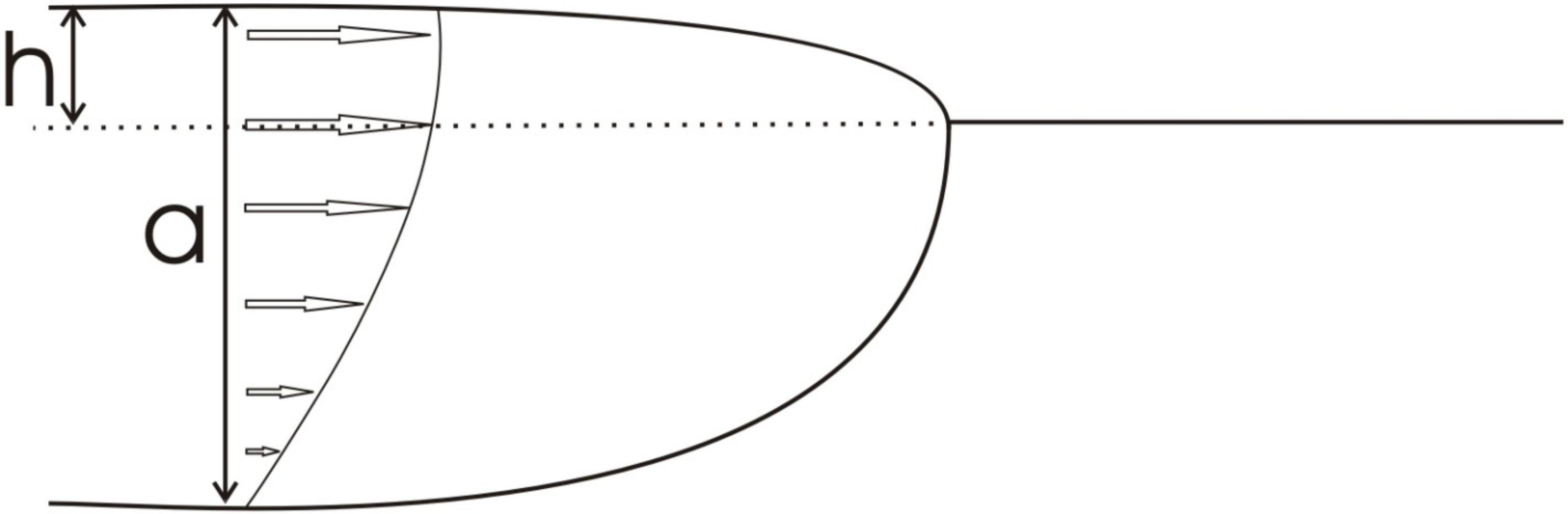
$$u = -\frac{\rho g (f + 1)^2}{2\eta} h^2 \nabla h$$

(McKenzie et al 2000)

Vertical planes deform by simple shear above the rigid base:



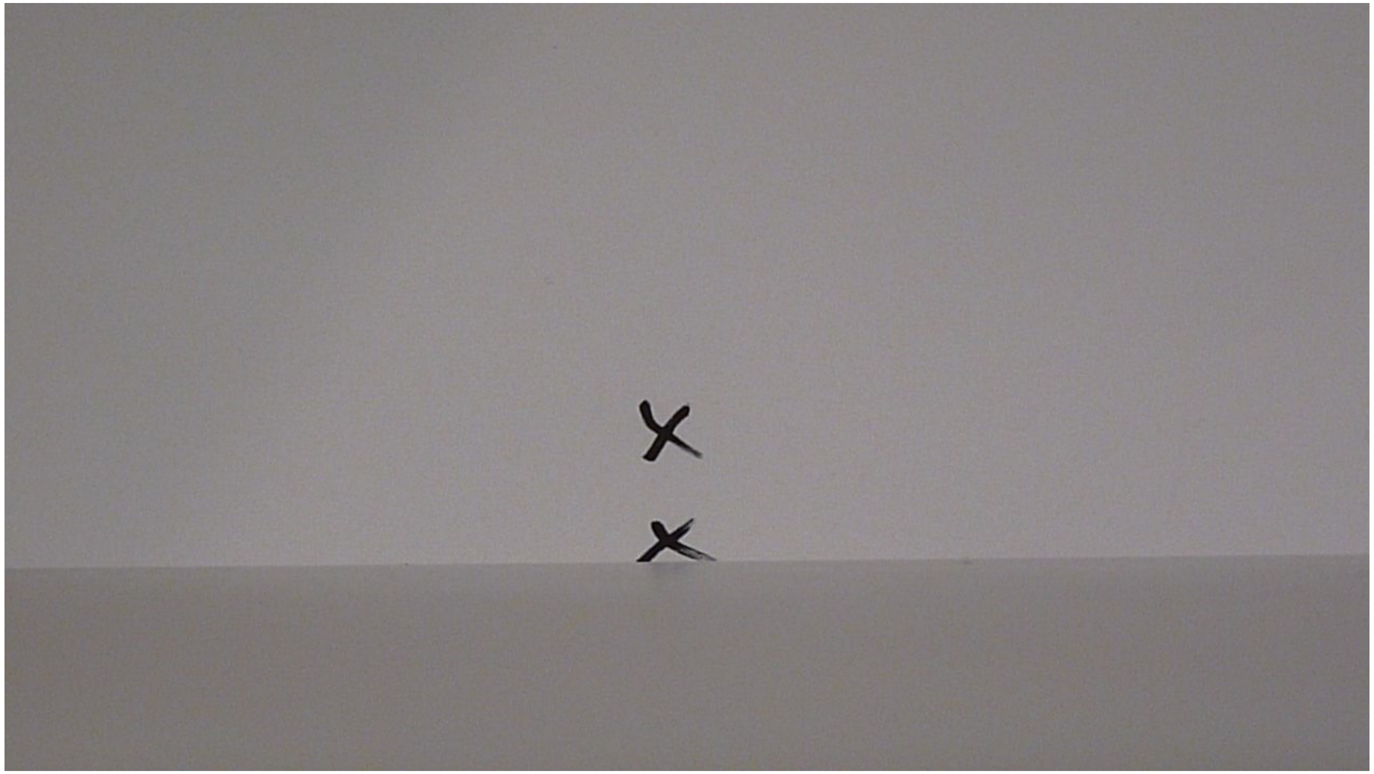
Behaviour controlled by the rate at which material can move to the nose of the flow, not by conditions at the nose



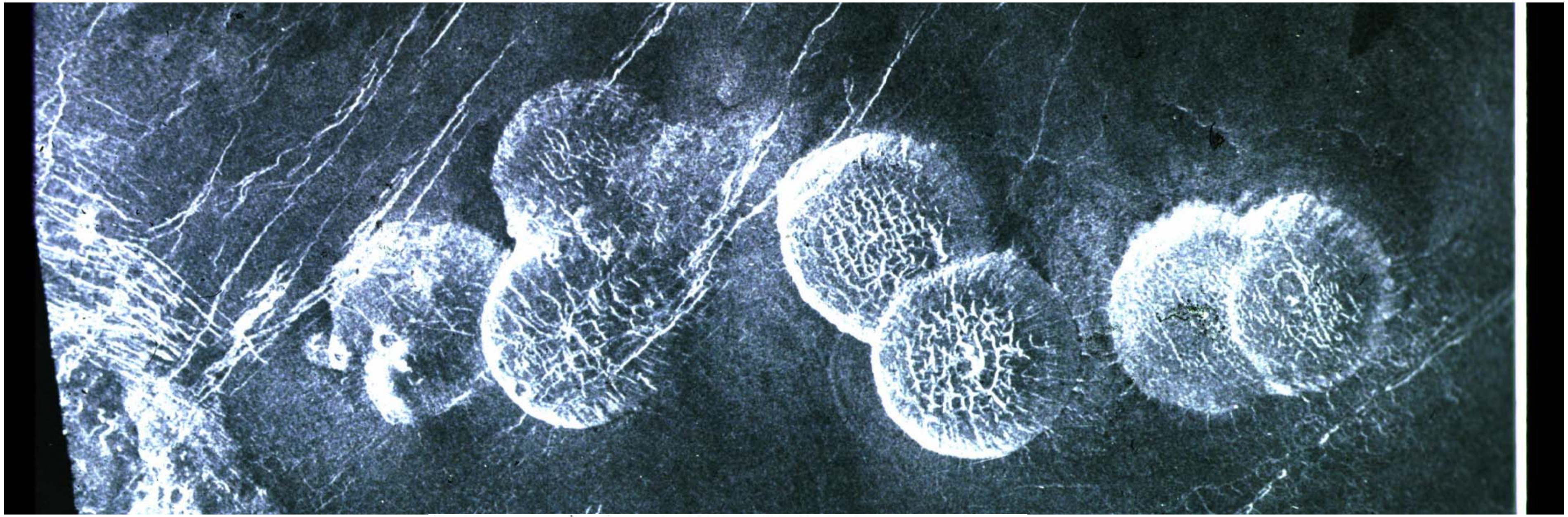
A 150 year old experiment…

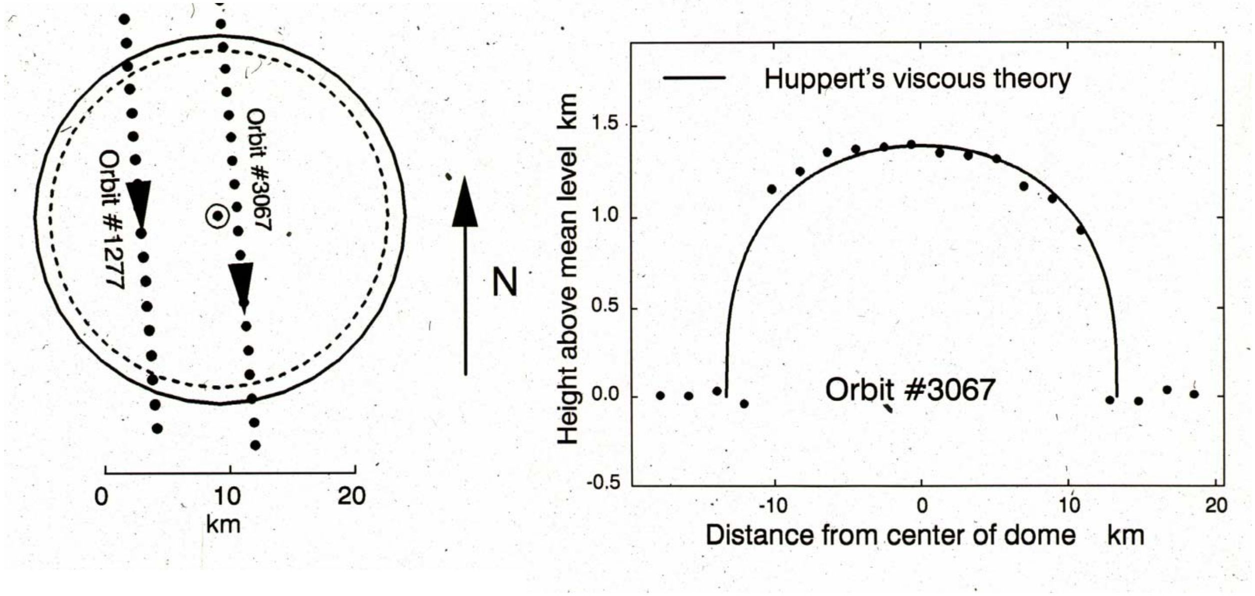
(Courtesy of Matt Crossland, Winchester College)

A video….



An example of a gravity current with a rigid base: the volcanic ‘pancake domes’ on Venus

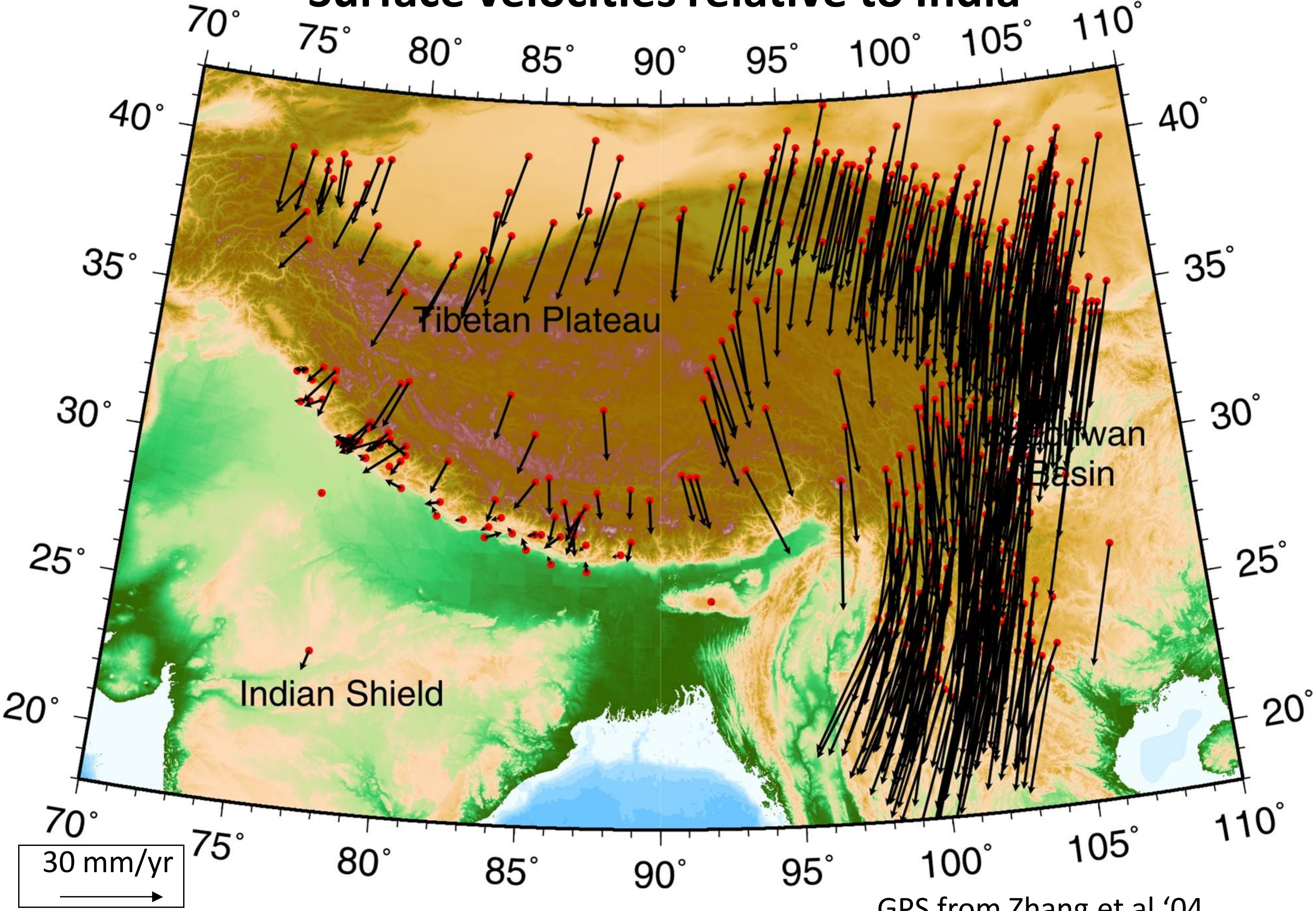




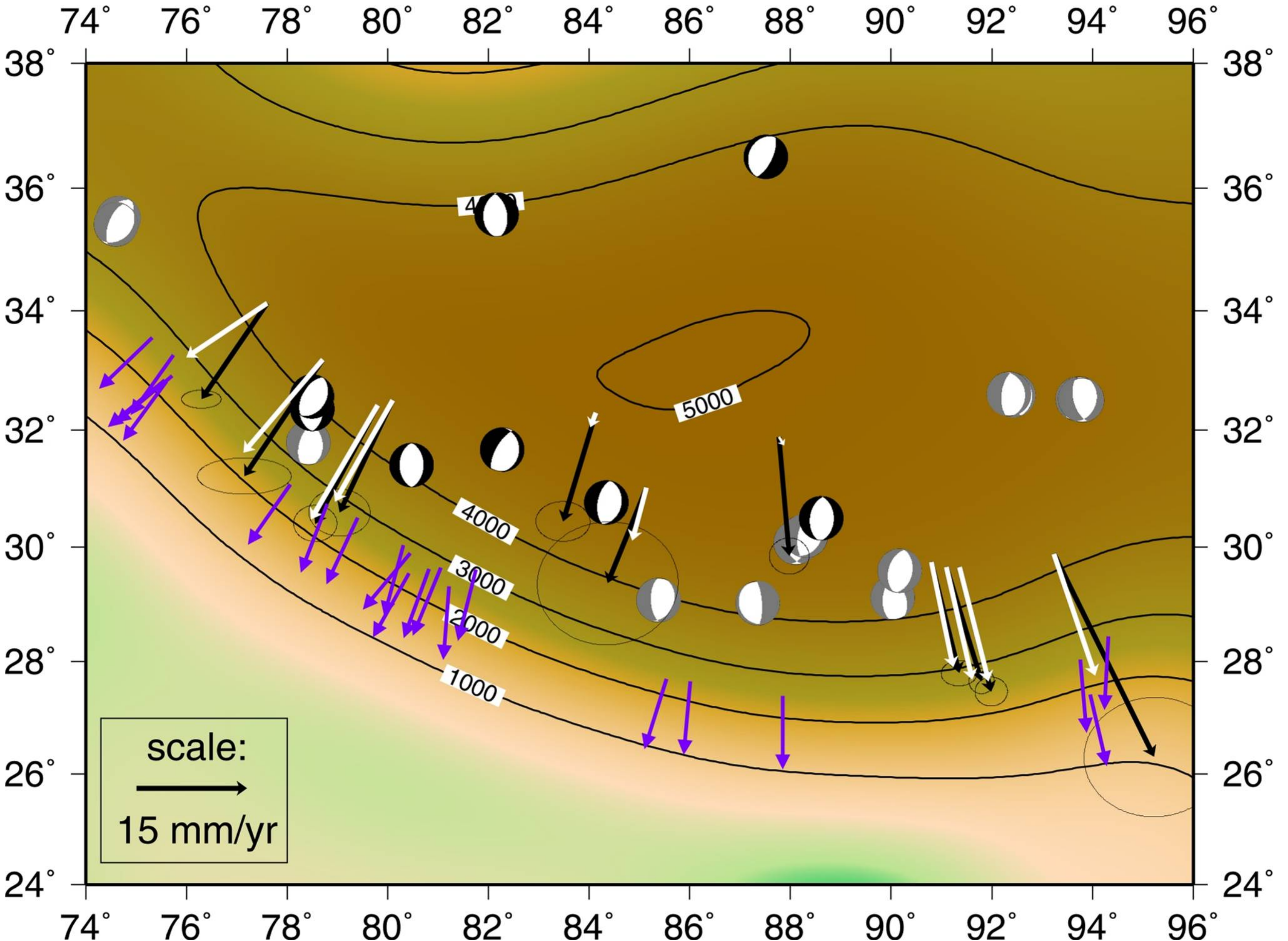
The circular shape and topographic profile (flat top with steep sides) are as expected for a gravity current spreading over a rigid base

[McKenzie et al 1992]

Surface velocities relative to India



GPS from Zhang et al ‘04

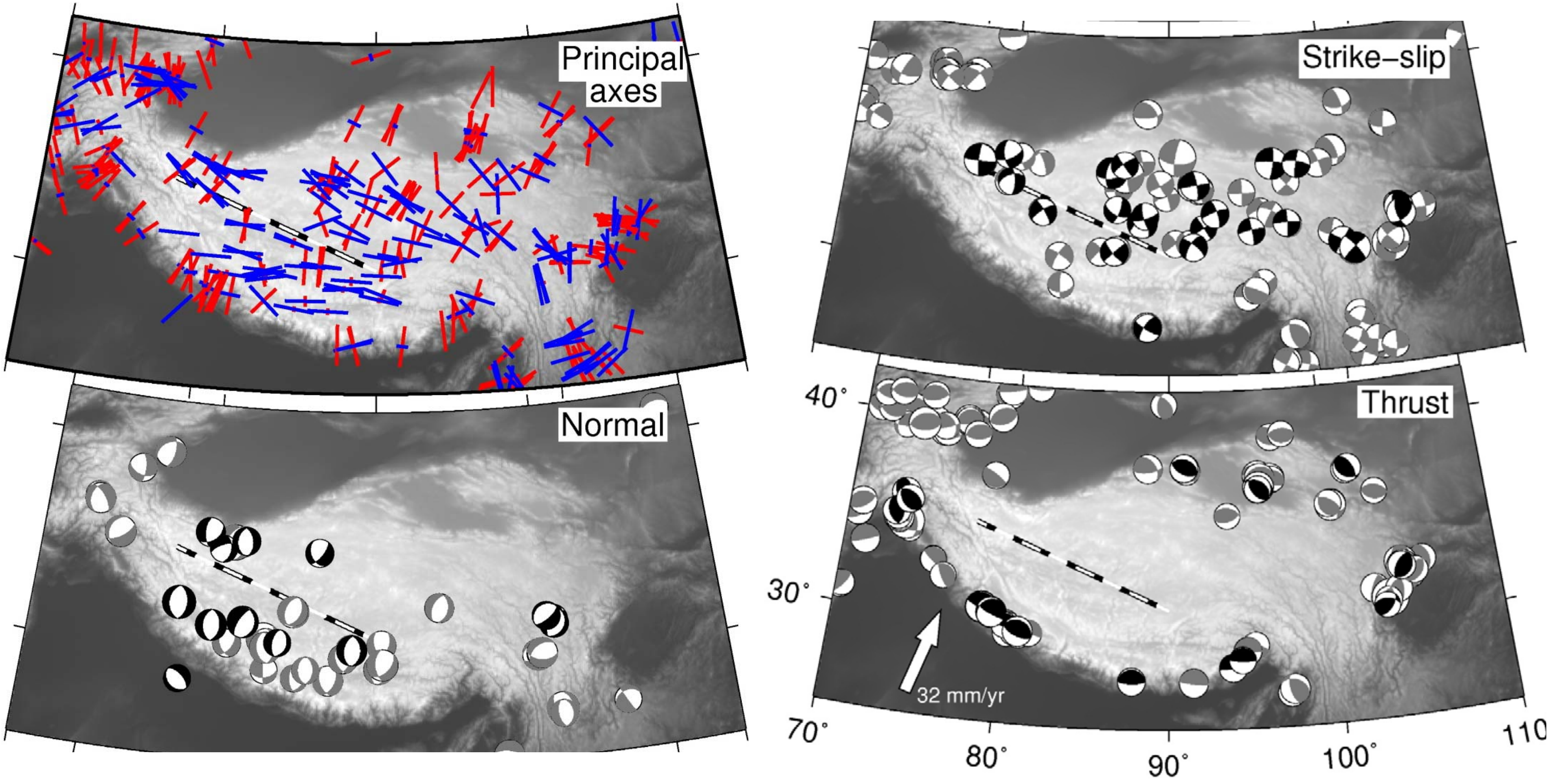


Copley and McKenzie 2007

Basic observation: the tectonic regime (style of faulting) varies within and around the Tibetan Plateau

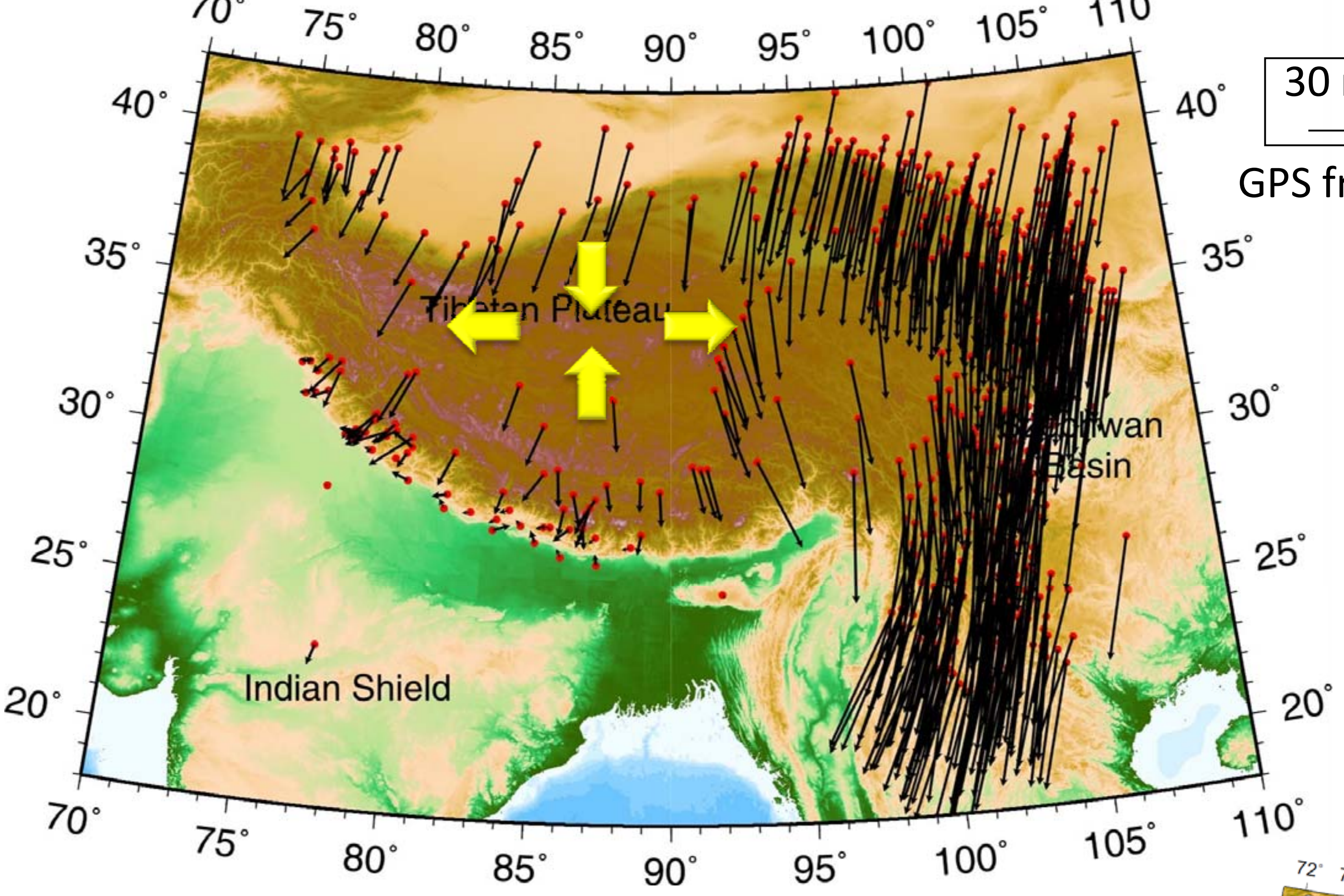
Earthquakes with depth < 40km,
Mw > 5.5, % double-couple > 50

[Black mechanisms are from the modelling of P and SH waveforms, grey are from CMT catalogue]



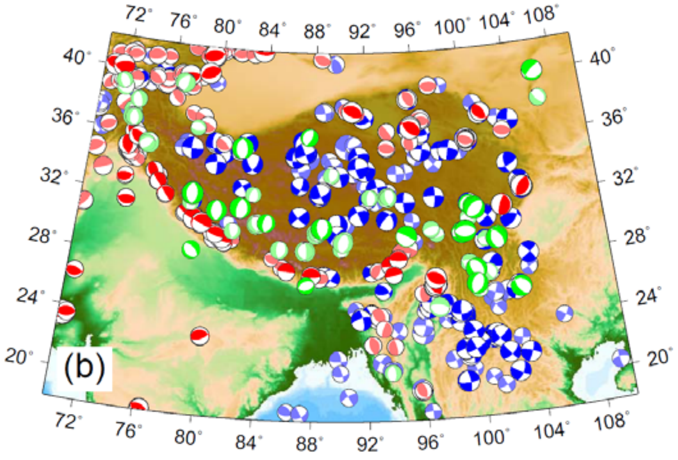
Copley et al 2011

Surface velocities relative to India

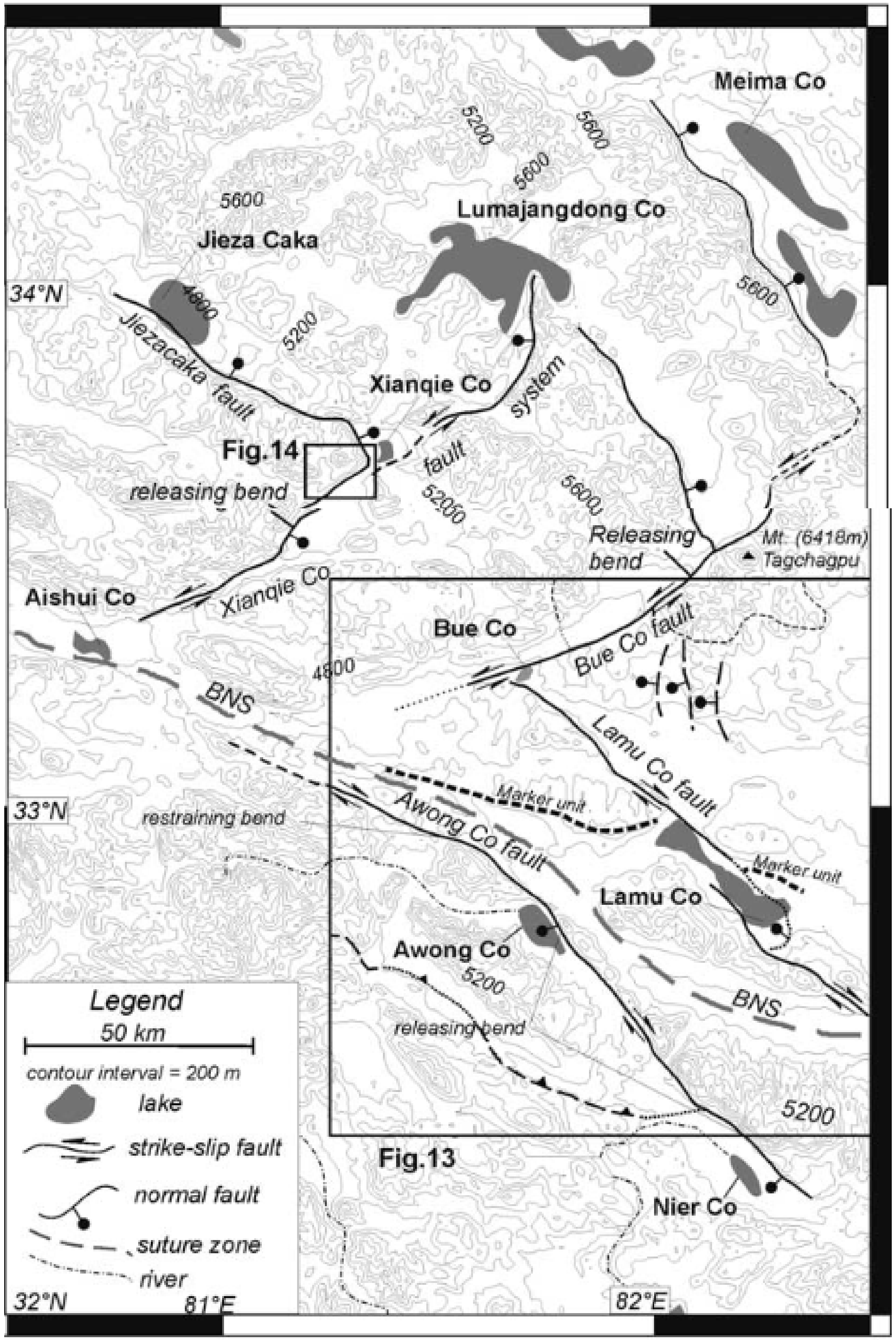


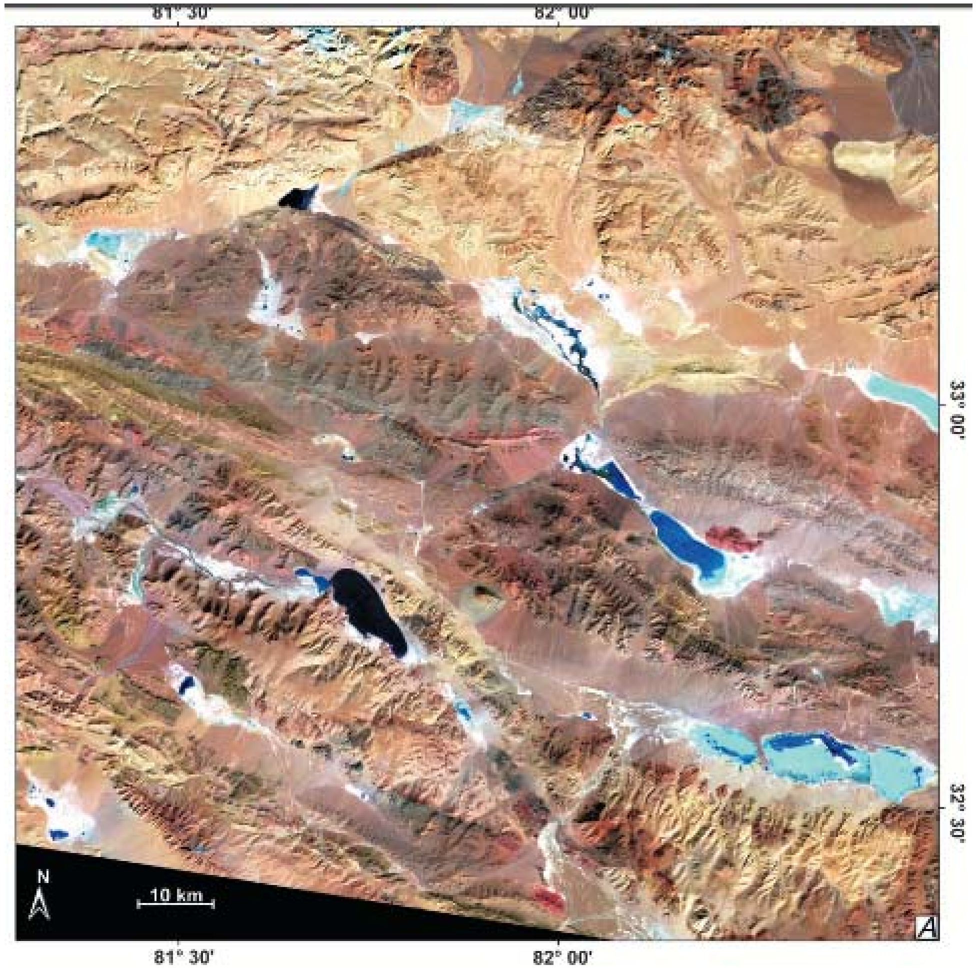
GPS from Zhang et al '04

N Tibet: ***permanent*** N-S shortening and ***permanent*** E-W extension

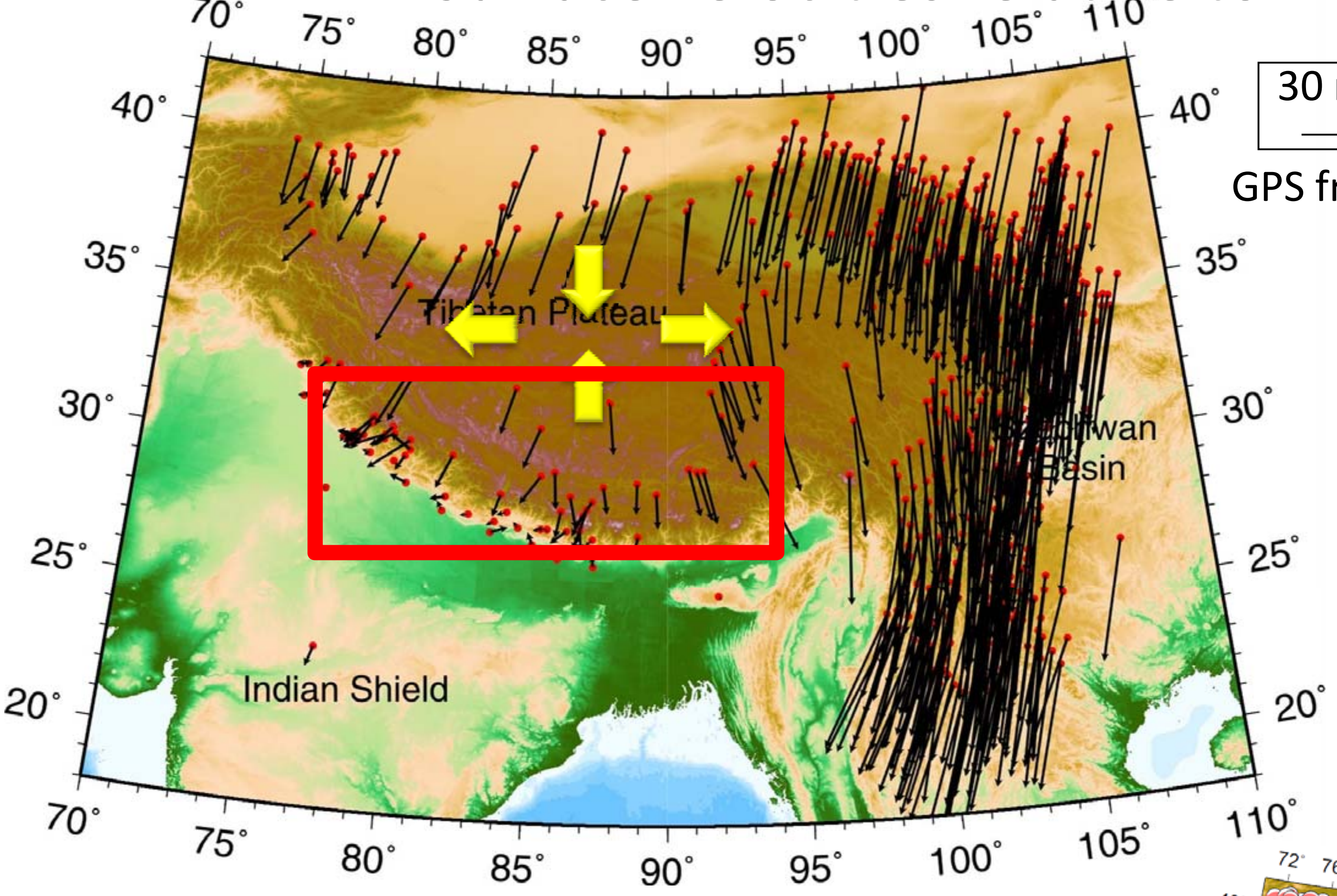


Conjugate strike-slip faulting in central Tibet
(Taylor et al 2003)

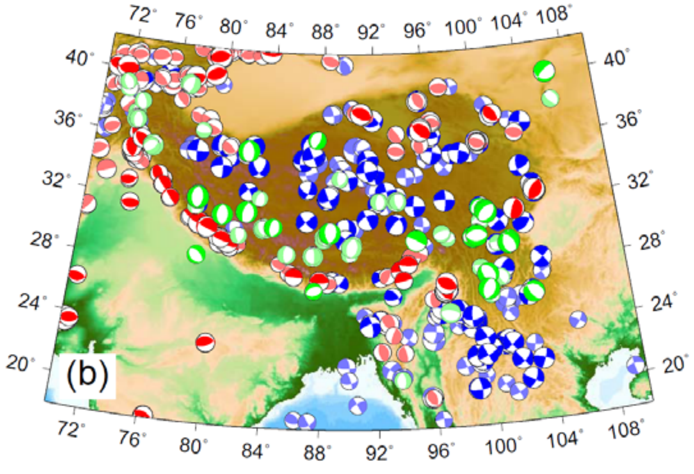




Surface velocities relative to India

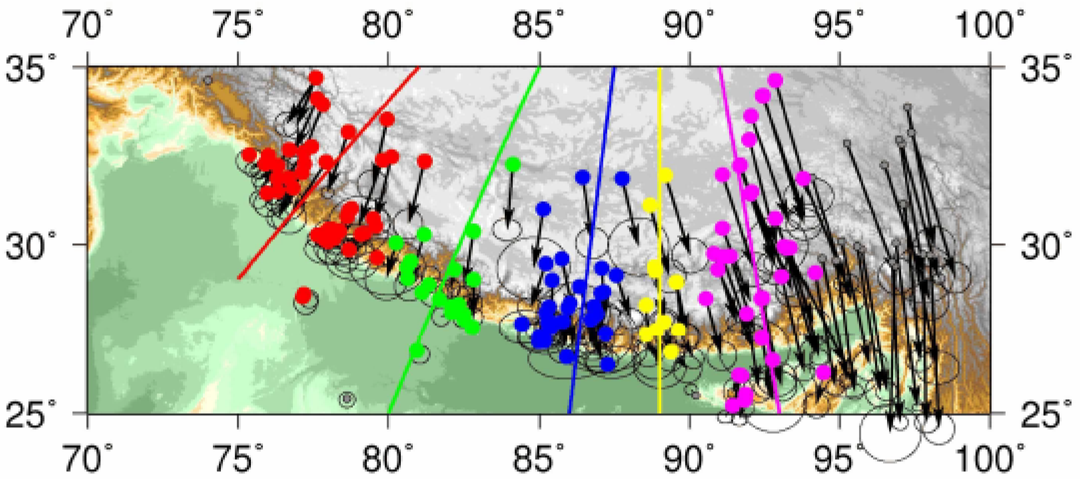


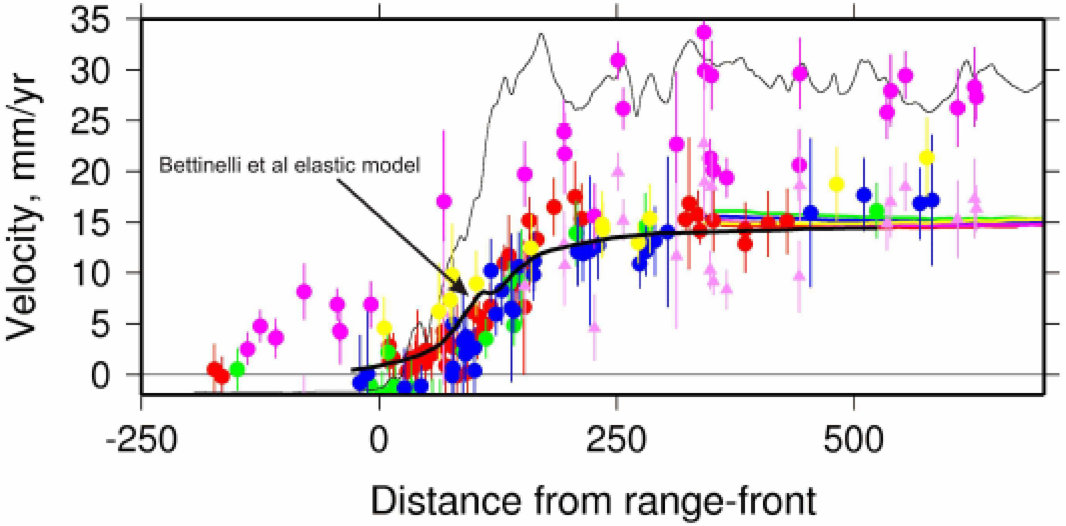
GPS from Zhang et al ‘04

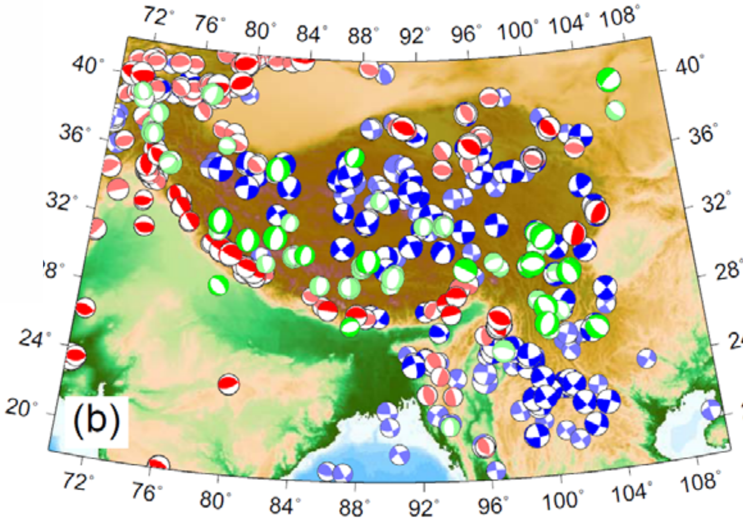


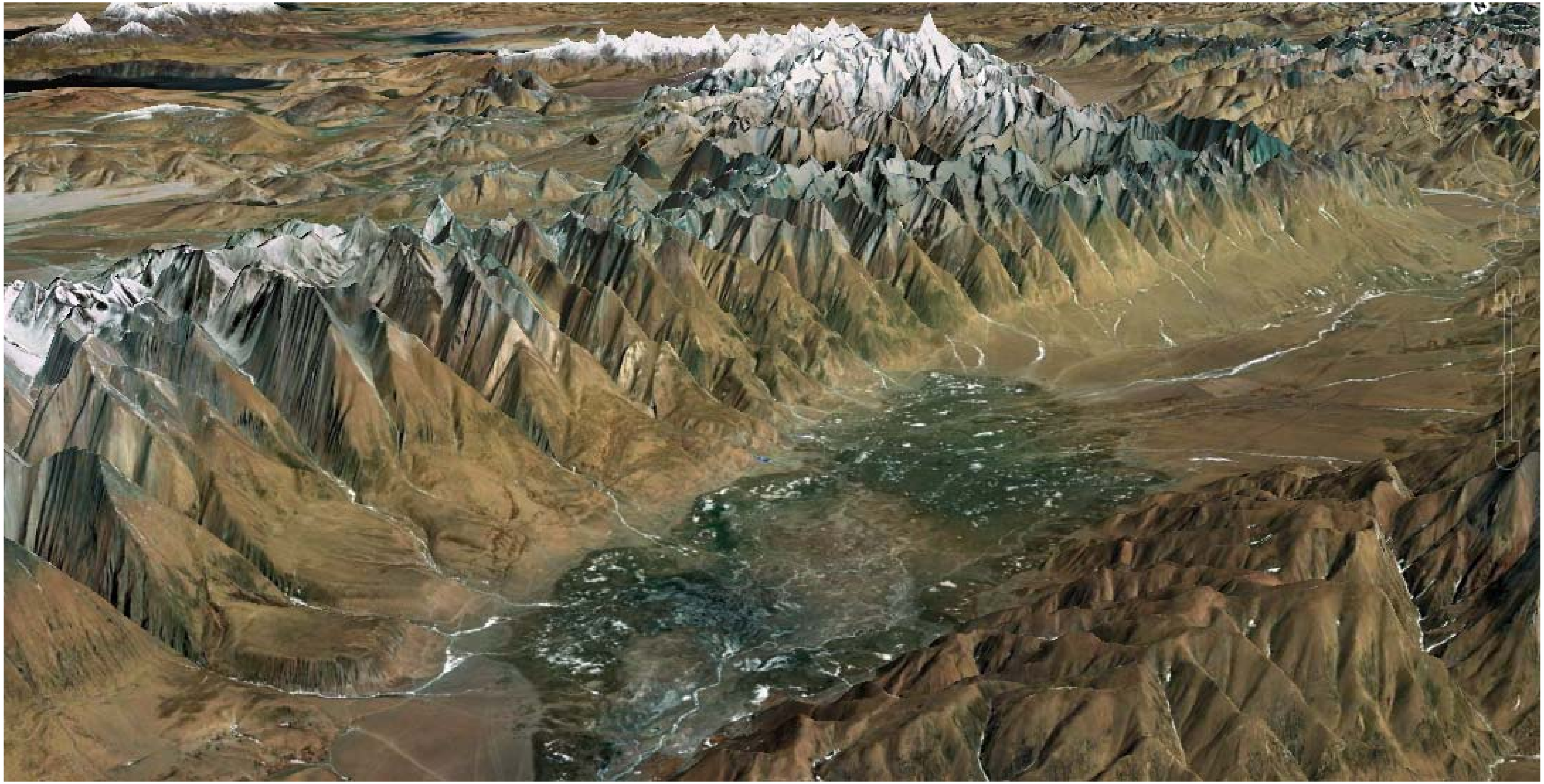
N Tibet: ***permanent*** N-S shortening and ***permanent*** E-W extension

N Tibet: ***Elastic and recoverable*** N-S shortening, and ***permanent*** E-W extension





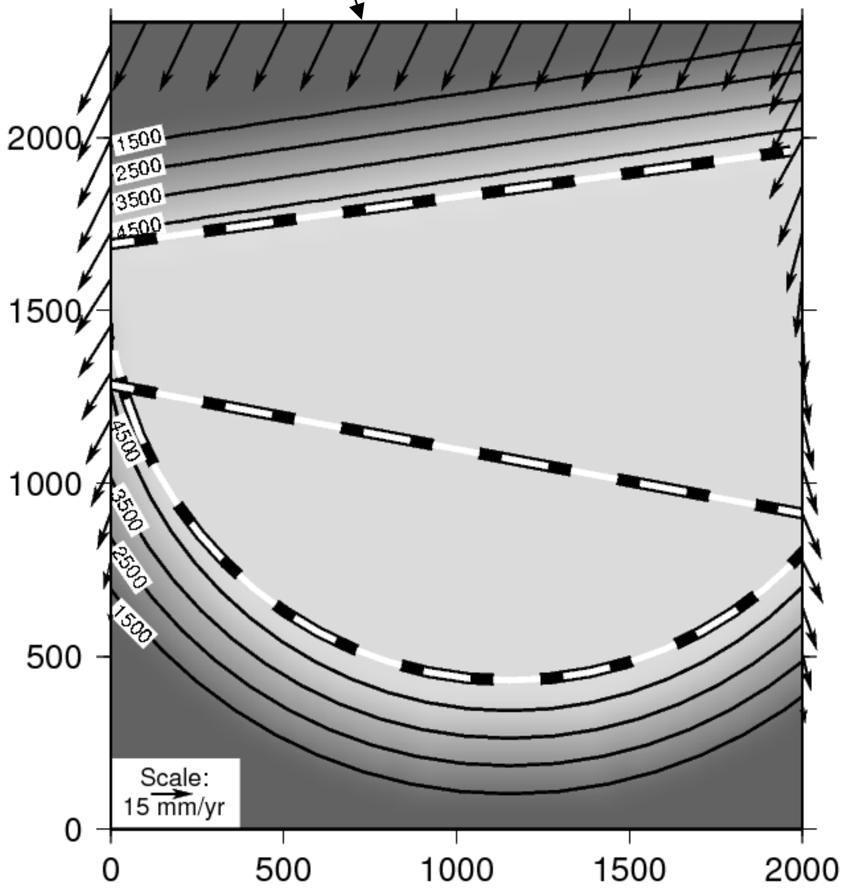




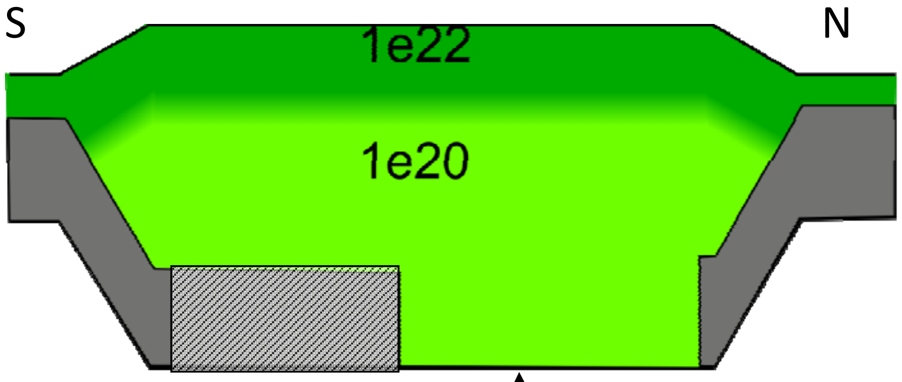
~30 km

Model setup

Velocities shown at every 4th model gridpoint



Modelled as a viscous fluid (solving the stokes flow equations in 3 dimensions)



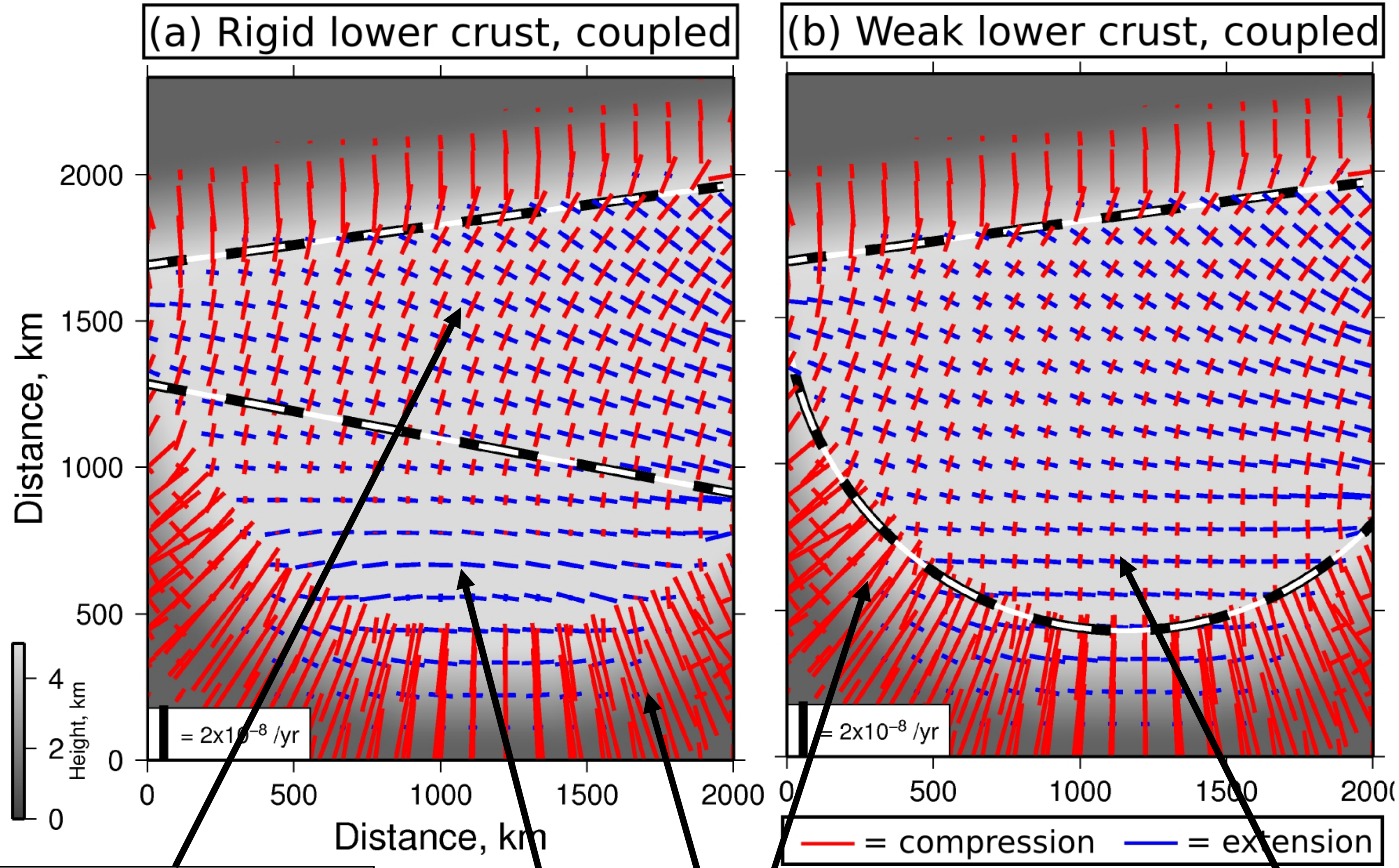
No shear stress on base

Driving forces: Gravity (topography)

Velocities on edges

Copley et al 2011

Modelled principal axes of horizontal strain-rate tensor



Strike-slip: NNE-SSW compression and ESE/WSW extension

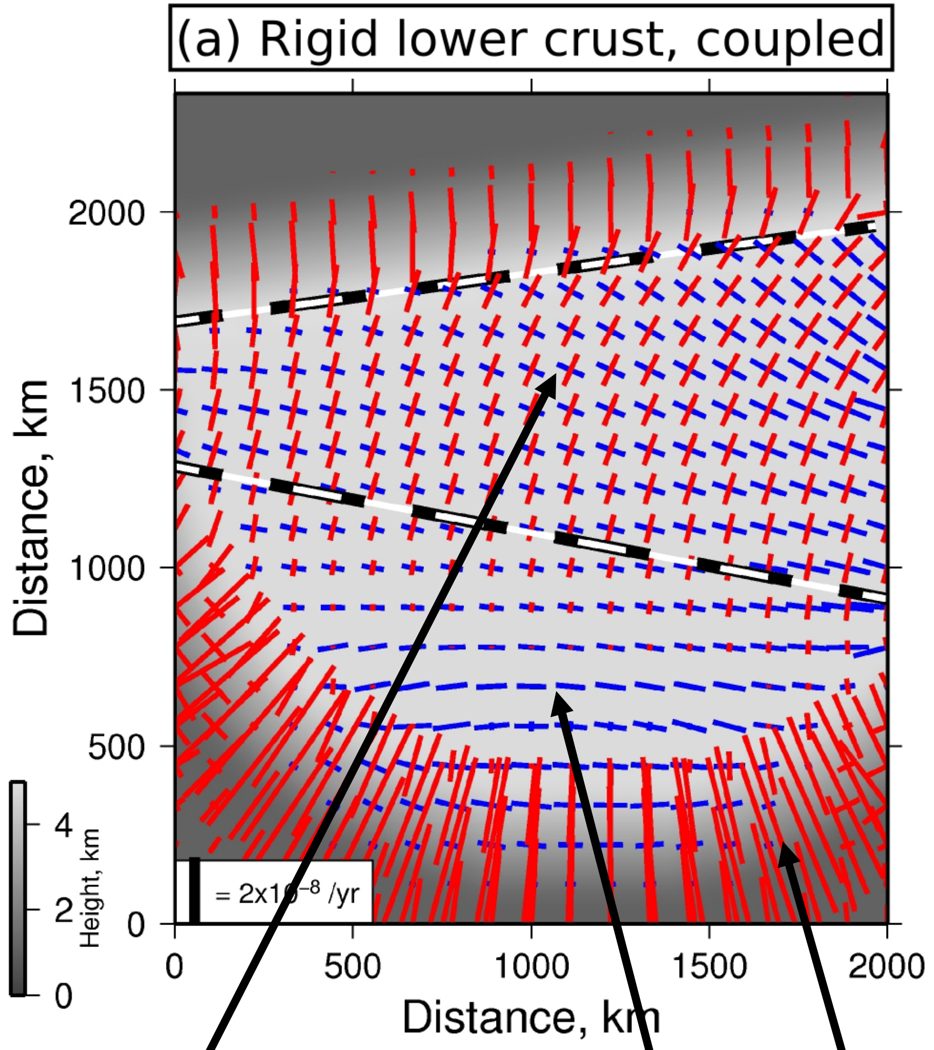
E-W extension

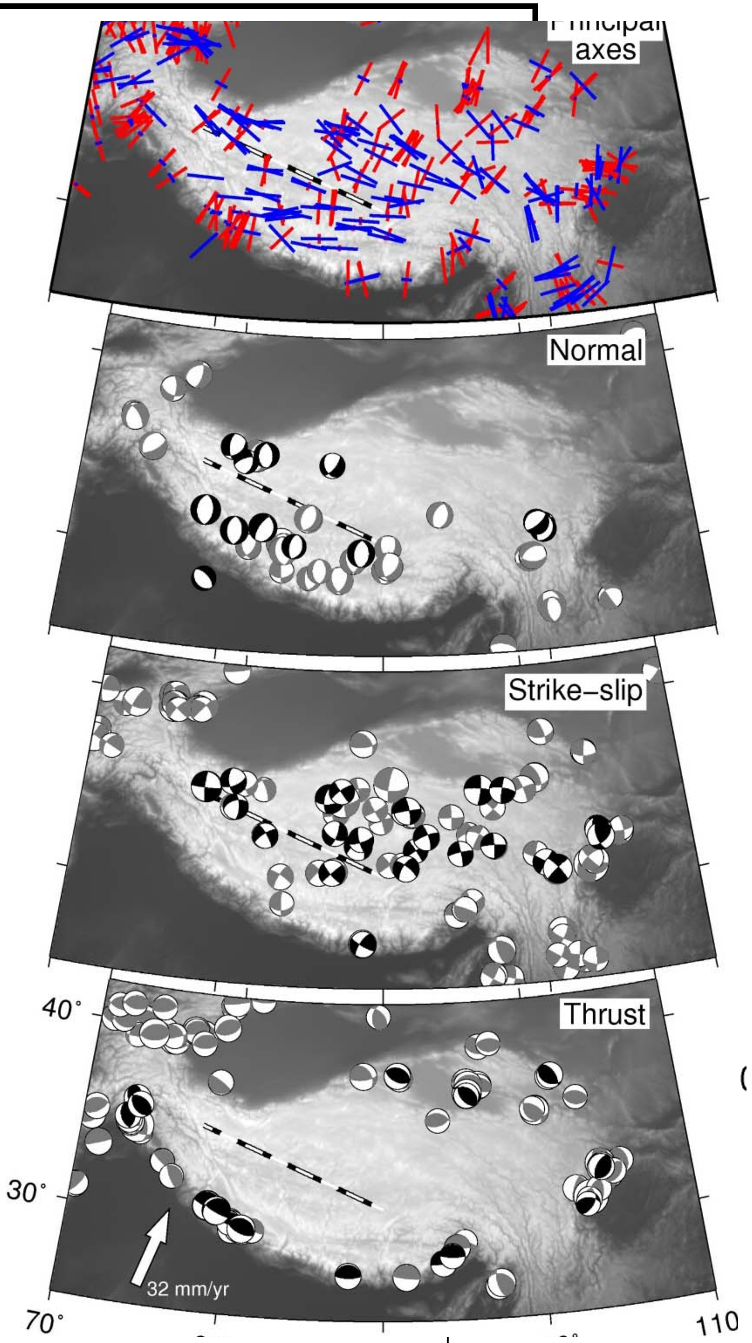
Arc-parallel extension, but also N-S shortening

Topography causes arc-normal shortening

Copley et al 2011

Modelled principal axes of horiz





Strike-slip: NNE-SSW compression and ESE/WSW extension

E-W extension

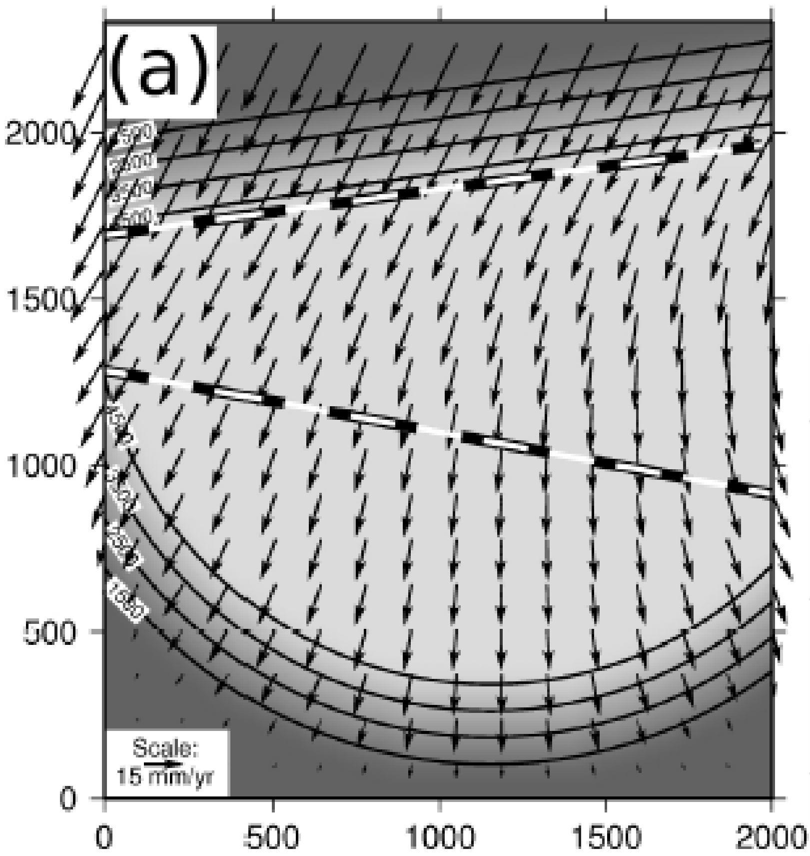
Topography causes arc-normal shortening

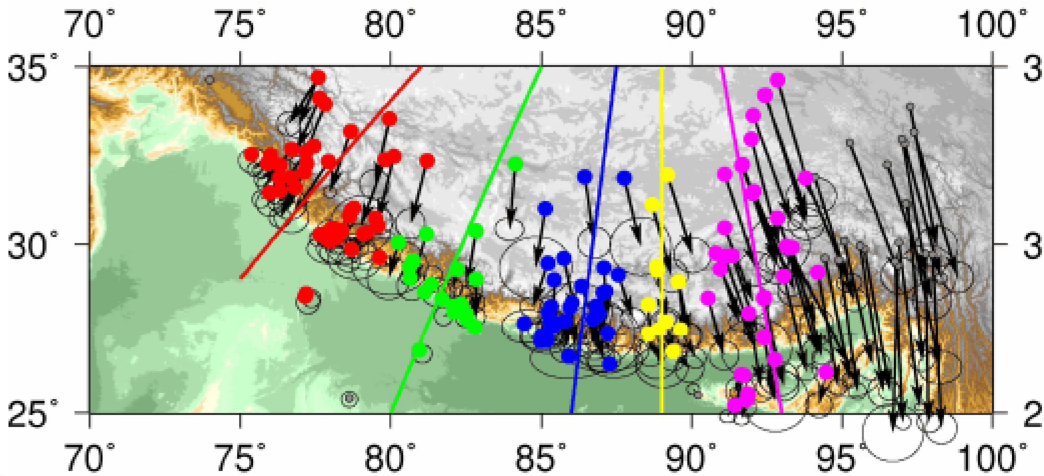
Copley et al 2011

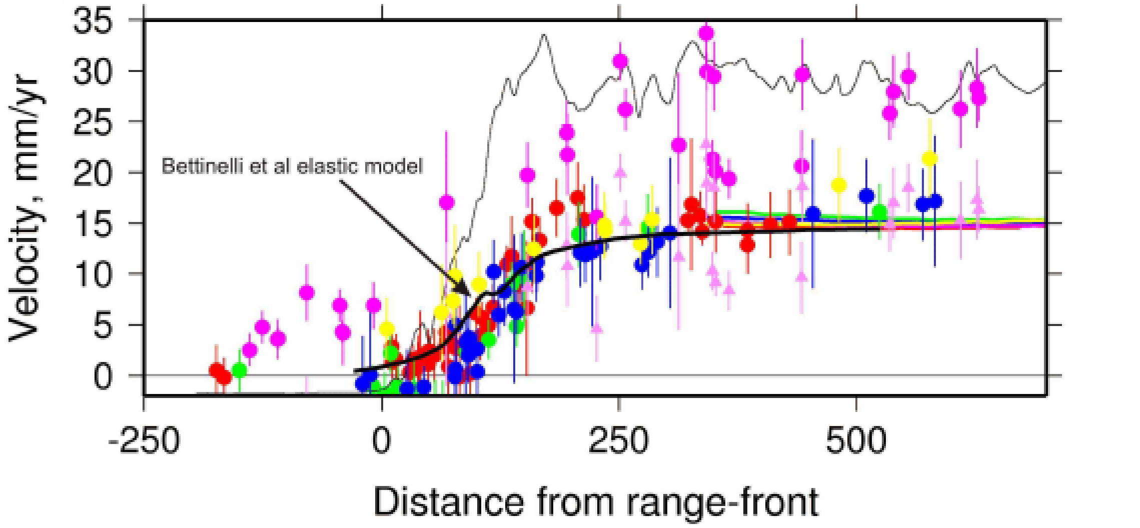
An explanation for spatial separation of the strike-slip and normal faults

Requires vertical mechanical coupling

Surface Velocities

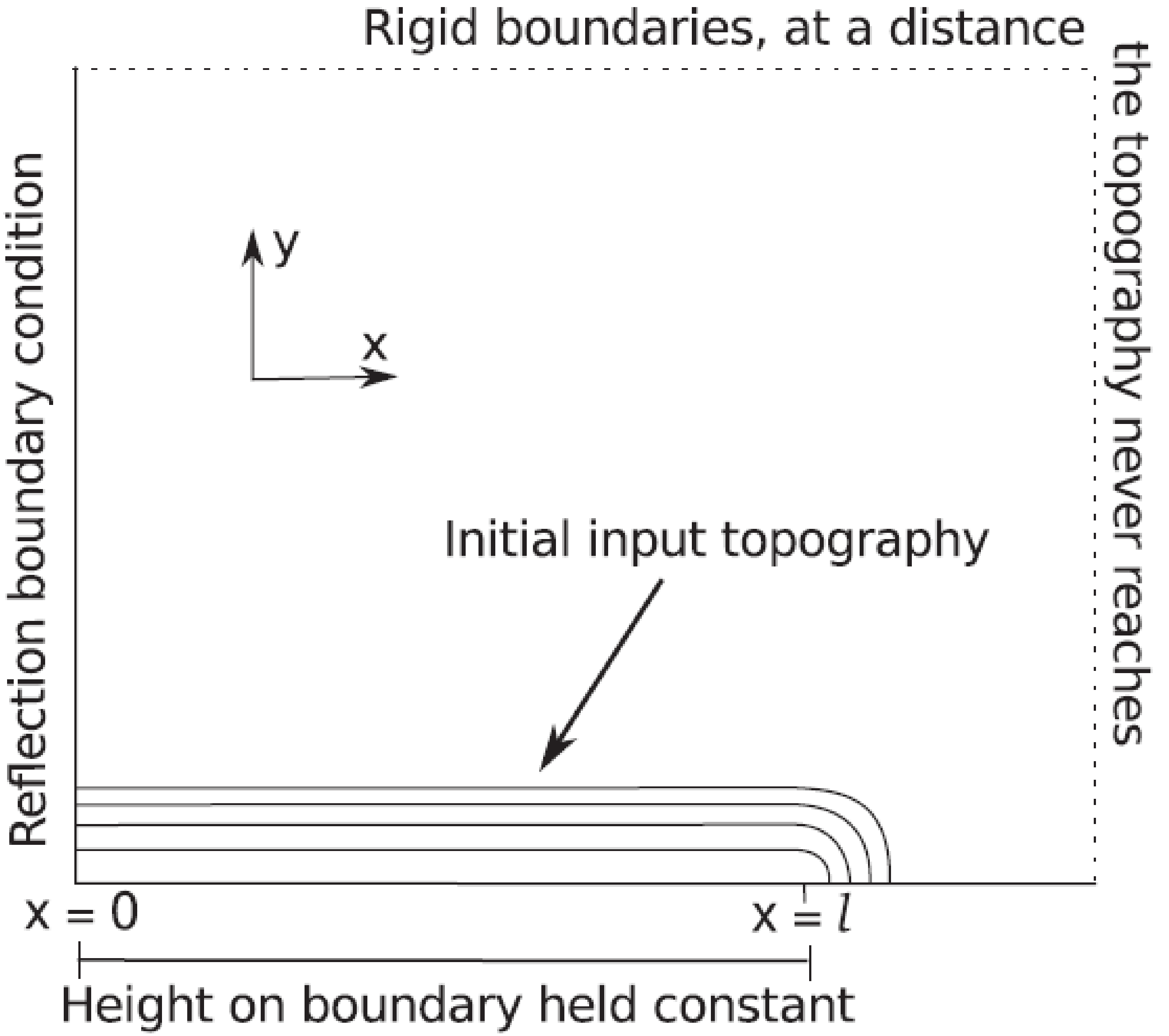




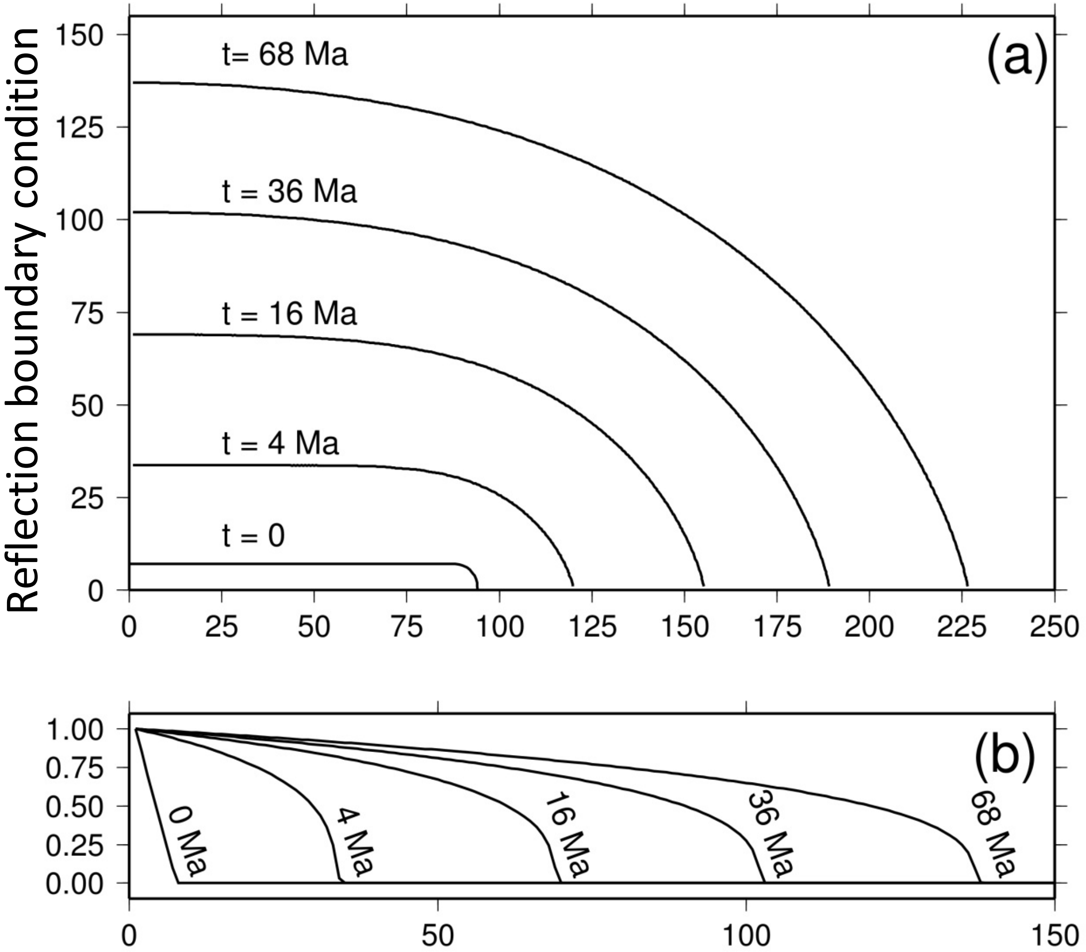


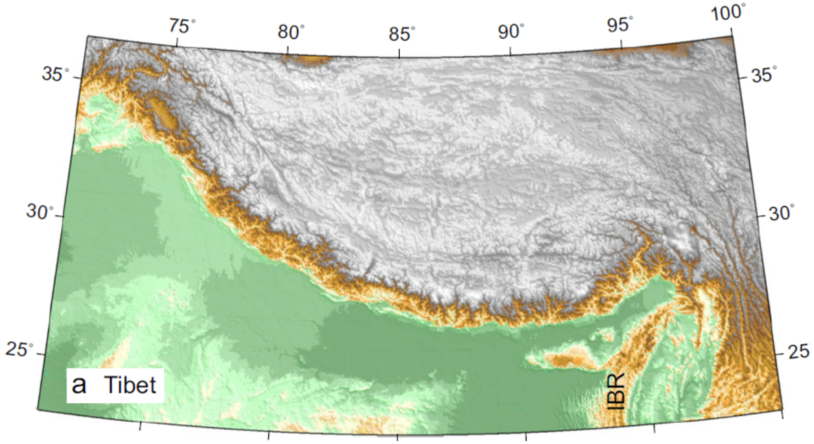
Copley et al 2011

Model to look at the plan-view evolution of flow over a rigid base



Evolution of flow with a rigid base

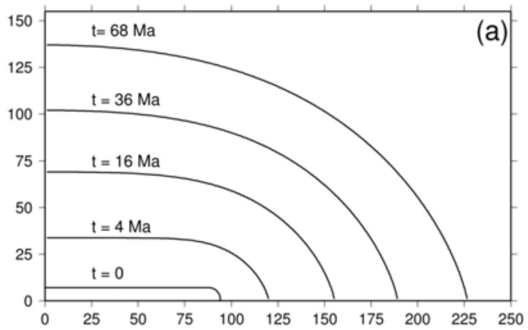




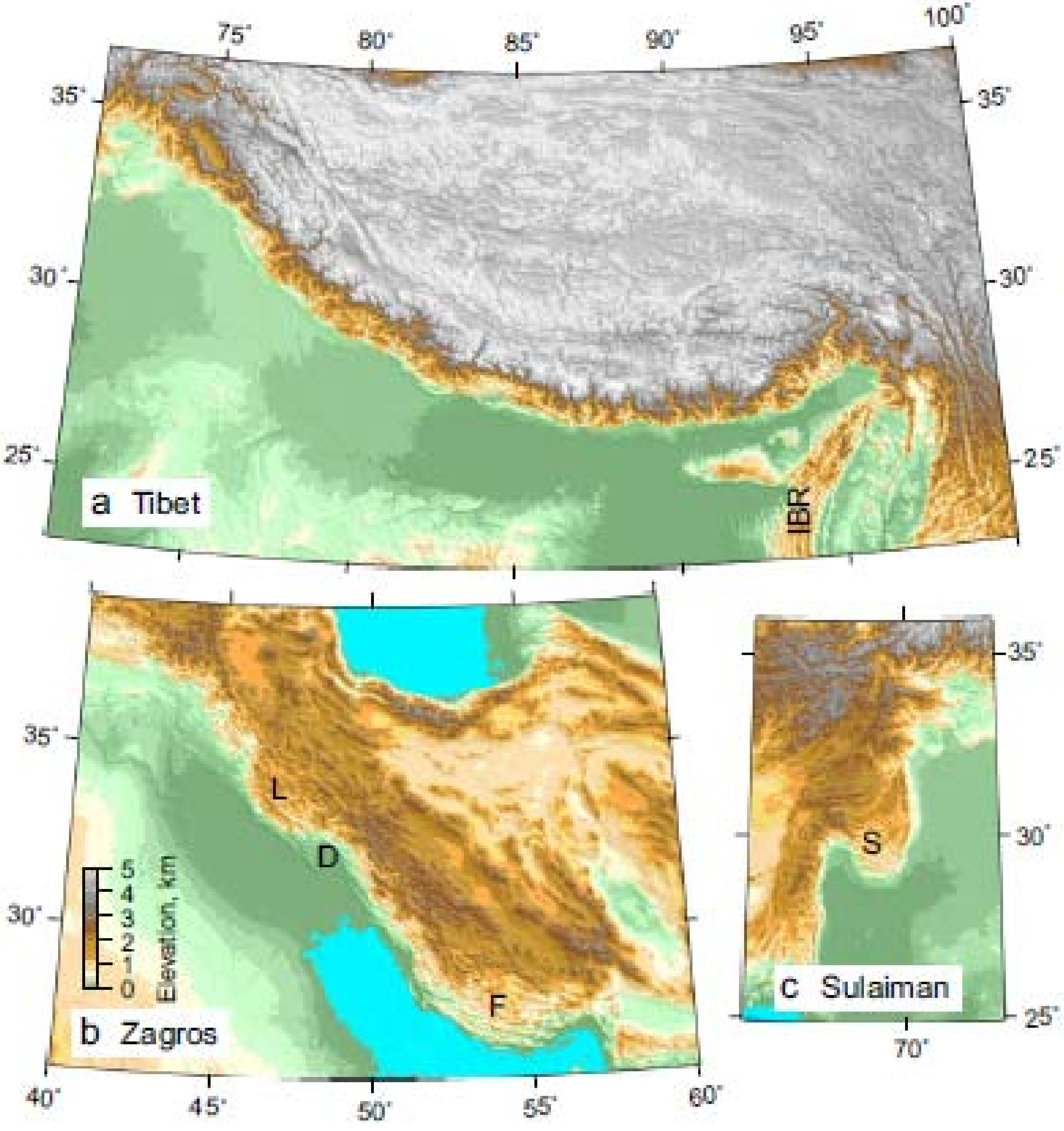
$$t = \frac{\beta \eta l^2}{h^3 \rho g (f+1)^2}$$

Viscosities:
From curvature formation: ~10^{20} Pa s
From active deformation: ~10^{20} Pa s

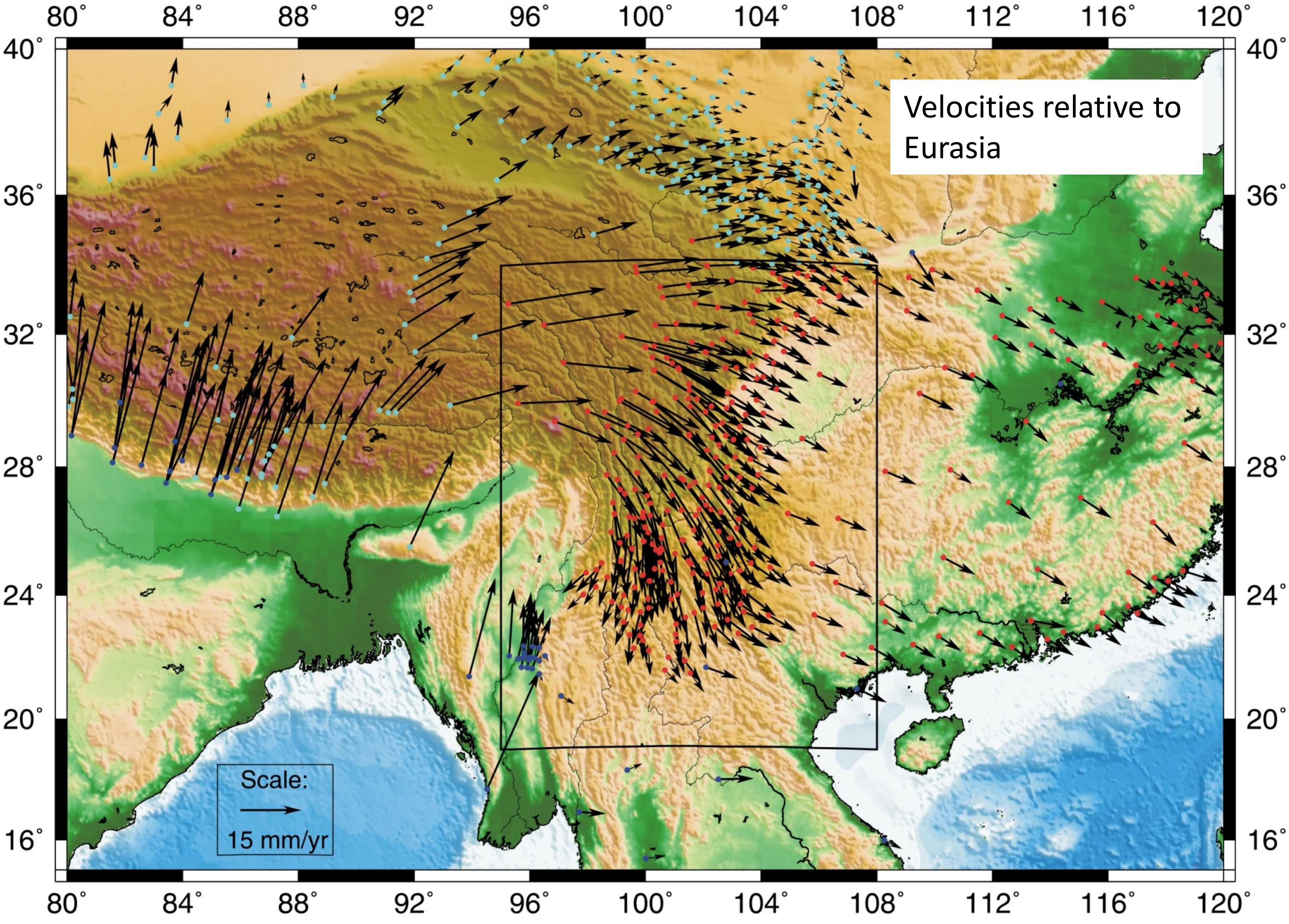
Copley 2012



$$t = \frac{\beta \eta l^2}{h^3 \rho g (f+1)^2}$$

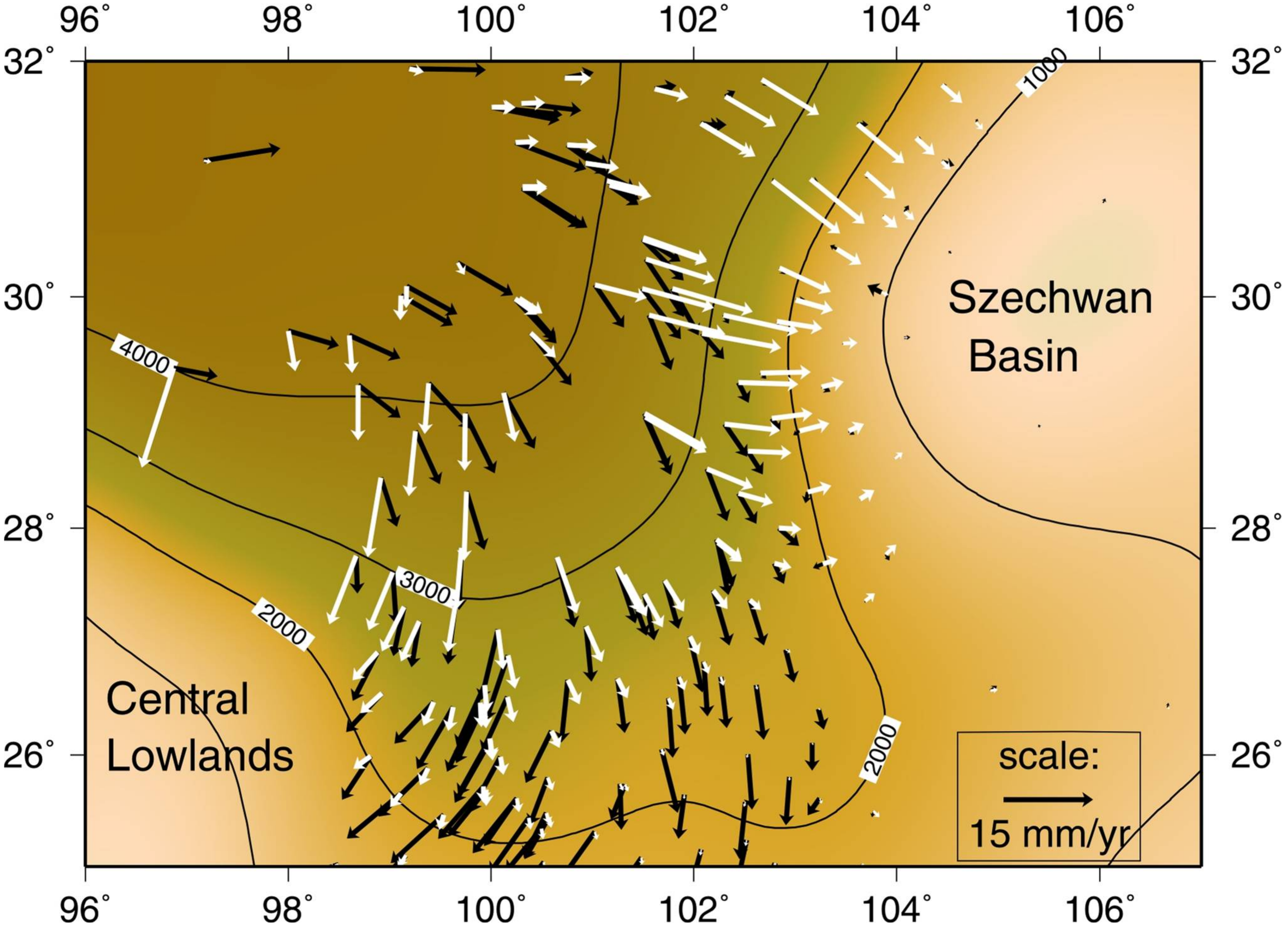


Copley 2012

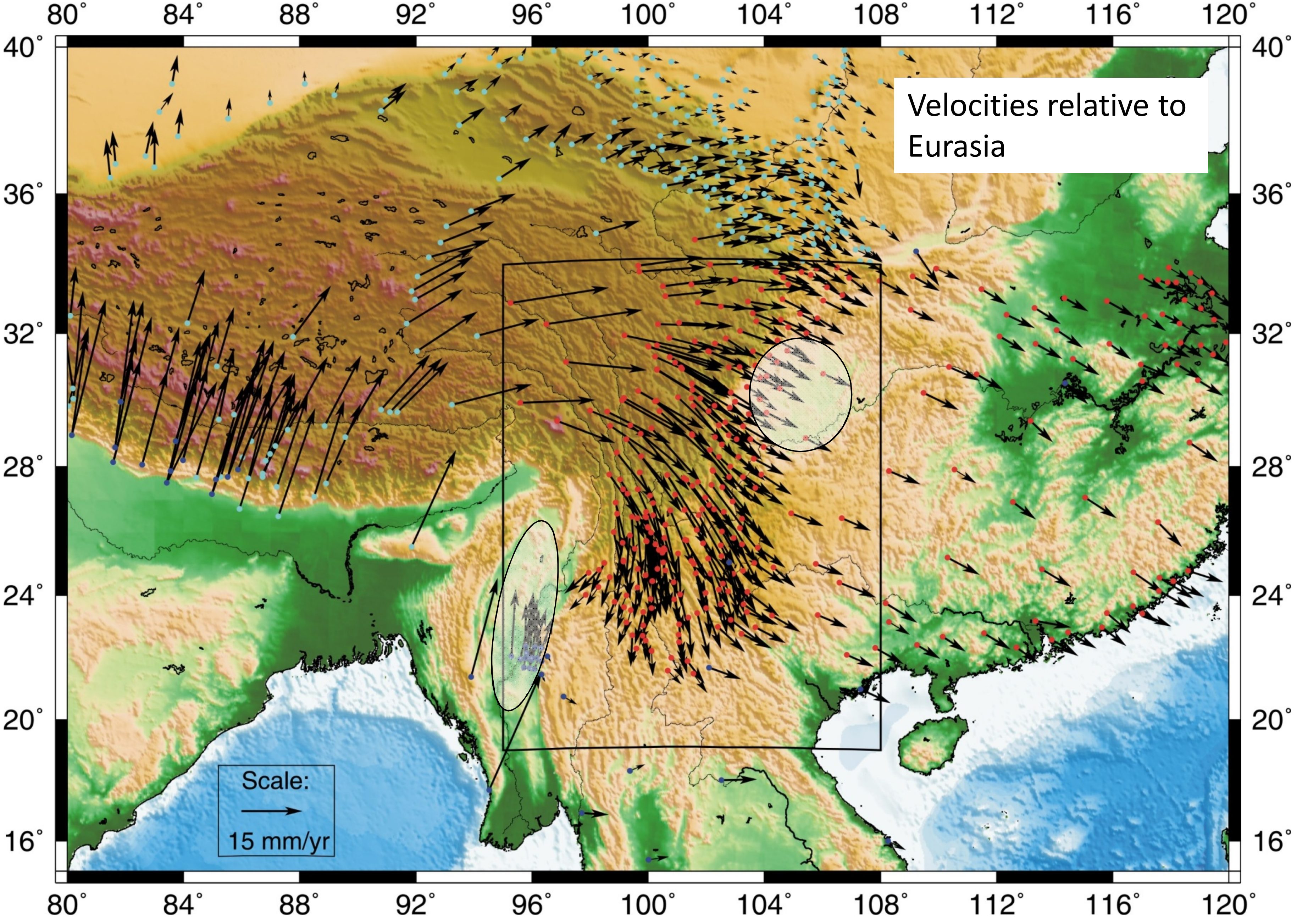


Velocities relative to Eurasia

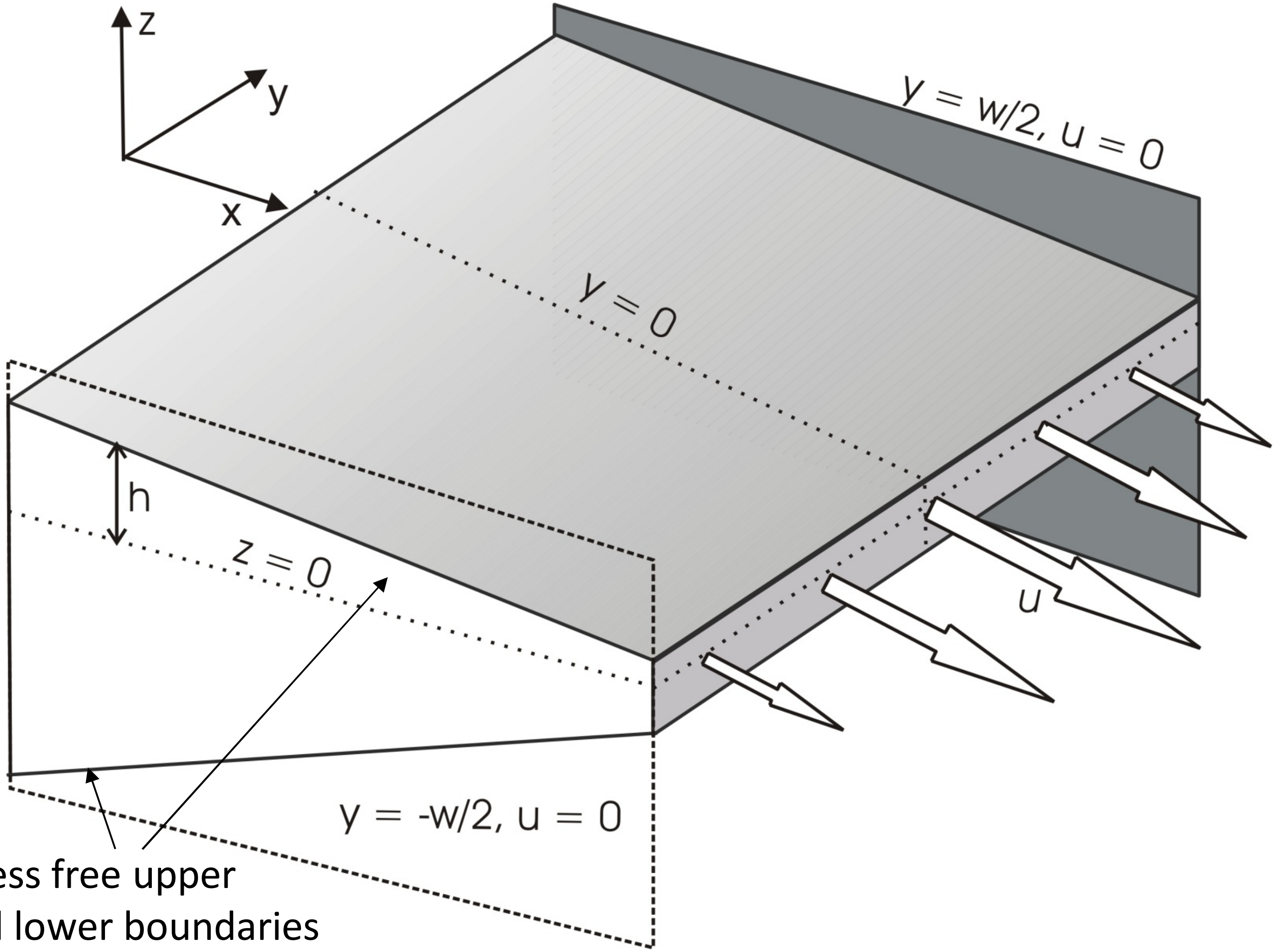
Pale blue bases = Zhang et al ‘04, red = Shen et al ’05, dark blue = Socquet et al ‘06



Velocities (relative to south China) from Shen et al '05

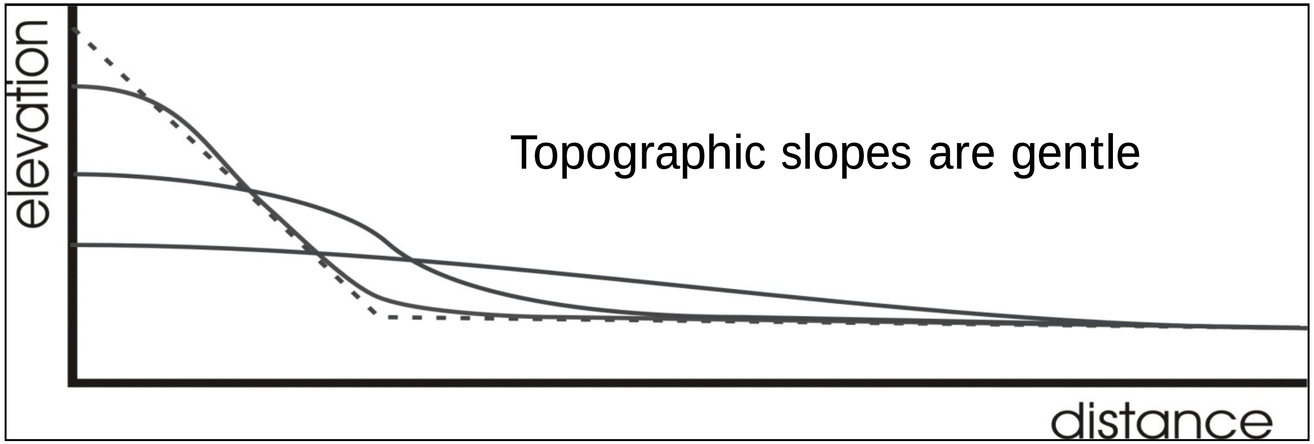


Pale blue bases = Zhang et al ‘04, red = Shen et al ’05, dark blue = Socquet et al ‘06 du/dy is now the dominant velocity gradient



Stress free upper
and lower boundaries

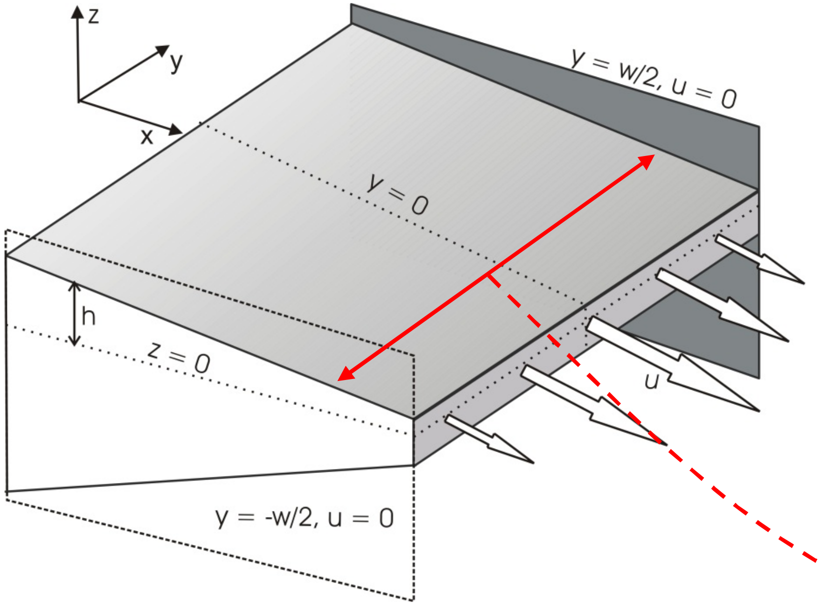
Flow in a thin layer with zero shear stress on the base

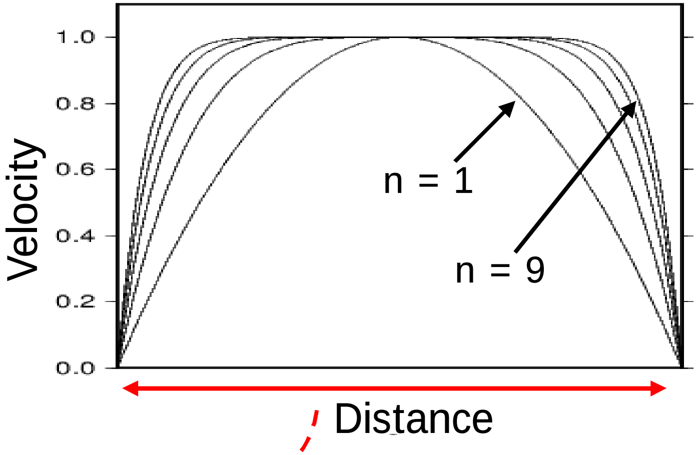


Topographic slopes are gentle

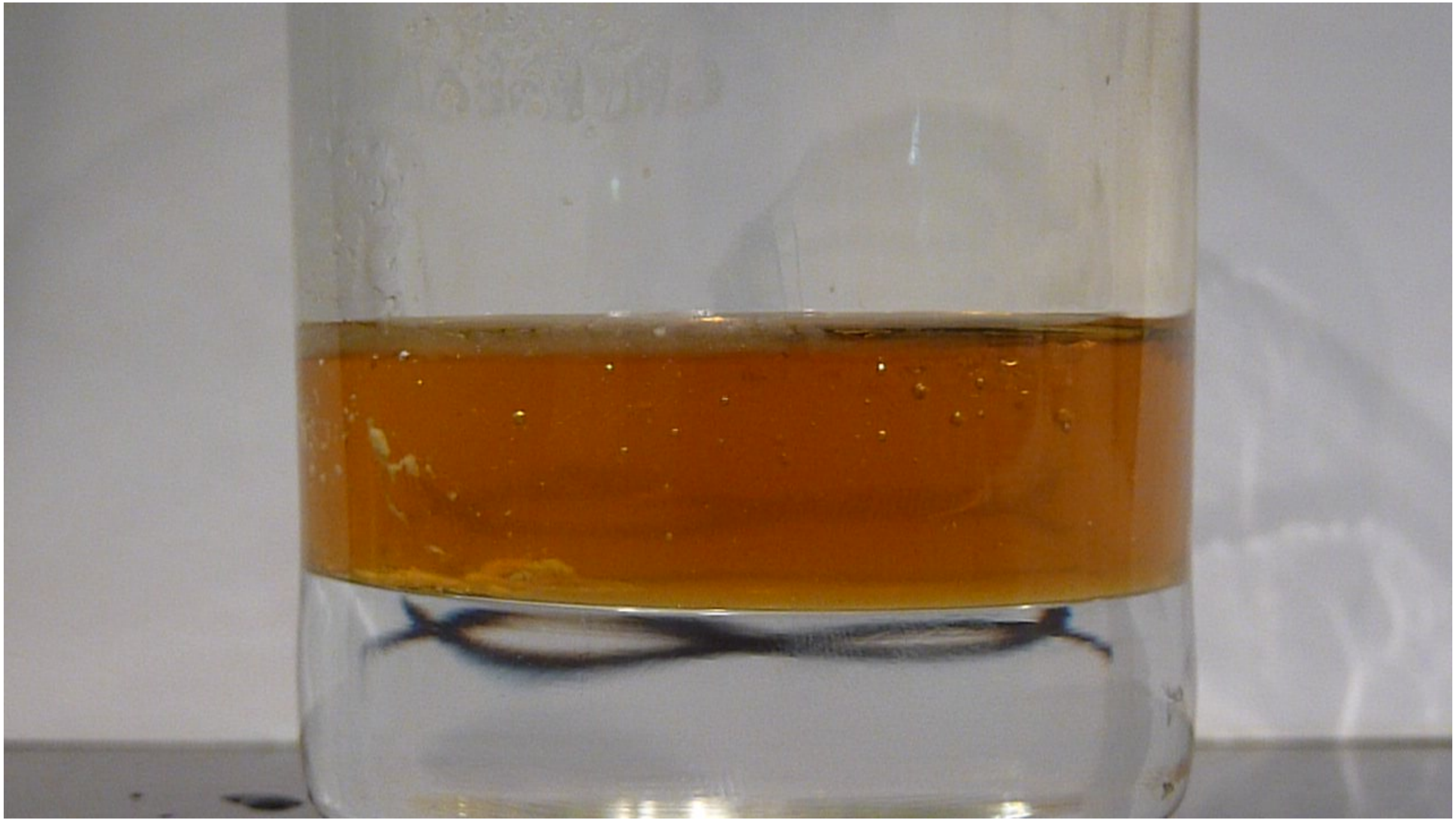
Velocity depends on viscosity, surface slope, and distance to the lateral boundaries:

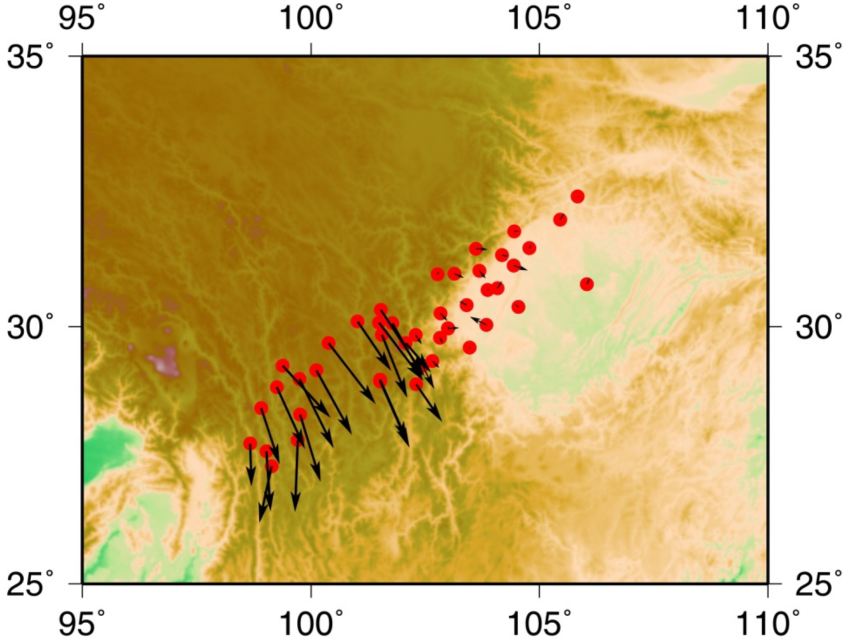
$$u = \left(\frac{\sqrt{2}^{1/n-1}}{B} \frac{\partial P}{\partial x} \right)^{n} \left(\frac{y^{n+1} - (w/2)^{n+1}}{n+1} \right)$$

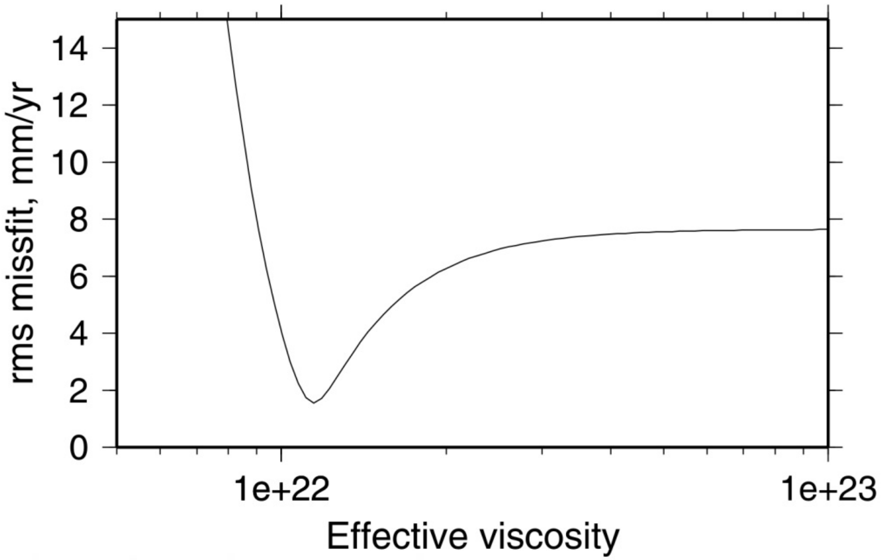


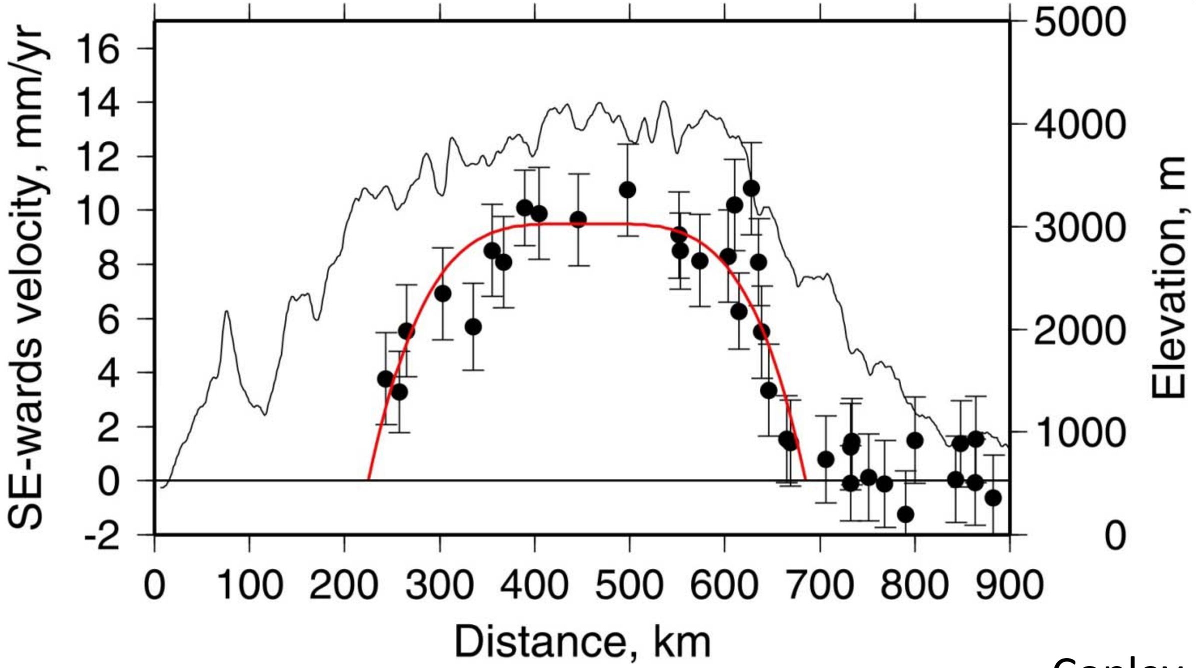


A video…

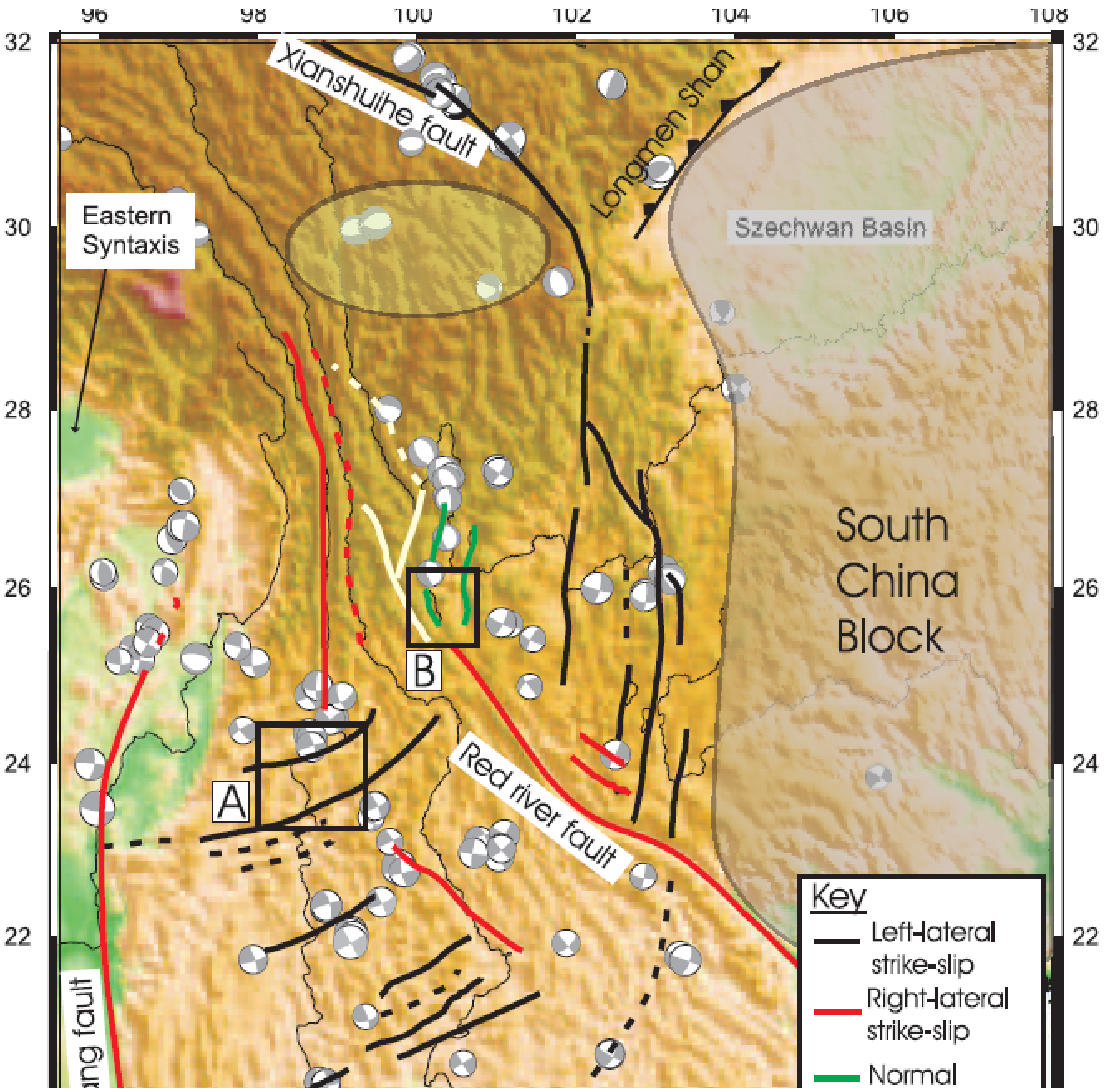








Copley & McKenzie 2007



Because of the change in boundary conditions, the velocity gradients are here accommodated by strike-slip faulting, rather than thrust and normal faults.

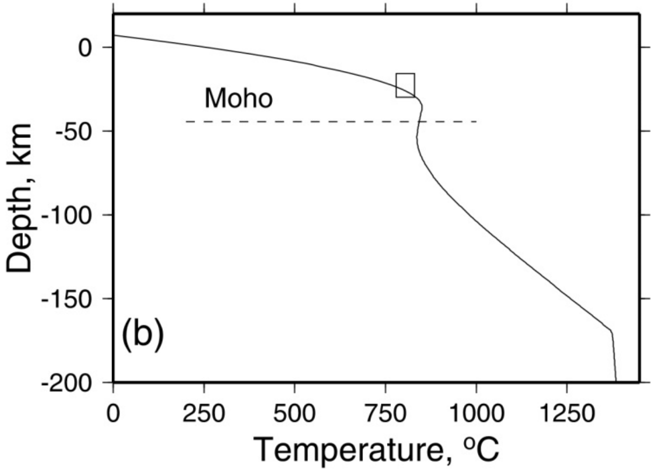
Copley 2008

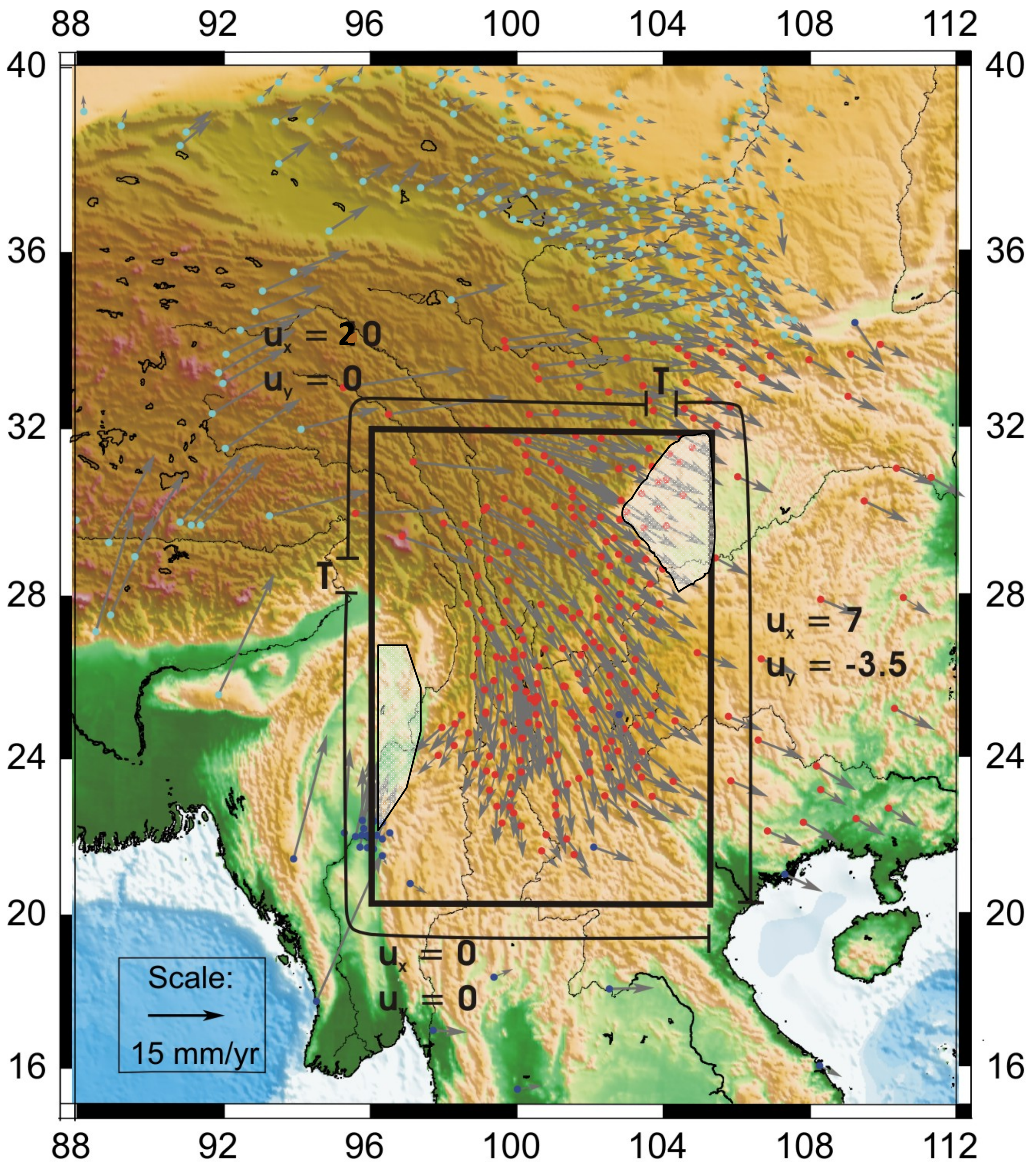
Boundary conditions and temperature structure

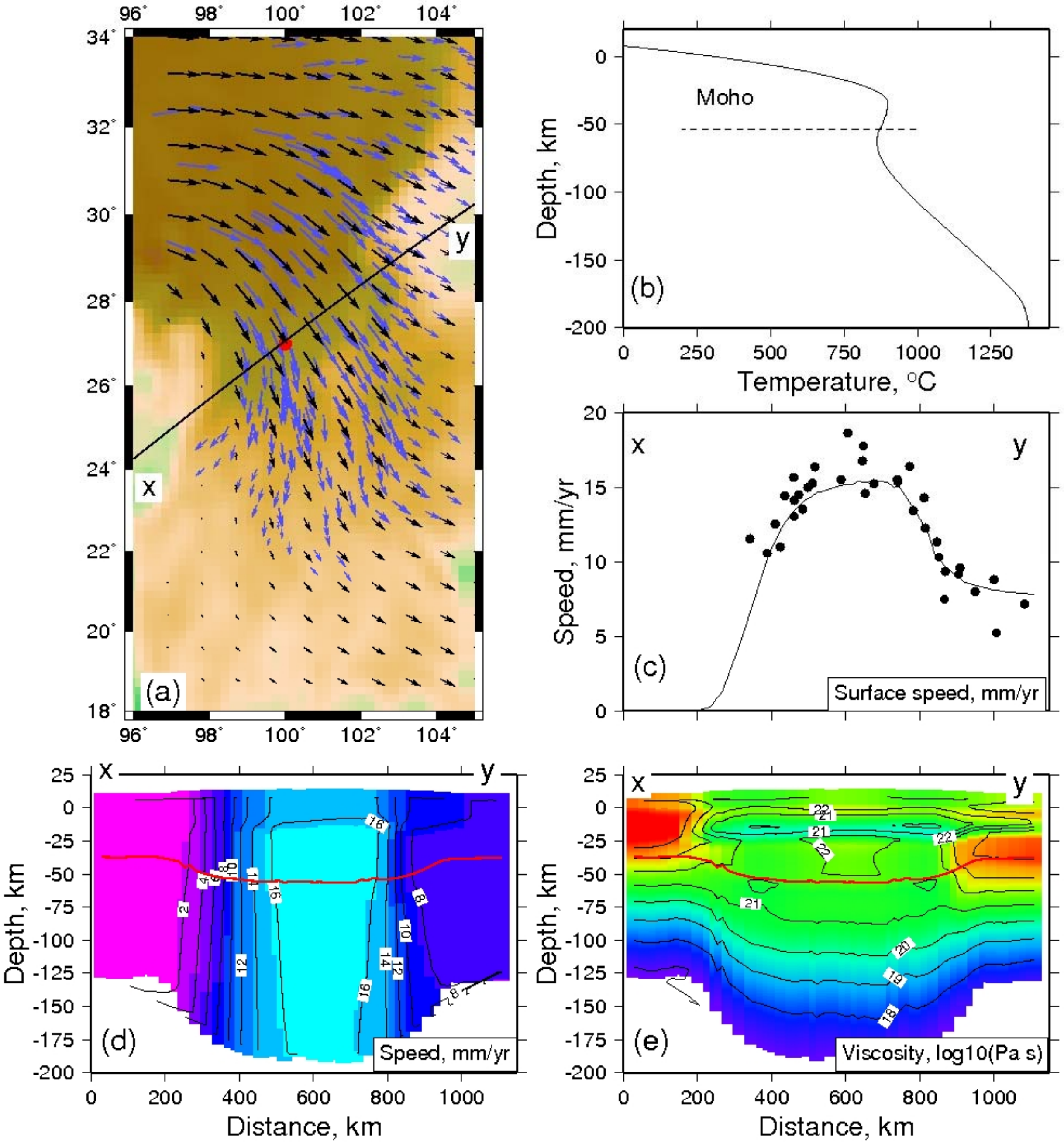
Upper and lower boundaries are stress-free

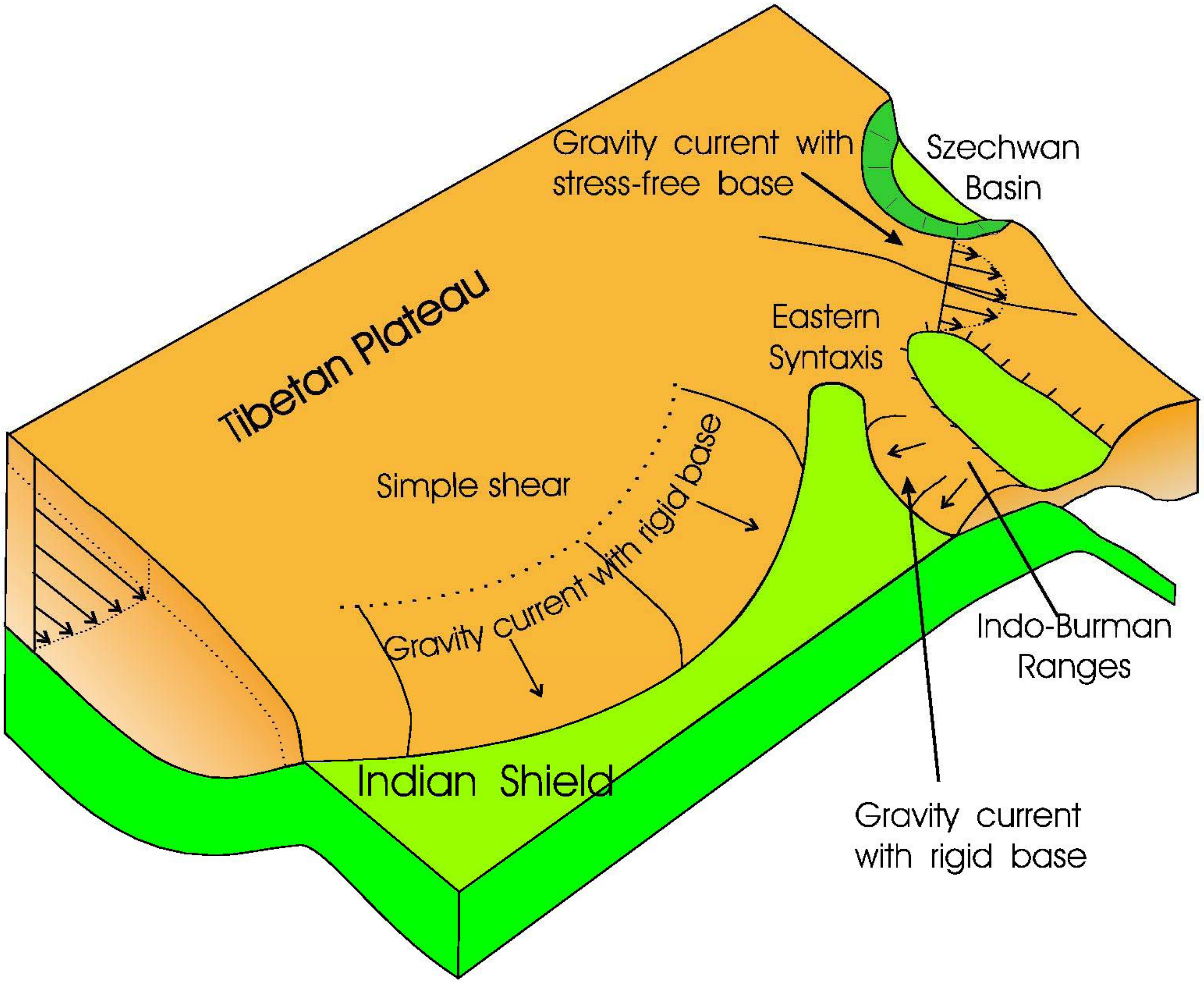
Brittle layer modelled with Byerlee's law

quartz upper crust, anorthite and clinopyroxene mix for lower crust, olivine mantle



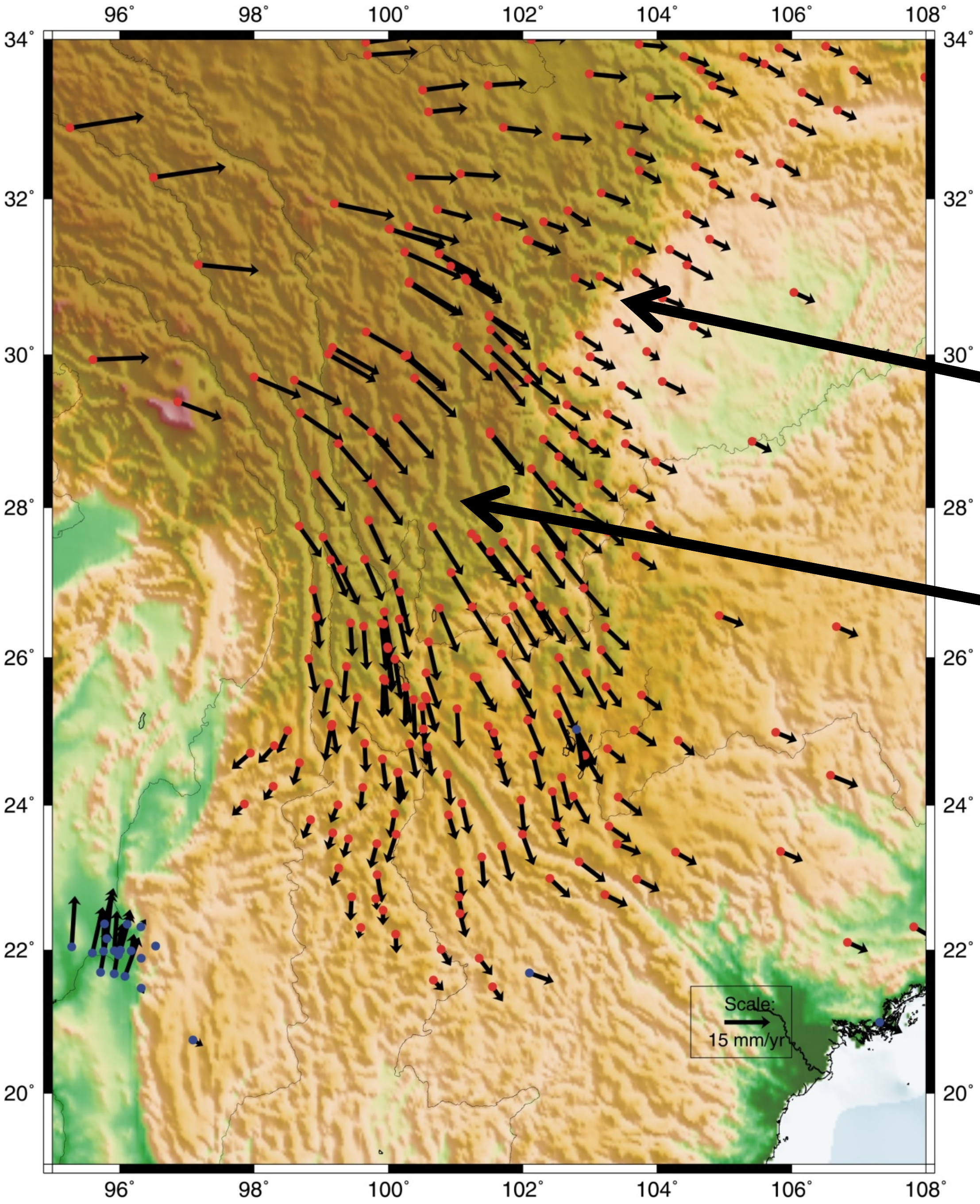



96° 98° 100° 102° 104°
34° 32° 30° 28° 26° 24° 22° 20° 18°
x
y
(a)
Depth, km
Moho
(b)
Temperature, °C
0 250 500 750 1000 1250
0 -50 -100 -150 -200
Speed, mm/yr
(c)
Surface speed, mm/yr
20 15 10 5 0
x
y
(d)
Speed, mm/yr
Distance, km
0 200 400 600 800 1000
25 0 -25 -50 -75 -100 -125 -150 -175 -200
2 4 6 8 10 12 14 16
(e)
Viscosity, log10(Pa s)
18 19 20 21 22



Copley & McKenzie 2007

Velocities relative to Eurasia



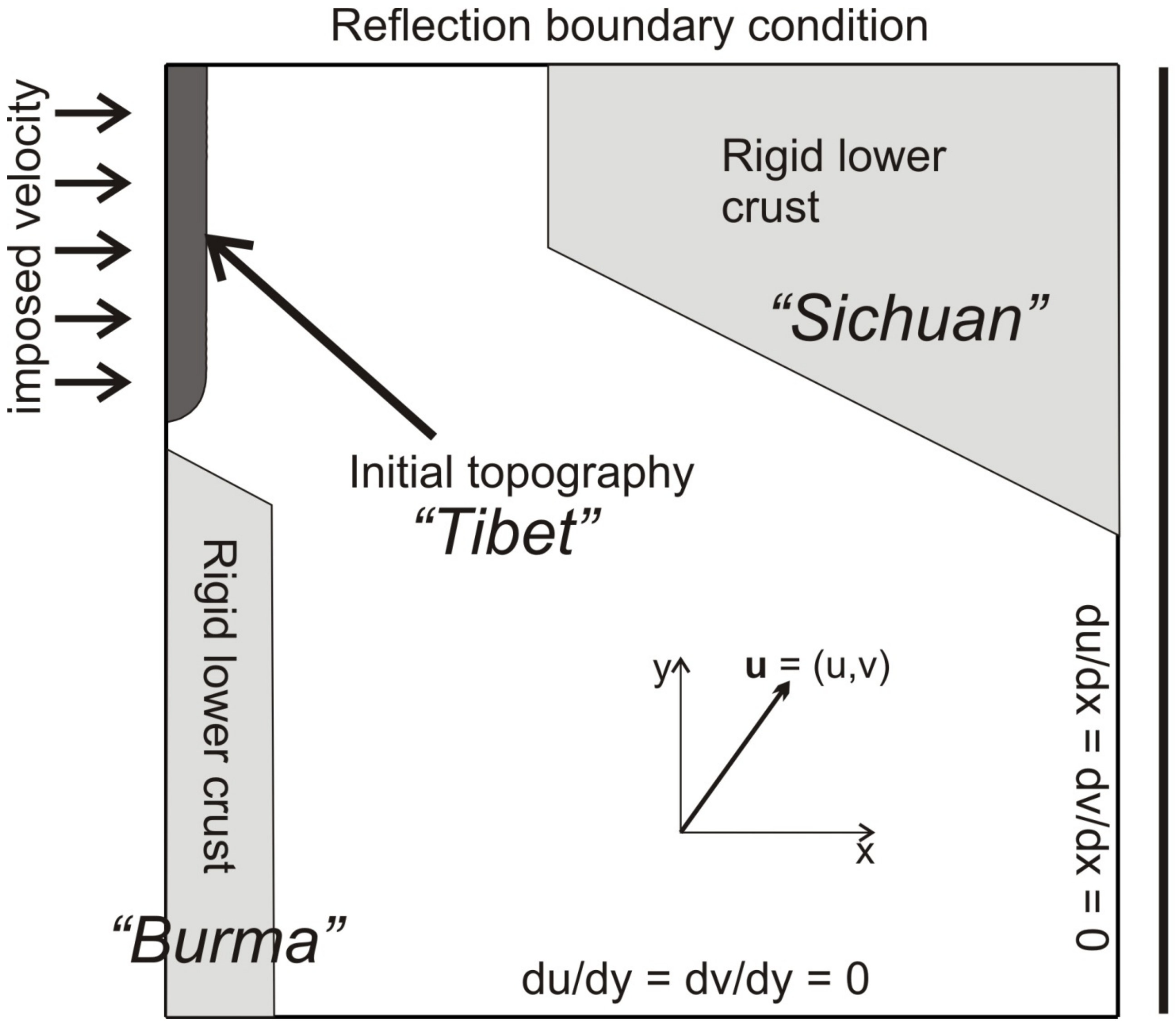
steep topography, low surface velocities, dominantly thrust faulting

low surface gradient, high velocities, dominantly strike-slip faulting

Red bases = Shen et al ’05
Dark blue = Socquet et al ‘06

Model setup

- Viscous flow in 3D
- Rigid crust represents model versions of Sichuan and Burma
- Model setup represents the appearance of high topography in central Tibet early in the India-Asia collision, and subsequent propagation to the SE.

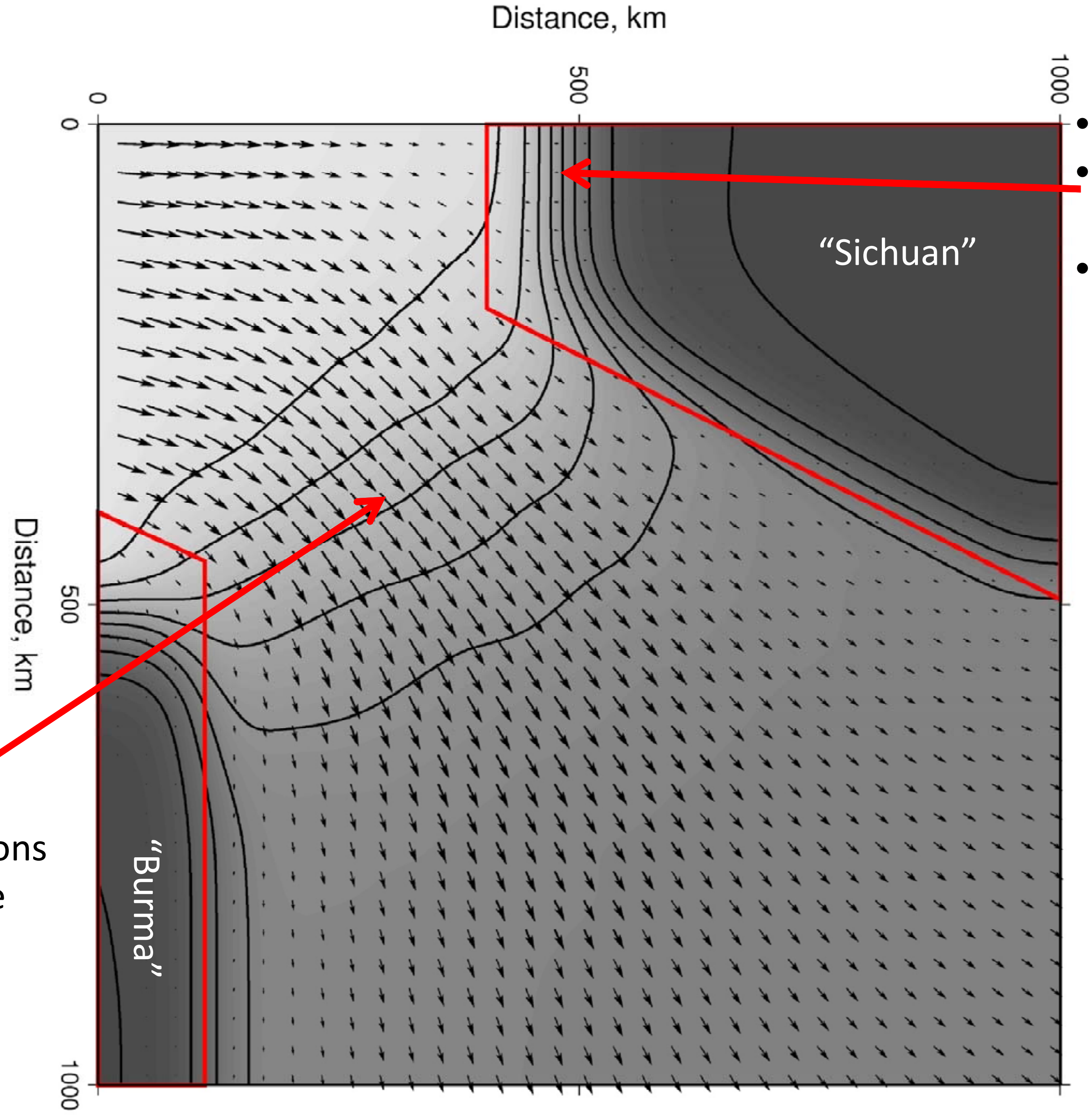


Model results after 35 Myr

Scale:

→

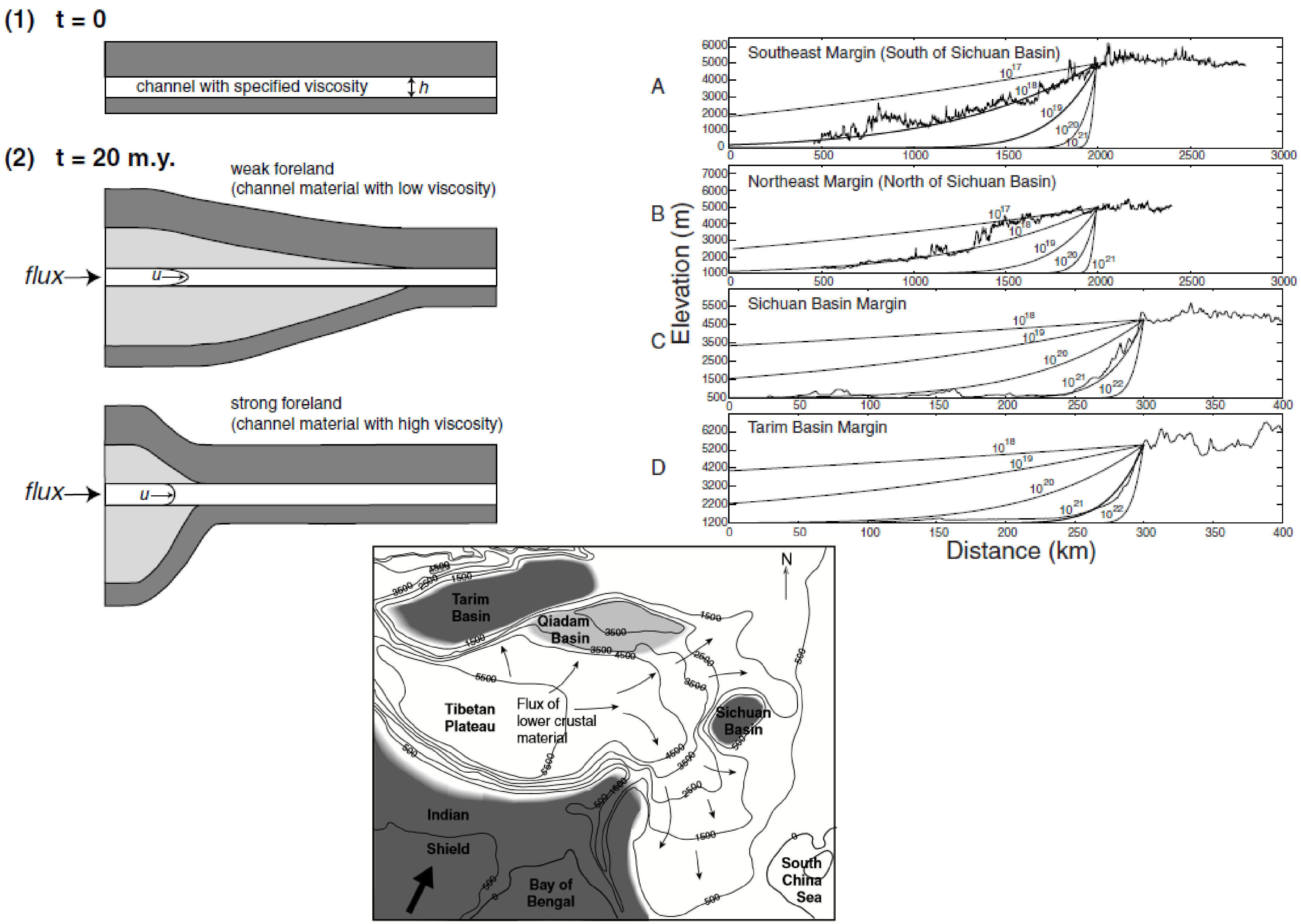
15 mm/yr



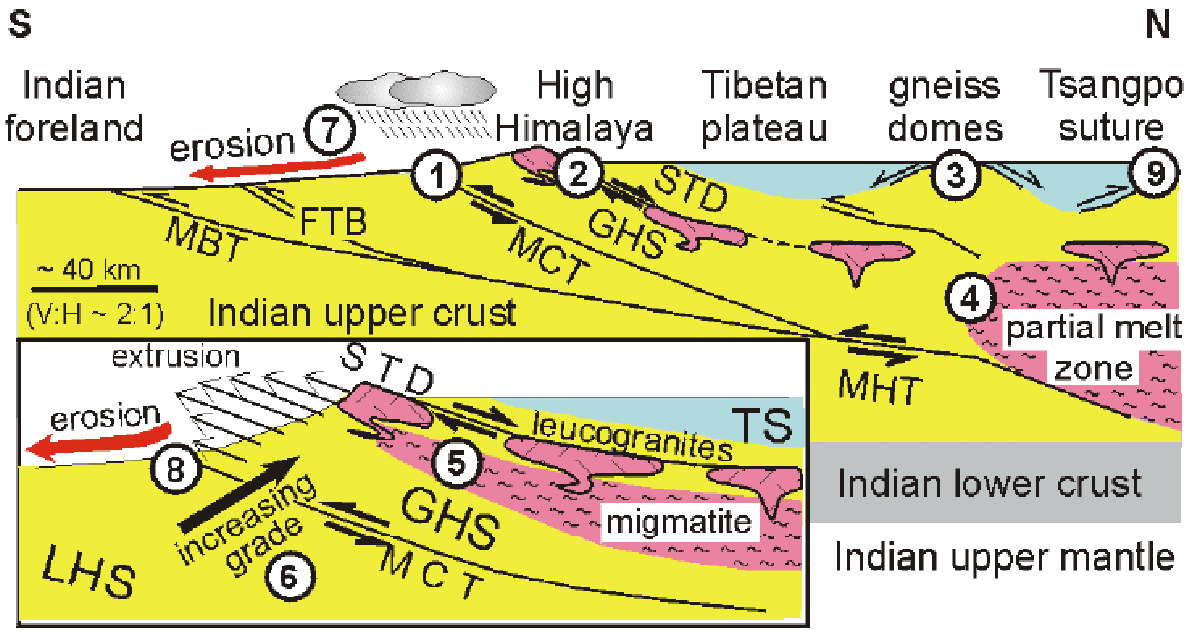
- Slow motions
- Steep surface slope
- Thrust strain

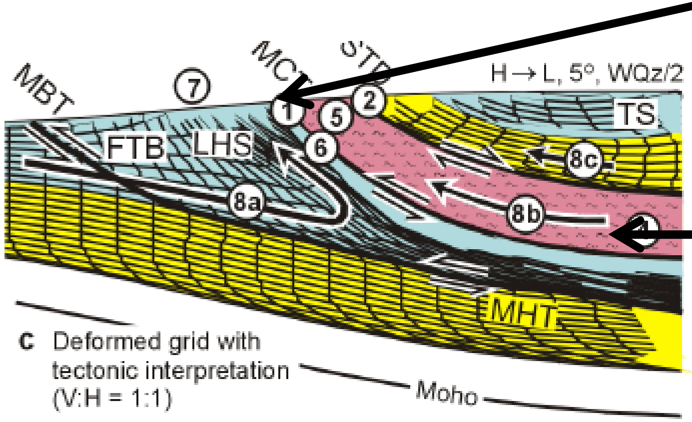
- Rapid motions
- Low surface slope
- Strike-slip strain

Other non-thin-sheet models (1): Clark and Royden (2000)



Other non-thin-sheet models (2): Beaumont et al (2001)

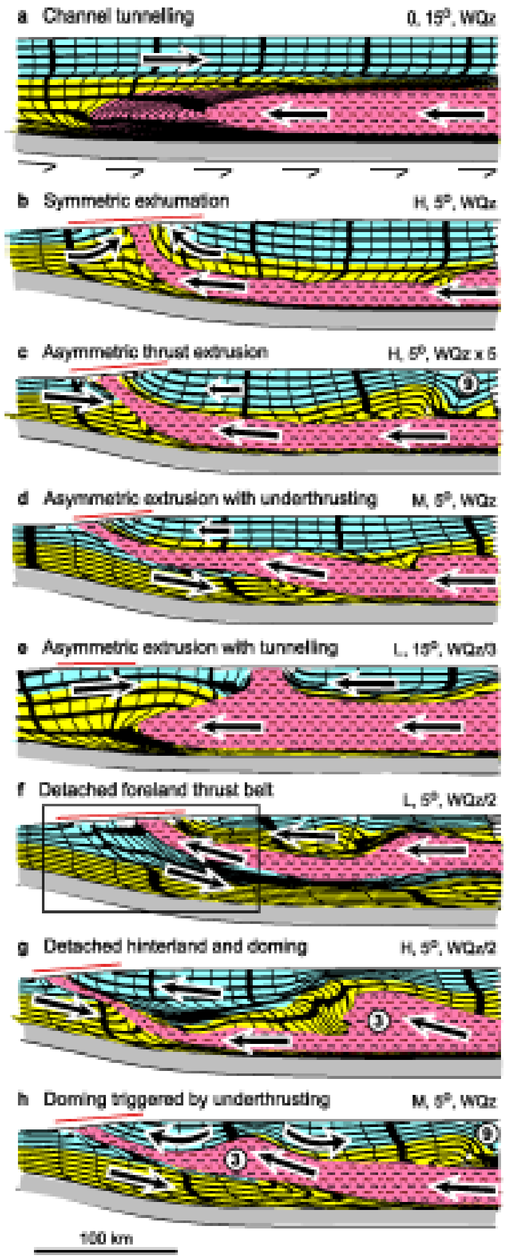




c Deformed grid with tectonic interpretation (V:H = 1:1)

Erosion since collision

Weakening by ***in situ*** melt



Main points

The rheology of the lower crust is controlling the evolution and deformation of the Tibetan Plateau (and presumably large mountain ranges in general)

Southern Tibet: Underlain by cold, strong, underthrust Indian lower crust

- Rigid base to deformation within the crust
- Flow forms steep front and flat top
- Curvature of range margin develops
- Surface tectonics is normal-faulting, with strike-slip further north

Southeast Tibetan Plateau (between Sichuan Basin and Burma):

- No rigid lower crust
- Driving forces resisted by the drag from the strong basins bounding the range
- Low surface gradients
- Strike-slip faulting accommodates shear in the region between the basins