Geodetic Inversion of Complex Fault Geometries for Strong Earthquakes

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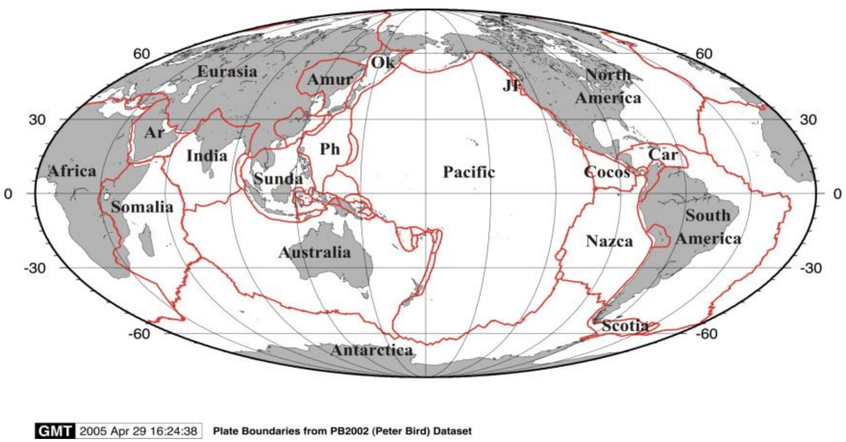
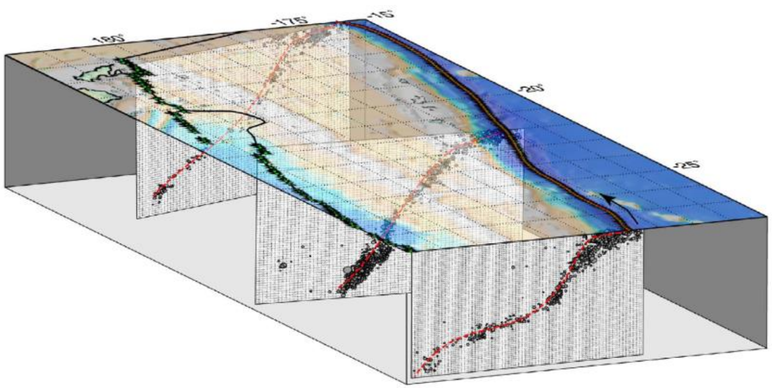
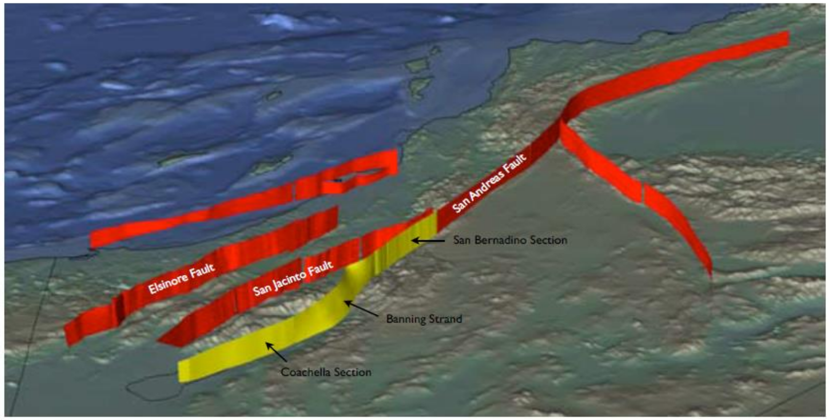
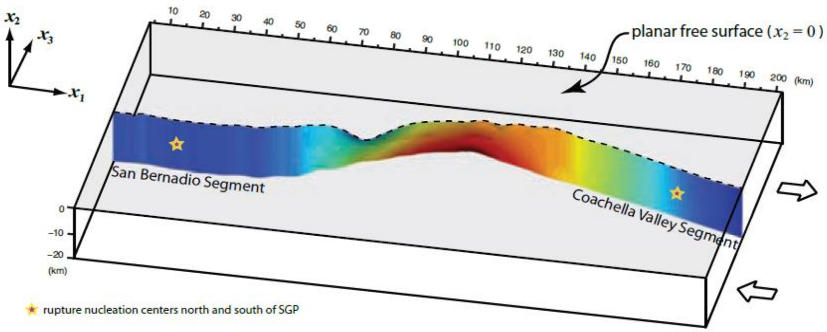
Content

The complexity of fault geometry exists in global and local scales







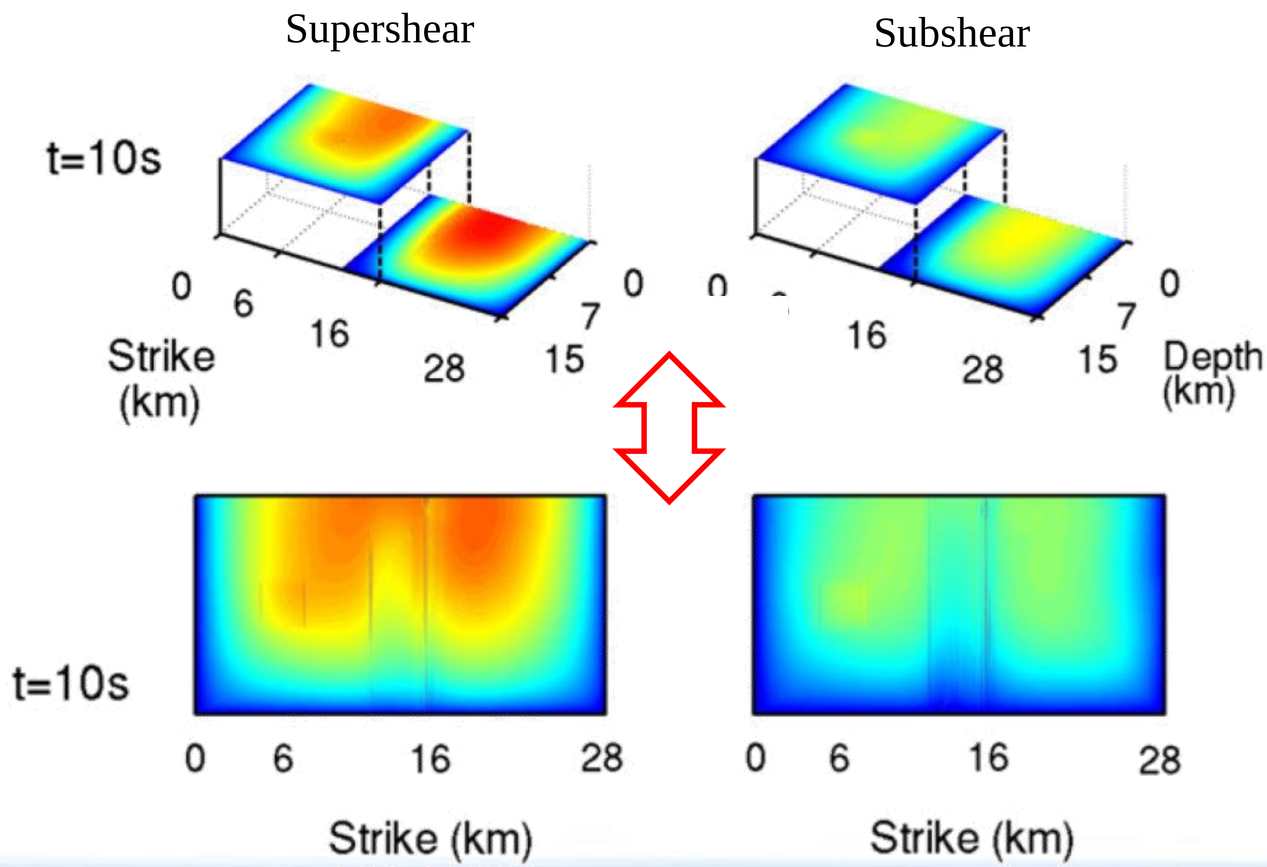


(Shi and Day, 2014)

Source dynamic simulations have suggested fault strength and geometric shape can cause similar fault slips

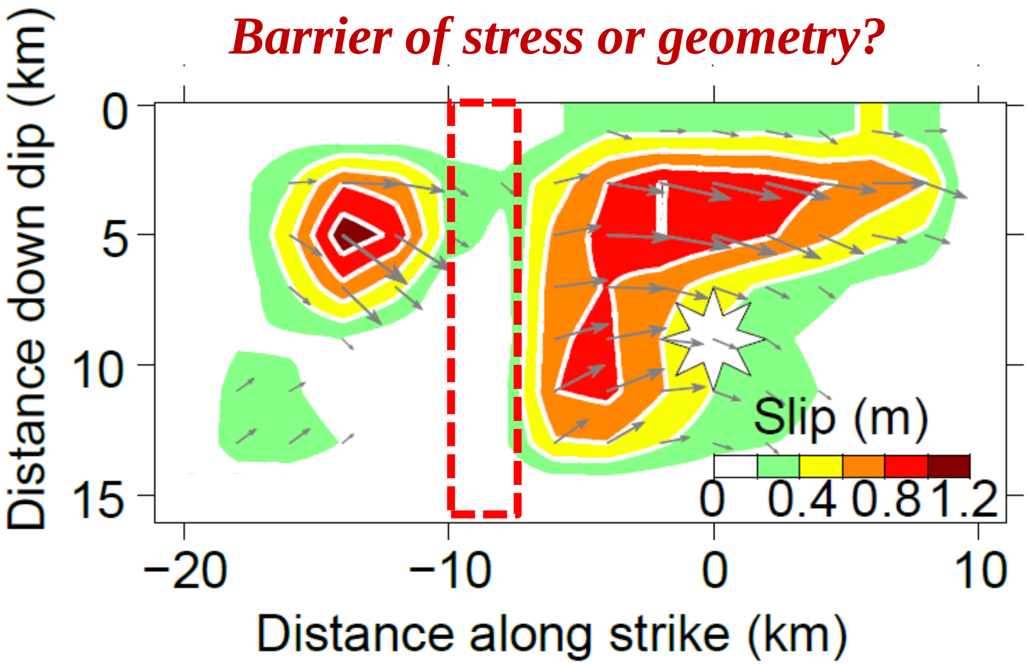
Two-segment fault

Equivalent single fault



(Hu et al., 2014)

For a given slip model, the slip gap may be caused by a barrier. Was it caused by stress heterogeneity or fault geometric change?



2017 Jiuzhaigou Mw6.5 earthquake
(Hu et al., 2020, Tectonophysics)

Note: The increased stress around the slip gap can sometimes exceed the co-seismic stress drop (Aki, 1979)

$$\sigma = \Delta\sigma \left(\frac{a}{2d}\right)^{1/2}$$

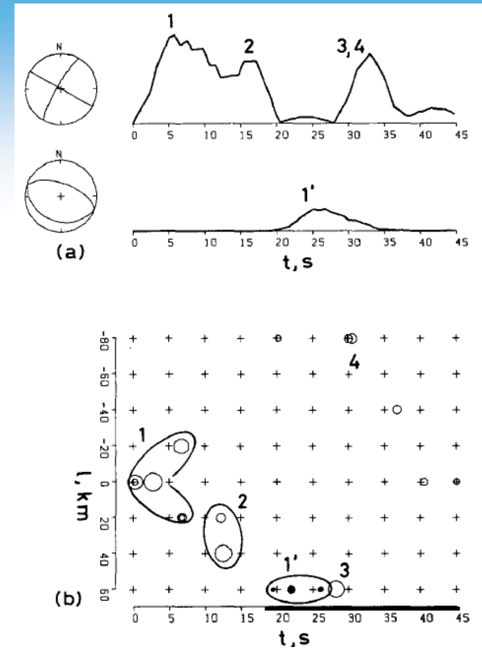
The fault geometric complexity can be estimated from either seismic or geodetic ways.

- In seismic studies, the multiple-point moment tensor solutions were estimated and thus the variations in fault strike, dip and rake can be obtained.

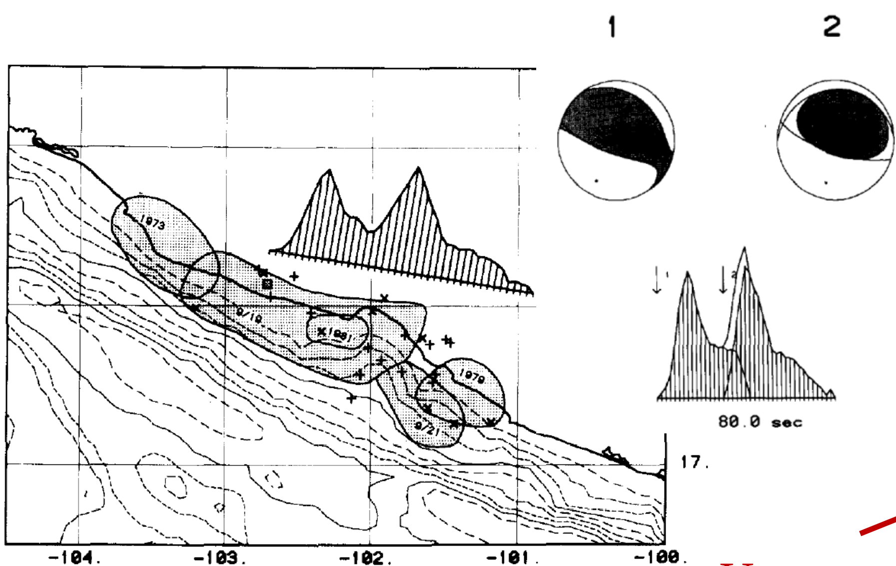
- In geodetic researches, the fault geometry was usually directly estimated in a non-linear way.

Seismic Inversion

The relation between moment tensor elements and ground motion is linear, but the inversion tend to be instable since the trade-off between moment tensor and rupture velocity. This may sometimes cause the mechanism solution unreasonable.

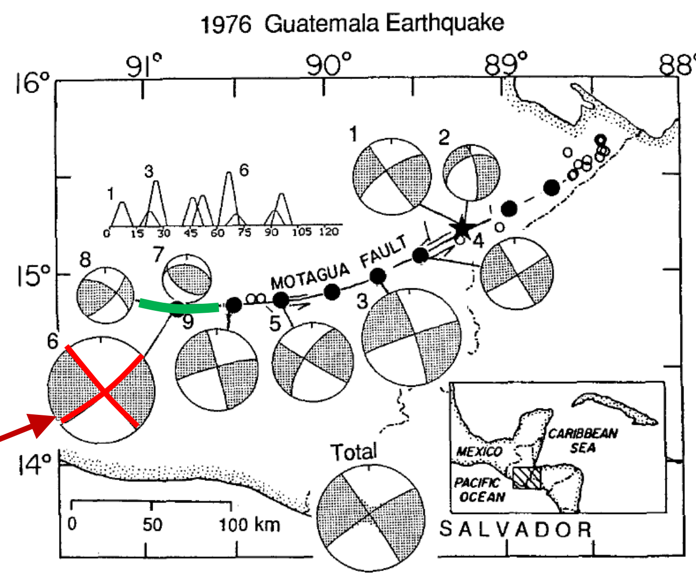


(Kikuchi and Kanamori, 1986)



(Ekstrom, 1989)

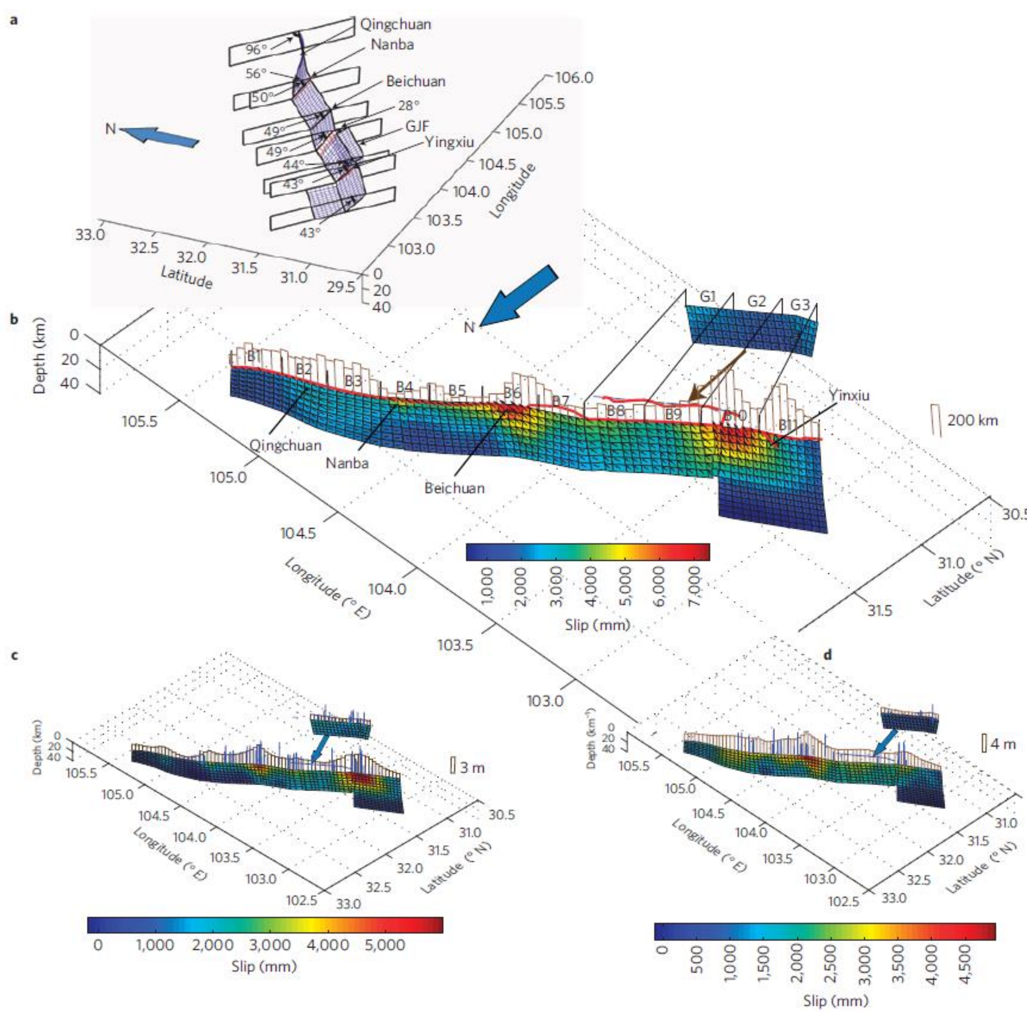
Unreasonable mechanism?



(Kikuchi and Kanamori, 1991)

Geodetic Inversion

Since there is no need to solve rupture velocity, co-seismic geodetic inversion has less unknowns compared with seismic inversion. However, the relation between the deformation data and fault parameters (strike, dip and rake) is nonlinear.



(Shen et al., 2009)

What we have done

- Discretizing the fault into sub-faults. If the sub-fault dimension is small enough (much less than the source-to-site distance), they can be treated as point sources.
- Based on the point source approximation, we can build a linear equation between the sub-fault moment tensors and co-seismic deformation.
- By determining the sub-fault moment tensors, we can get the strikes, dips, and rakes of each sub-fault, and get the knowledge of fault geometric complexity.

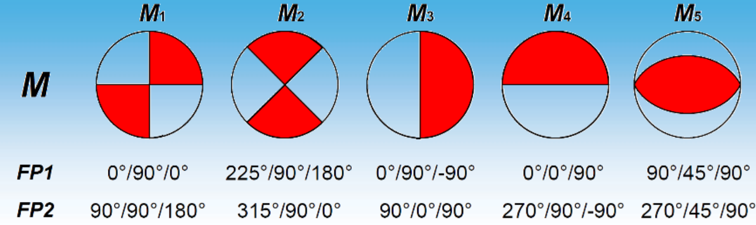
Content

Introduction

The 2008 Wenchuan Earthquake

The 2015 Gorkha earthquake

Discussion



Five elementary moment tensors

Method

As pointed out by Kikuchi and Kanamori (1991), a deviatoric moment tensor can be represented by five elementary double-couple moment tensors

$$\mathbf{M} = \sum_{i=1}^{5} (\alpha_i \cdot \mathbf{M}_i)$$

Thus the surface deformation U caused by sub-faults (j=1, …, N) is

$$U = \sum_{j=1}^{N} \sum_{i=1}^{5} (\alpha_{ij} \cdot g_{ij}),$$

where g_{ij} is the deformation caused by moment tensor $\mathbf{M}_i$ of sub-fault j. The equation with the spatial smoothing is

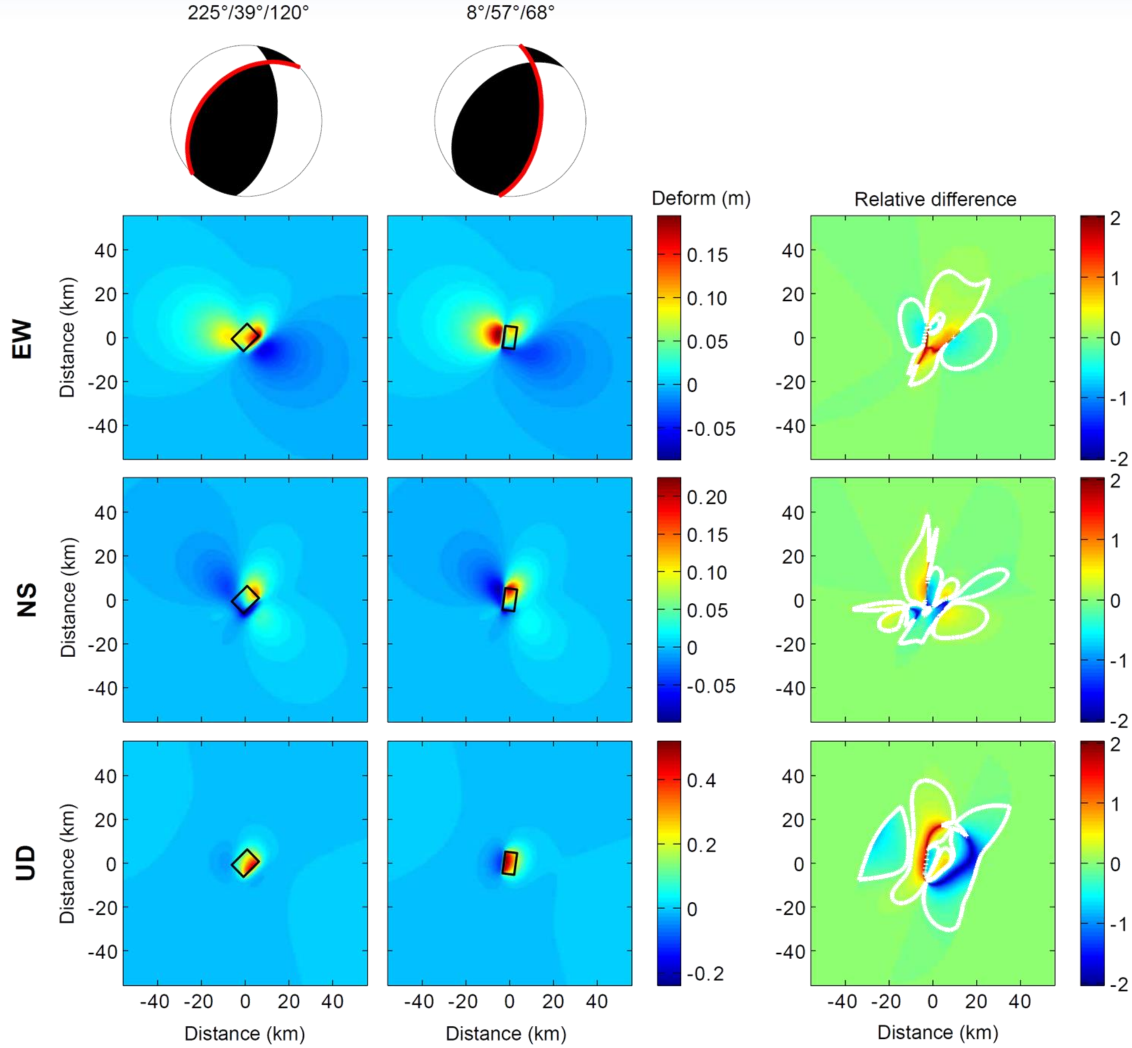
$$\begin{bmatrix} U \\ 0 \end{bmatrix} = \begin{bmatrix} G \\ \lambda D \end{bmatrix} [m]$$

(Zhang and Wang, 2015, GJI)

The point source approximation

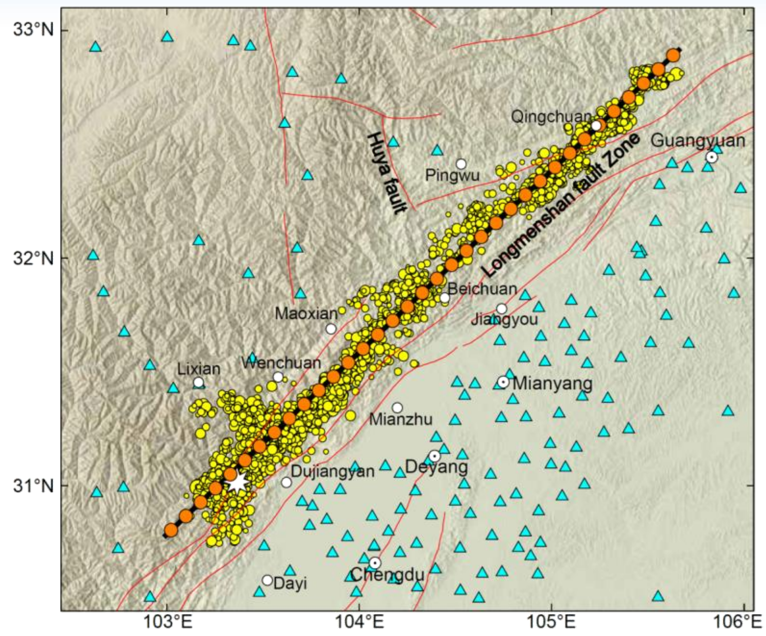
We calculated the surface deformation based on uniform slip (1 m) on a 10 km × 10 km fault plane with a pair of conjugated fault parameters.

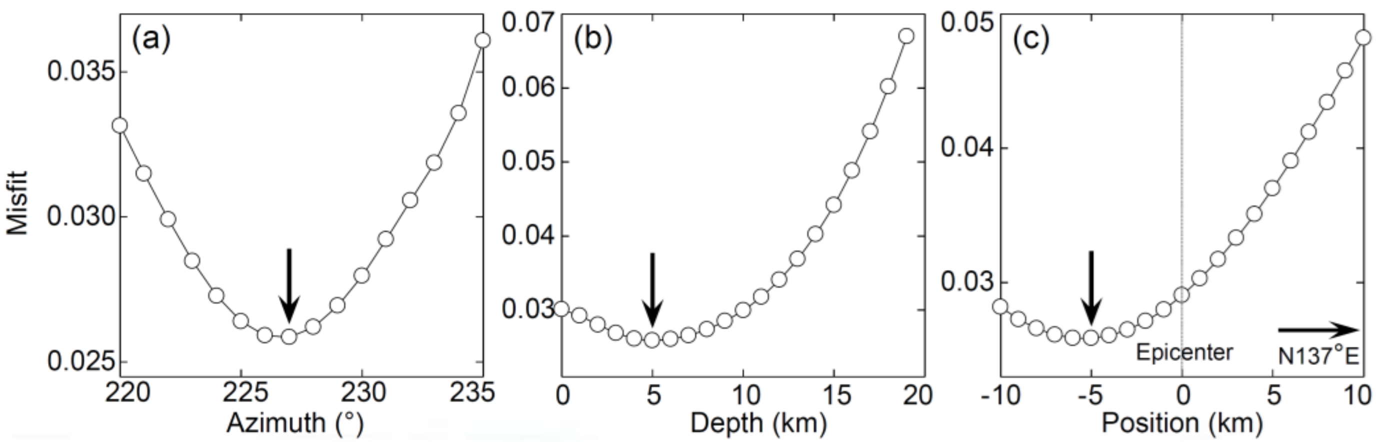
From the relative difference, we found the source-to-site distance should be ~3 times larger than the fault dimension to satisfy the point source approximation.



(Zhang and Wang, 2015)

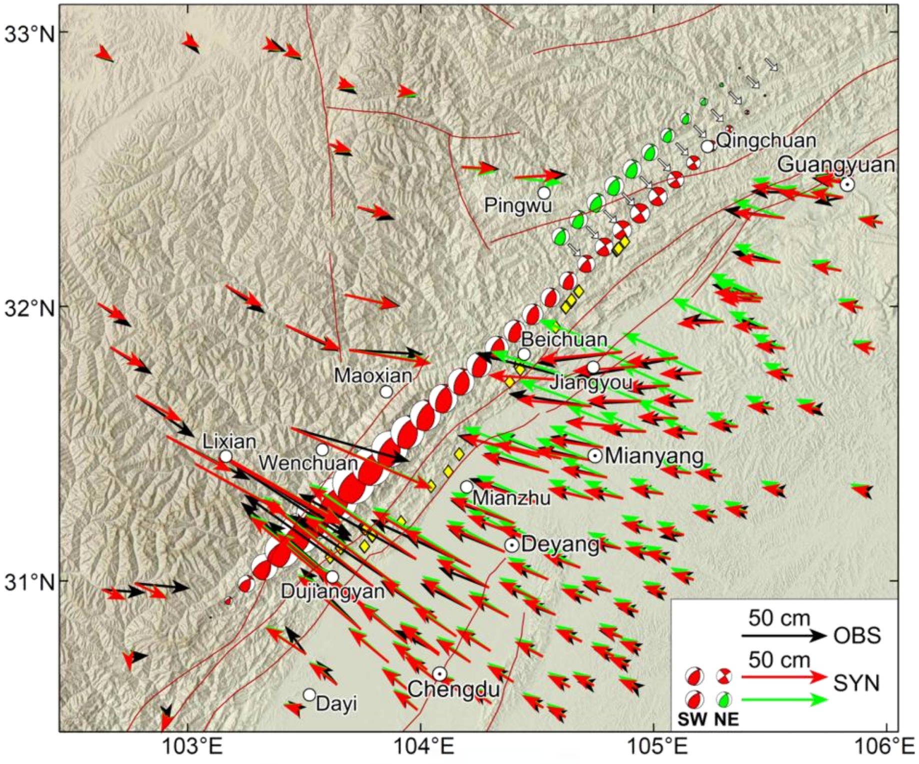
In application to the 2008 Wenchuan earthquake, a line fault was used and divided into 31 sub-faults. Co-seismic GPS data were used in the application.



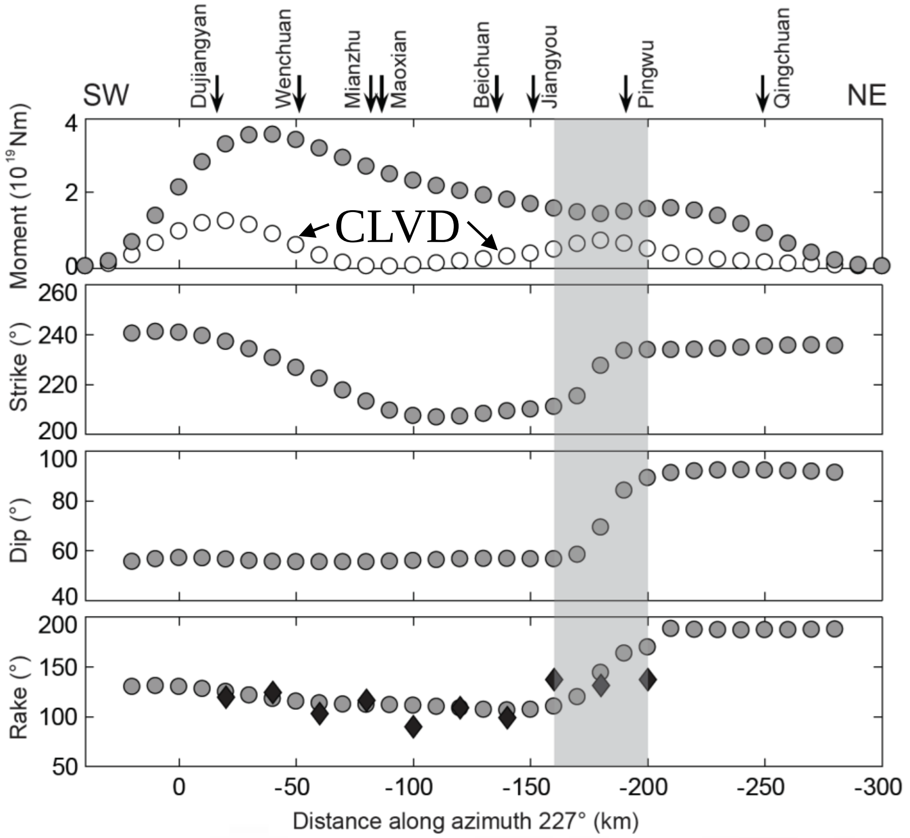


The direction, depth and the position of the line fault was optimized through a 3-D grid search.

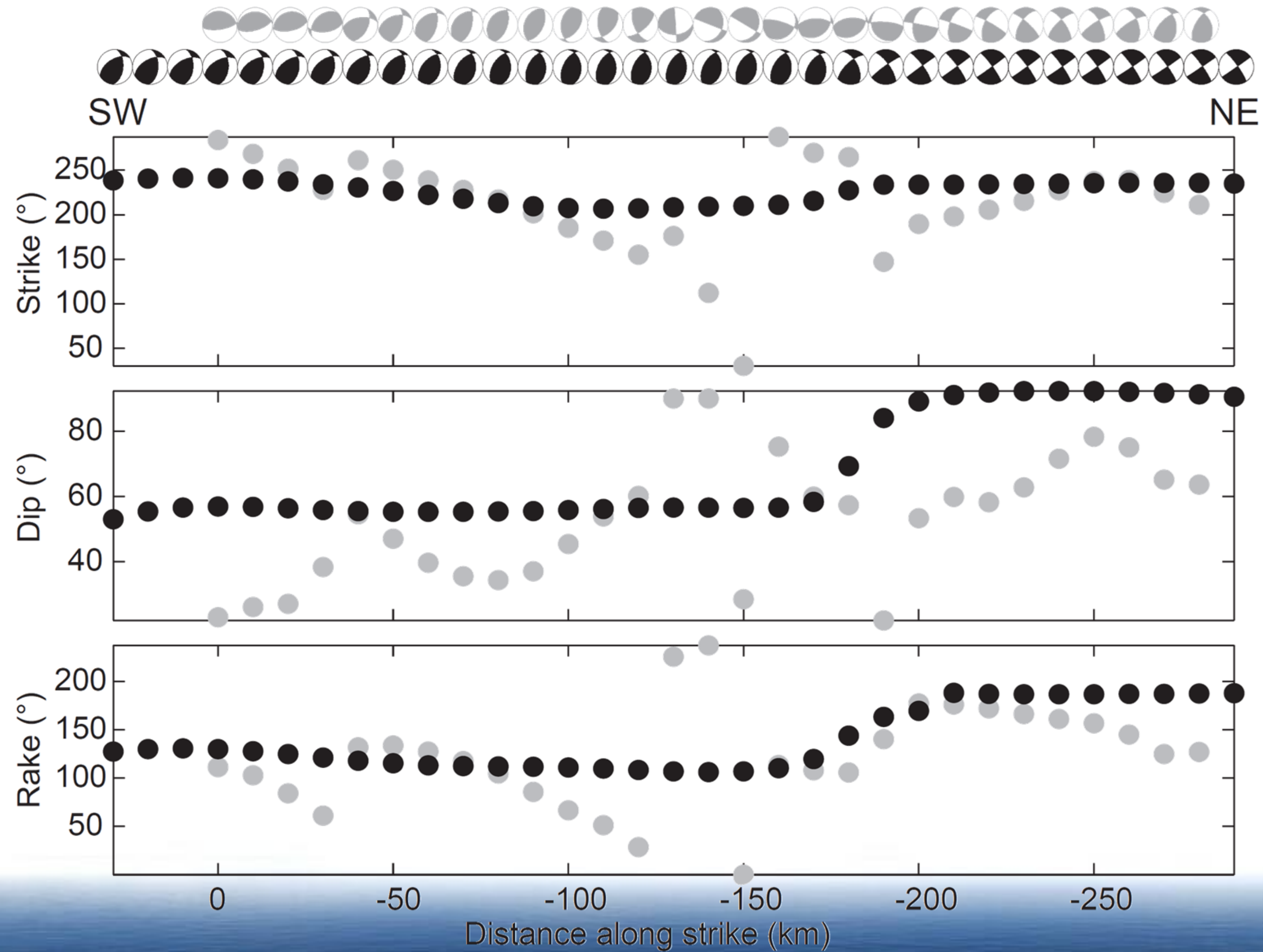
The sub-fault moment tensors of the 2008 Wenchuan earthquake, showing thrust and strike slips in the southwest and northeast, respectively.



The variations of scalar moment, strike, dip, and rake along the strike

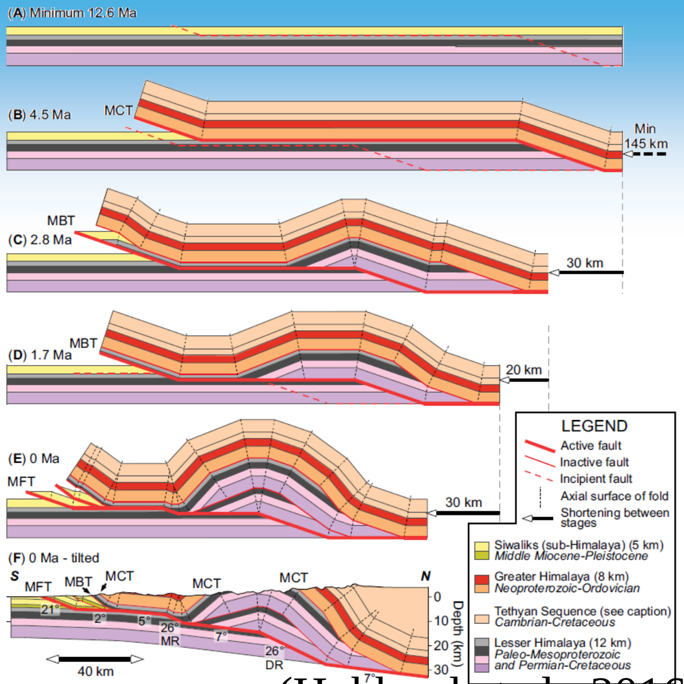


Comparison between our geodetic model obtained in this study (black) and previous teleseismic model (gray cicles, Zhang et al., 2009). The geodetic mechanism variations are relatively more smooth and systematic.

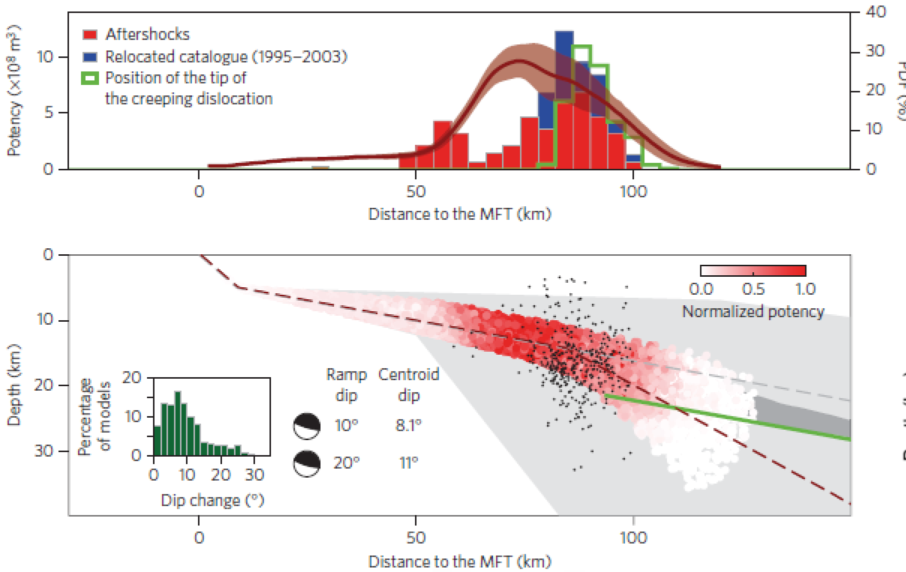


Content

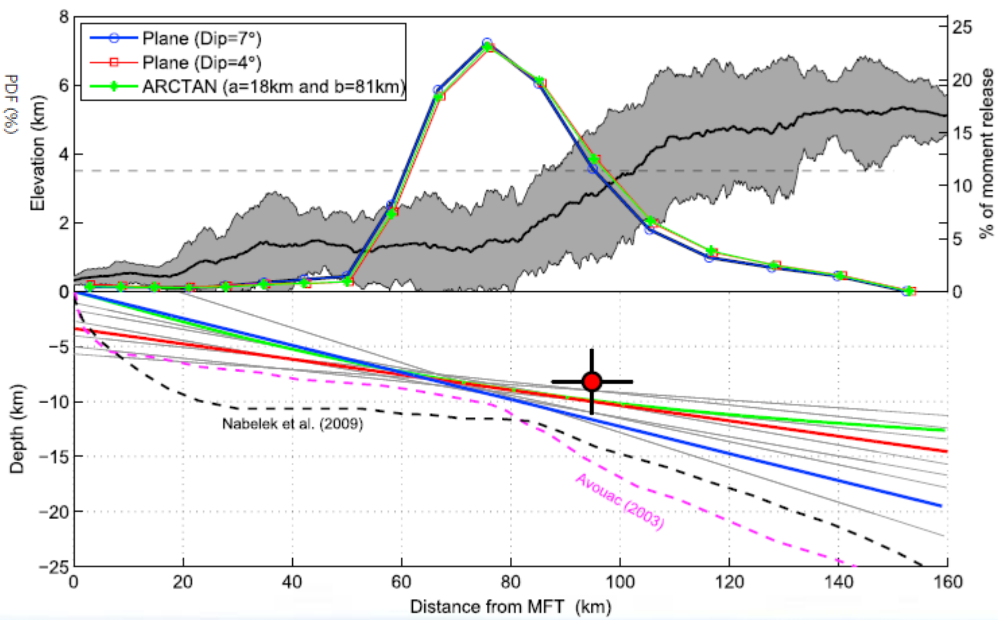
The 2015 Gorkha earthquake has drawn interests on its complex fault geometry, particularly on its dip angles and variations.



(Hubbard et al., 2016)



(Elliott et al., 2016)



(Wang et al., 2015)

Method

The moment tensor of a fault

$$M_{xx} = -M_0(\sin\delta\cos\lambda\sin 2\phi_S + \sin 2\delta\sin\lambda\sin^2\phi_S)$$

$$M_{xy} = +M_0(\sin\delta\cos\lambda\cos 2\phi_S + \frac{1}{2}\sin 2\delta\sin\lambda\sin 2\phi_S) = M_{yx}$$

$$M_{xz} = -M_0(\cos\delta\cos\lambda\cos\phi_S + \cos 2\delta\sin\lambda\sin\phi_S) = M_{zx}$$

$$M_{yy} = +M_0(\sin\delta\cos\lambda\sin 2\phi_S - \sin 2\delta\sin\lambda\cos^2\phi_S)$$

$$M_{yz} = -M_0(\cos\delta\cos\lambda\sin\phi_S - \cos 2\delta\sin\lambda\cos\phi_S) = M_{zy}$$

$$M_{zz} = +M_0\sin 2\delta\sin\lambda$$

It can be separated into strike-slip and dip-slip components

$$M = \cos\delta\cos\lambda M^1 + \sin\delta\cos\lambda M^2 + \cos 2\delta\sin\lambda M^3 + \sin 2\delta\sin\lambda M^4$$

$$M^1 = M_0\begin{pmatrix} 0 & 0 & -\cos\phi_S \\ 0 & 0 & -\sin\phi_S \\ -\cos\phi_S & -\sin\phi_S & 0 \end{pmatrix}, \quad M^3 = M_0\begin{pmatrix} 0 & 0 & -\sin\phi_S \\ 0 & 0 & \cos\phi_S \\ -\sin\phi_S & \cos\phi_S & 0 \end{pmatrix},$$

$$M^2 = M_0\begin{pmatrix} -\sin 2\phi_S & \cos 2\phi_S & 0 \\ \cos 2\phi_S & \sin 2\phi_S & 0 \\ 0 & 0 & 0 \end{pmatrix}, \quad M^4 = M_0\begin{pmatrix} -\sin^2\phi_S & 0.5\sin 2\phi_S & 0 \\ 0.5\sin 2\phi_S & -\cos^2\phi_S & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Strike-slip ***Dip-slip***

（Aki and Richards, 1980）

For a dip-slip fault with a known or assumed strike

$$M = M^D = \alpha M_0^D + \beta M_{45}^D,$$

where

$$M_0^D = M^D(\delta = 0) = \begin{bmatrix} 0 & 0 & -sin\varphi \\ 0 & 0 & cos\varphi \\ -sin\varphi & cos\varphi & 0 \end{bmatrix},$$

$$M_{45}^D = M^D(\delta = 45) = \begin{bmatrix} -sin^2\varphi & \frac{1}{2}sin2\varphi & 0 \\ \frac{1}{2}sin2\varphi & -cos^2\varphi & 0 \\ 0 & 0 & 1 \end{bmatrix}.$$

(Zhang et al., 2017, GRL)

Particularly for a thrust fault

$$M = M^D = \alpha M_0^D + \beta M_{45}^D,$$

By minimizing the following equation

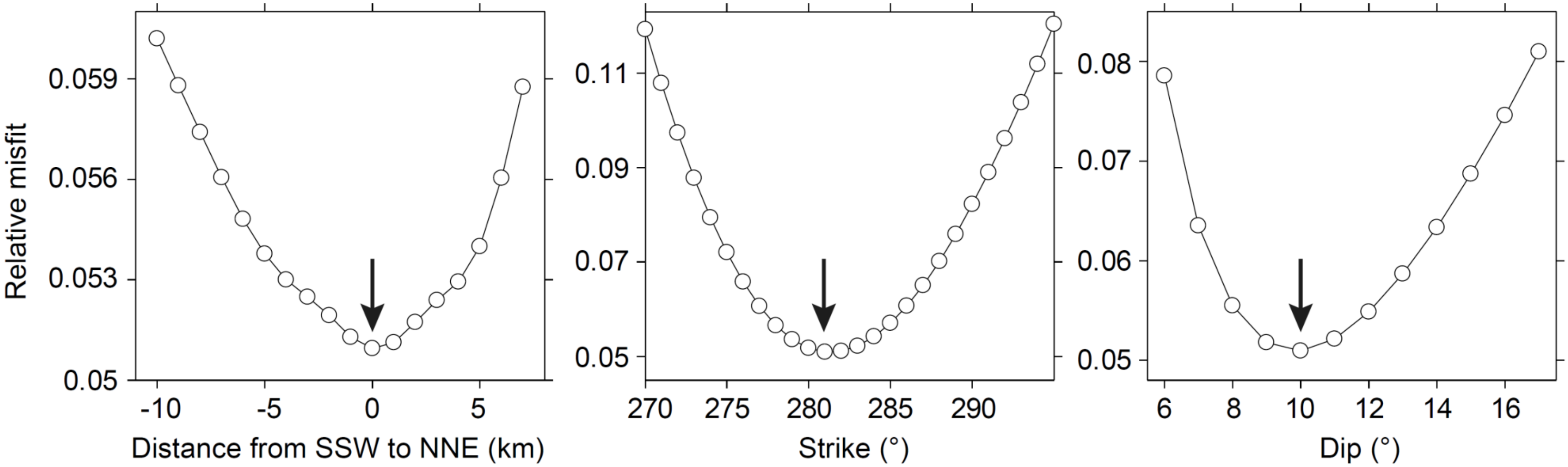
$$\Delta = \left\| u - \sum_{k=1}^{N} (g_{0k}^D \alpha_k + g_{45k}^D \beta_k) \right\|_2 + \kappa \|\nabla^2 \alpha\|_2 + \kappa \|\nabla^2 \beta\|_2,$$

The dip and slip distributions can be obtained

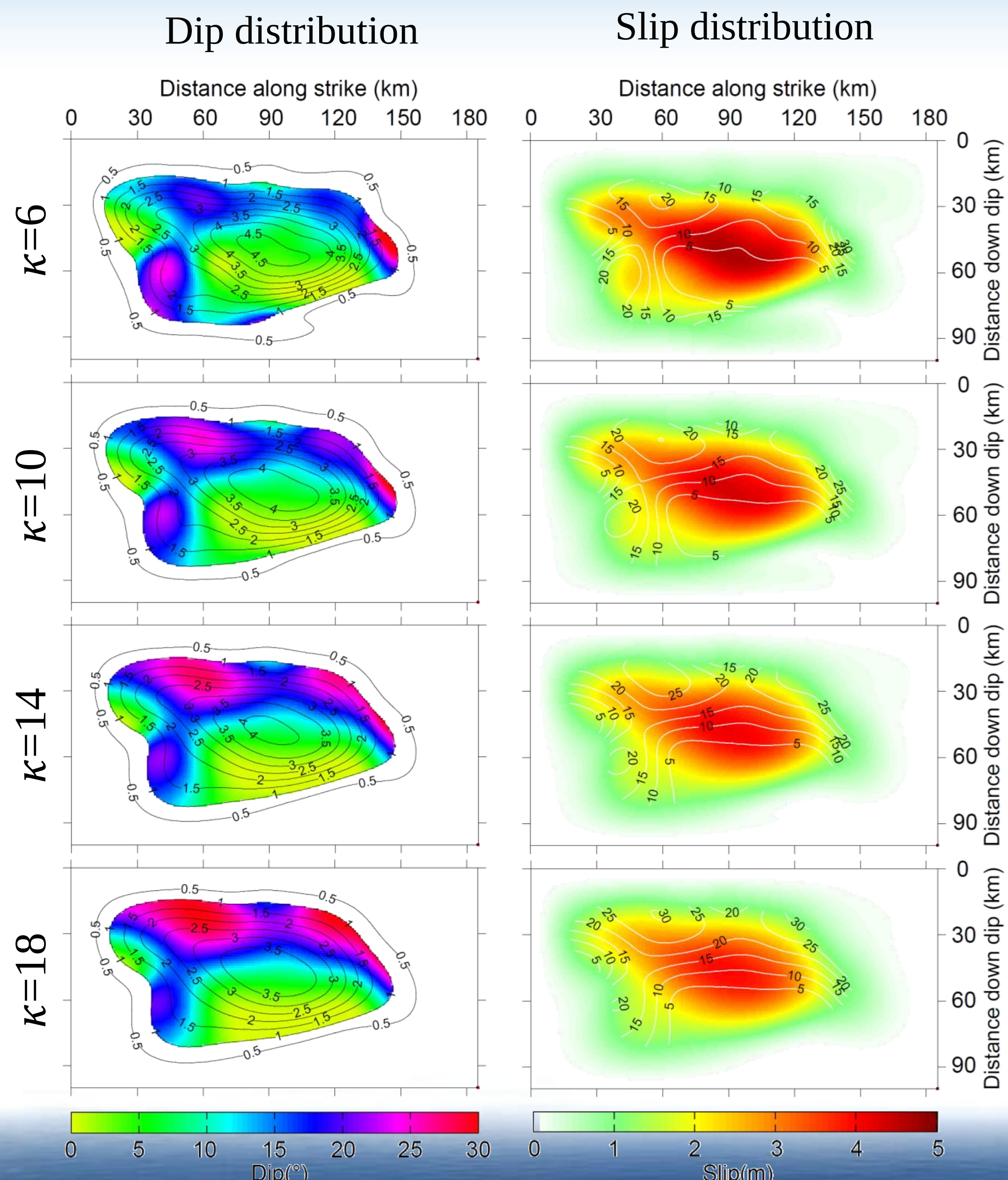
$$\delta = \frac{1}{2}\arctan(\beta/\alpha), M_0 = \sqrt{\alpha^2+\beta^2}.$$

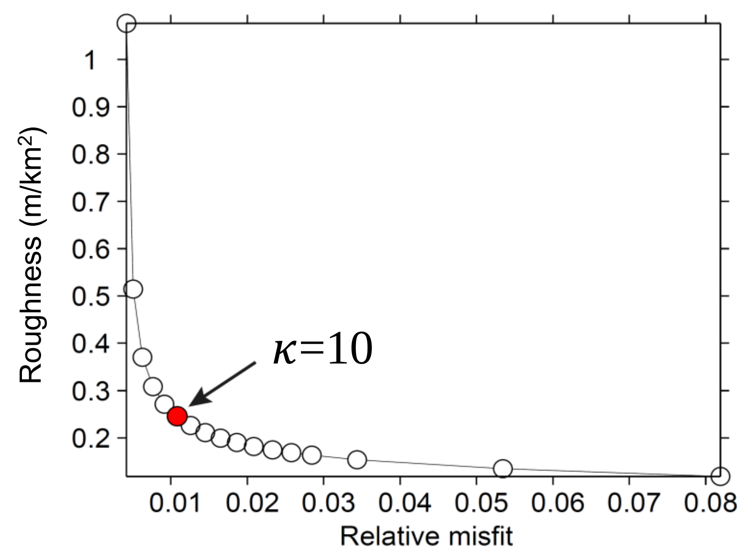
(Zhang et al., 2017, GRL)

Optimize the fault position through a 3-D grid search

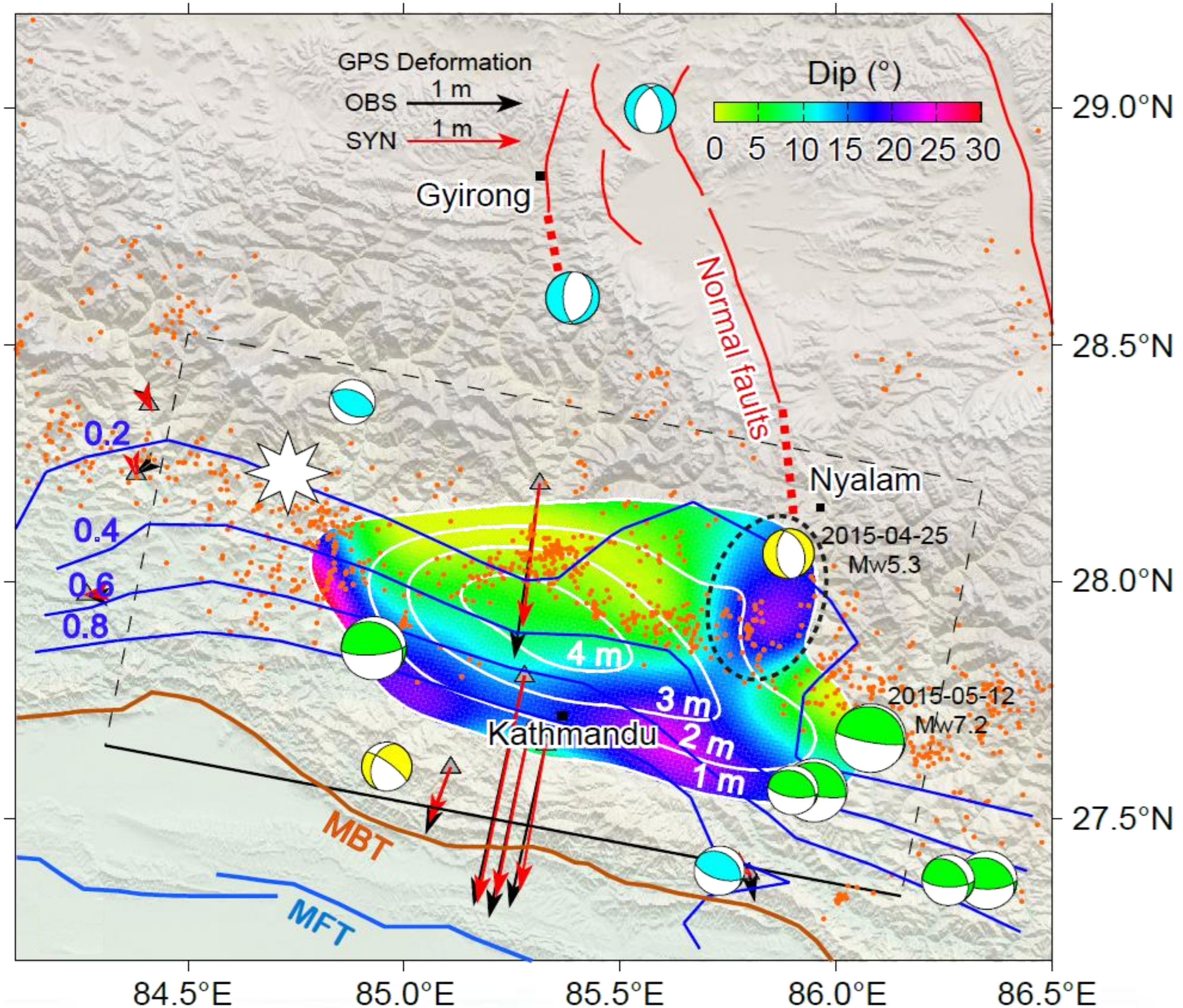


Choosing the spatial smoothing weight on the L-curve





Dip and slip model



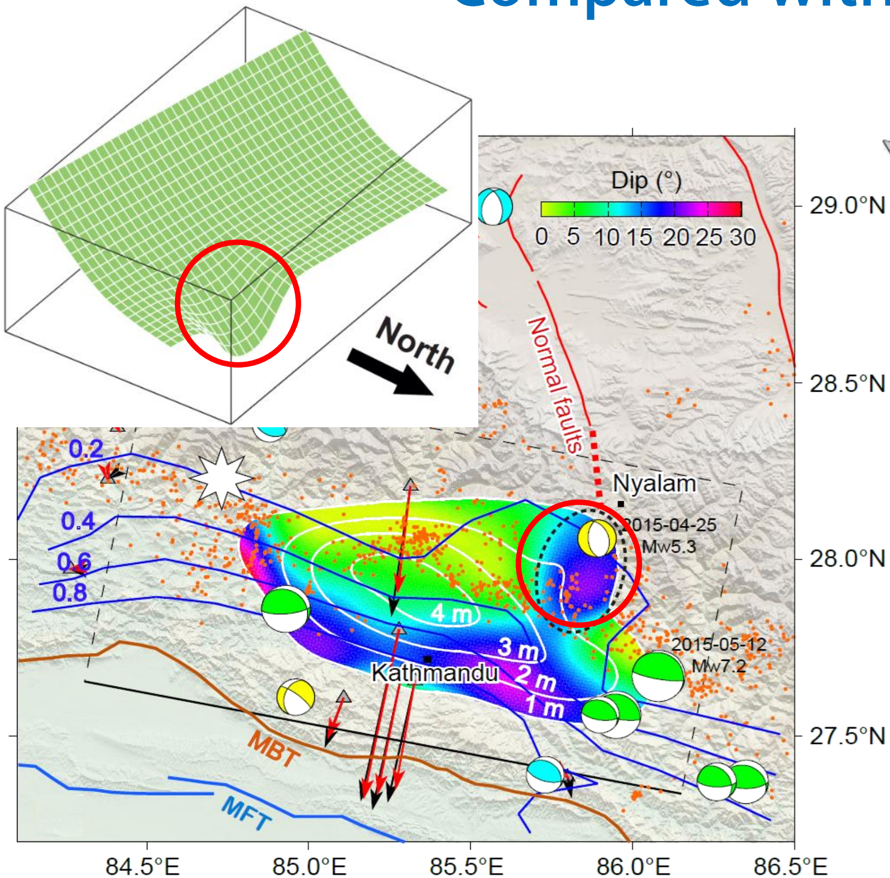
Feature I

The dip decreases from shallow to deep depths, suggesting ramp-flat fault geometry.

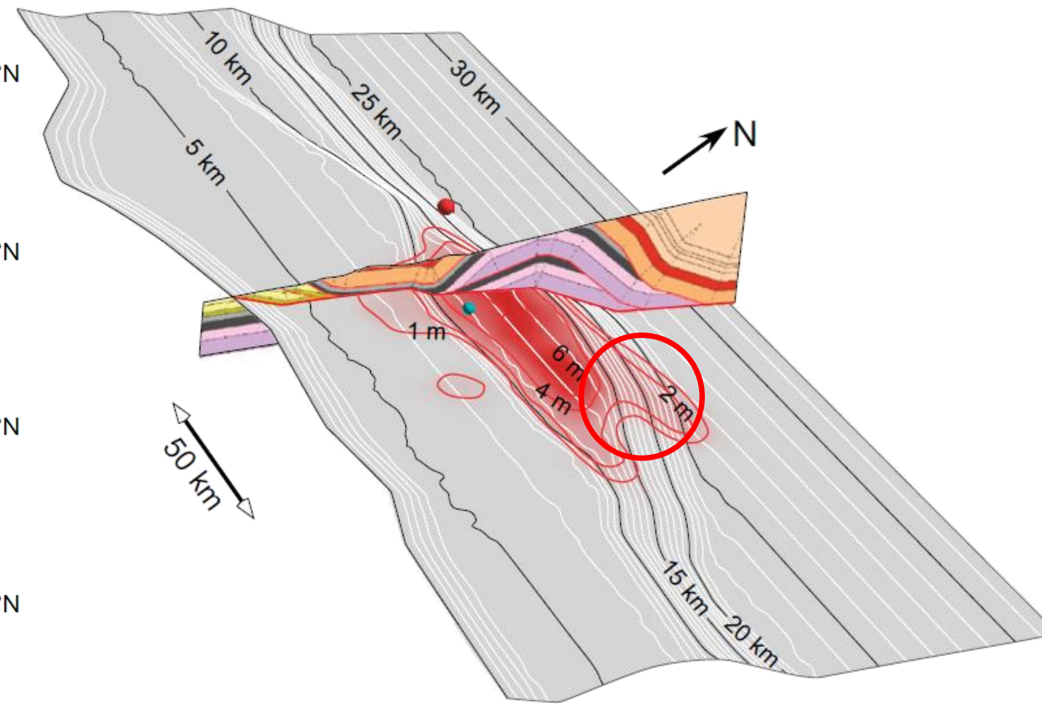
Feature II

A lateral dip anomaly with dip larger than 15° appears in the northeast corner of the slip area, where the easternward ruptures were blocked.

Compared with geologic model

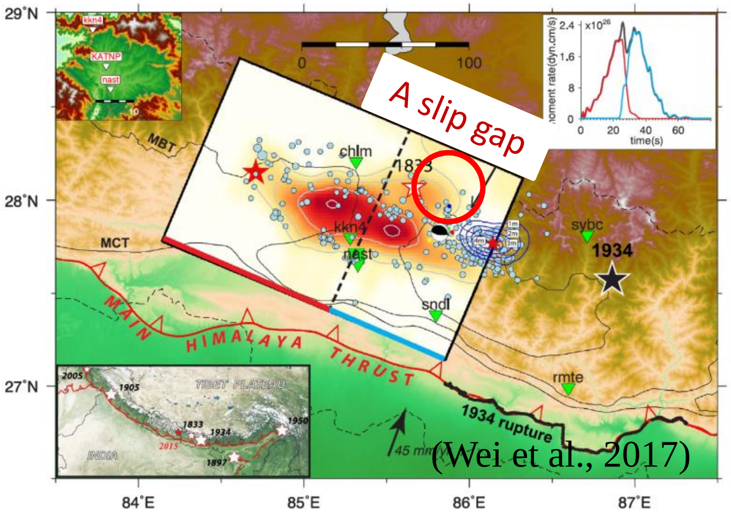


(Zhang et al., 2017, GRL)

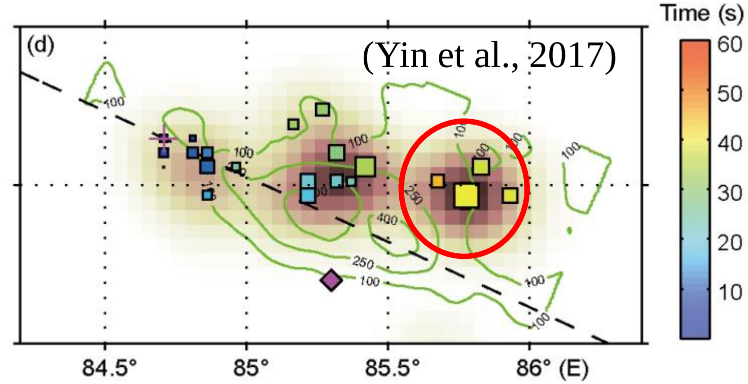


(Hubbard et al., 2016, Geology)

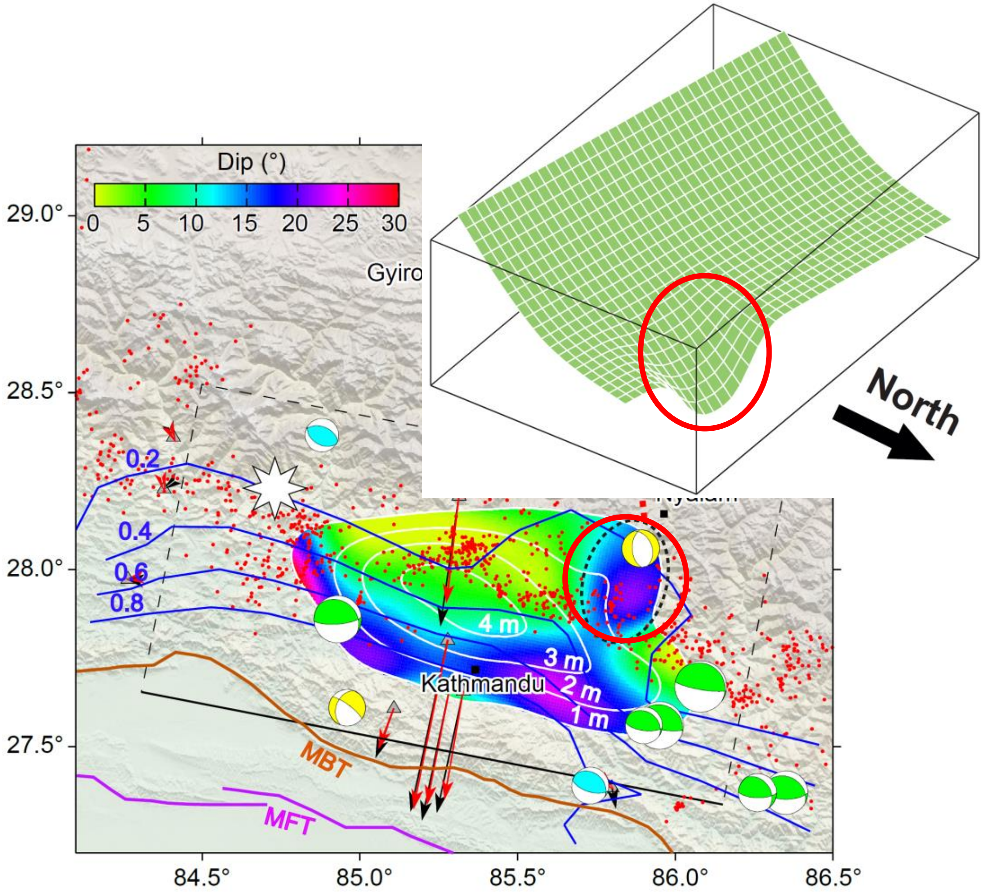
From the dip model, we can conclude that the slip gap previously identified in the northeast of the slip area should have been caused by a geometric barrier. The barrier may have blocked the ruptures, causing significant high-frequency seismic signals.



(Wei et al., 2017)



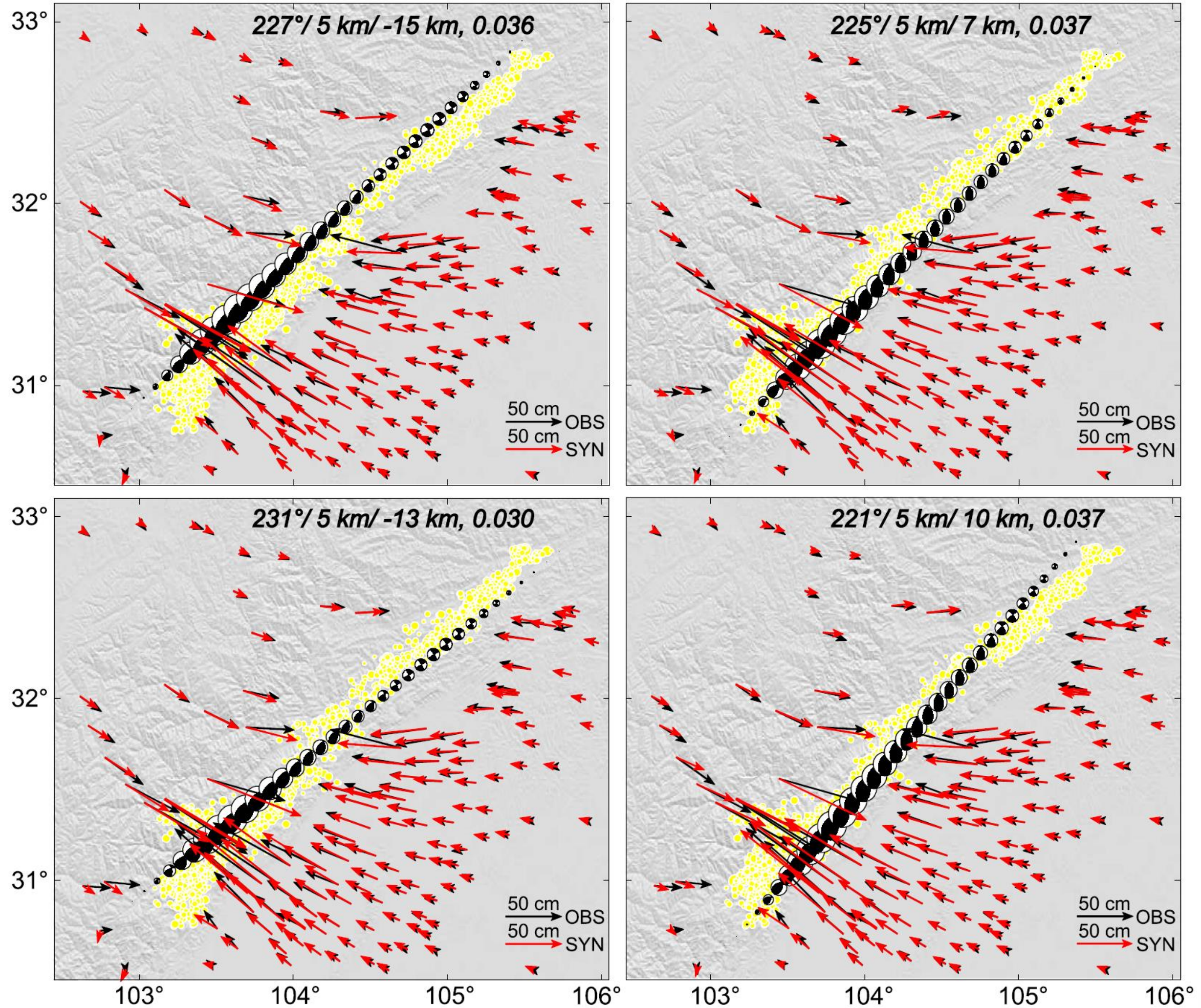
(Yin et al., 2017)

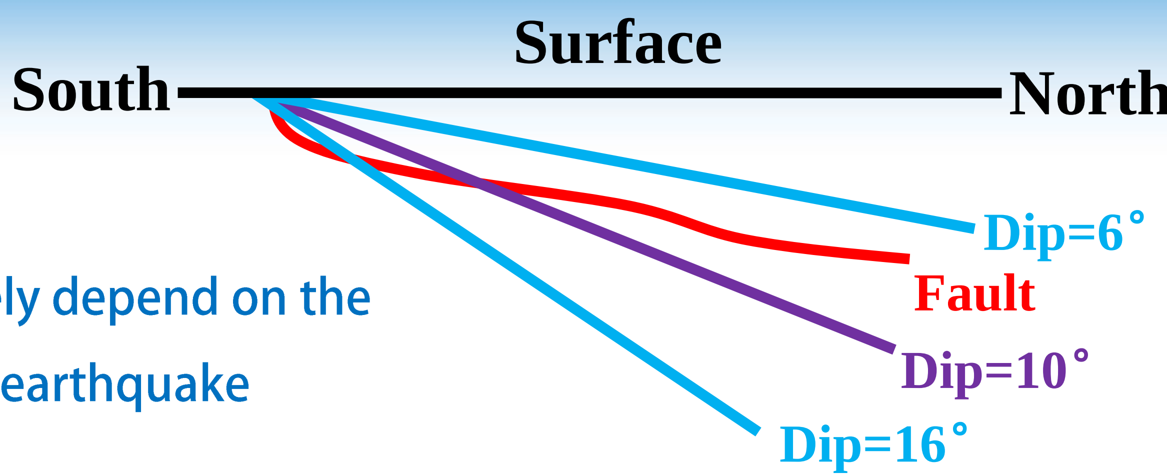


(Zhang et al., 2017, GRL)

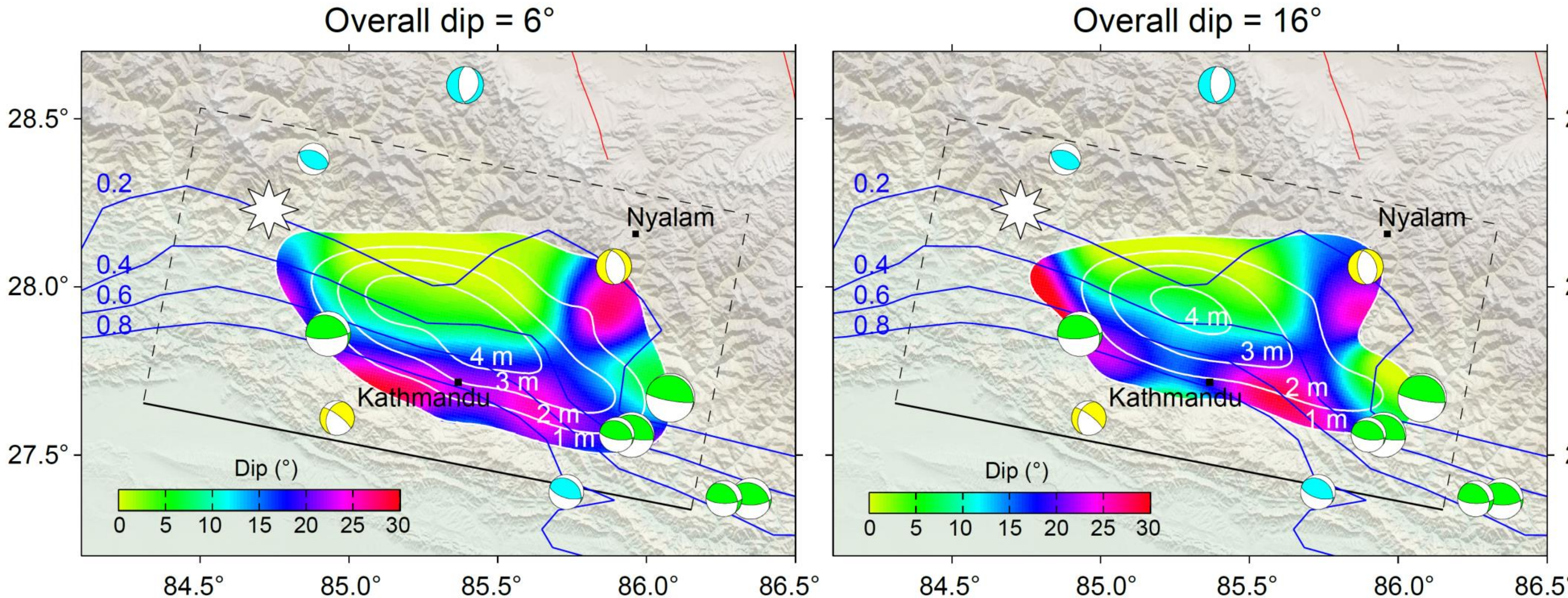
Content

Whether the inversion closely depend on the fault position: Wenchuan earthquake

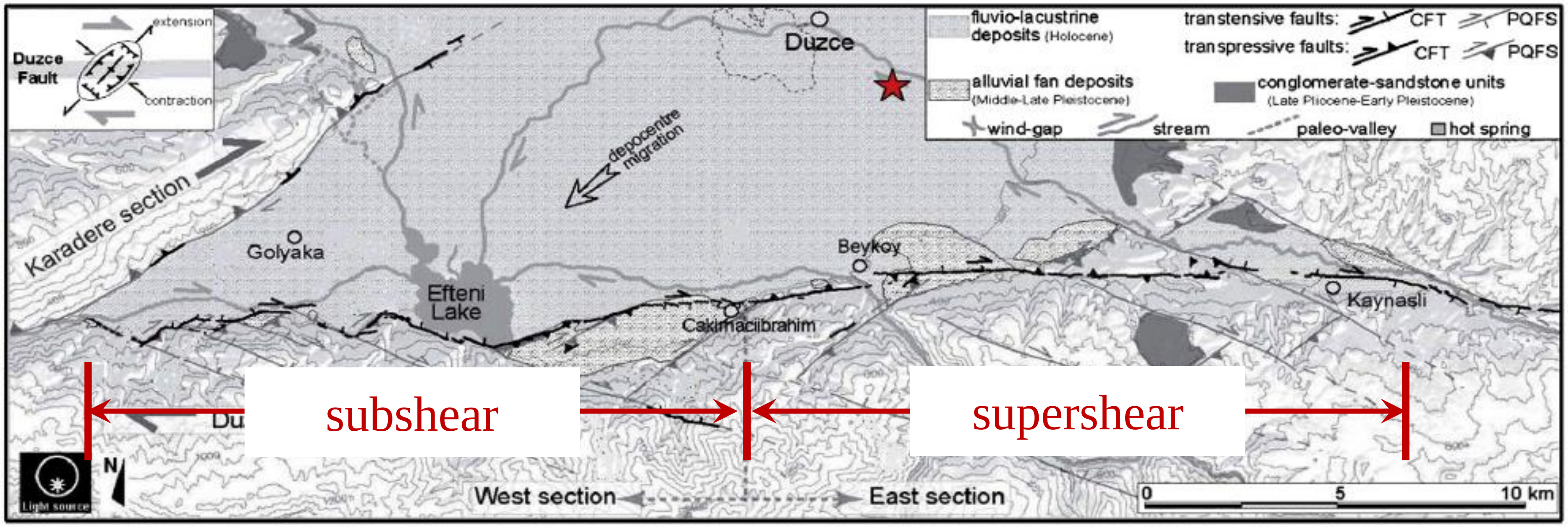




Whether the inversion closely depend on the fault position: Gorkha earthquake



Future works: Potential relation between variations of fault geometry and rupture velocity



1999 M_W7.4 Izmit earthquake (Bouchon et al., 2010)

Thanks!