

Supplementary information for “Three-dimensional Kinematics of the India-Eurasia Collision”

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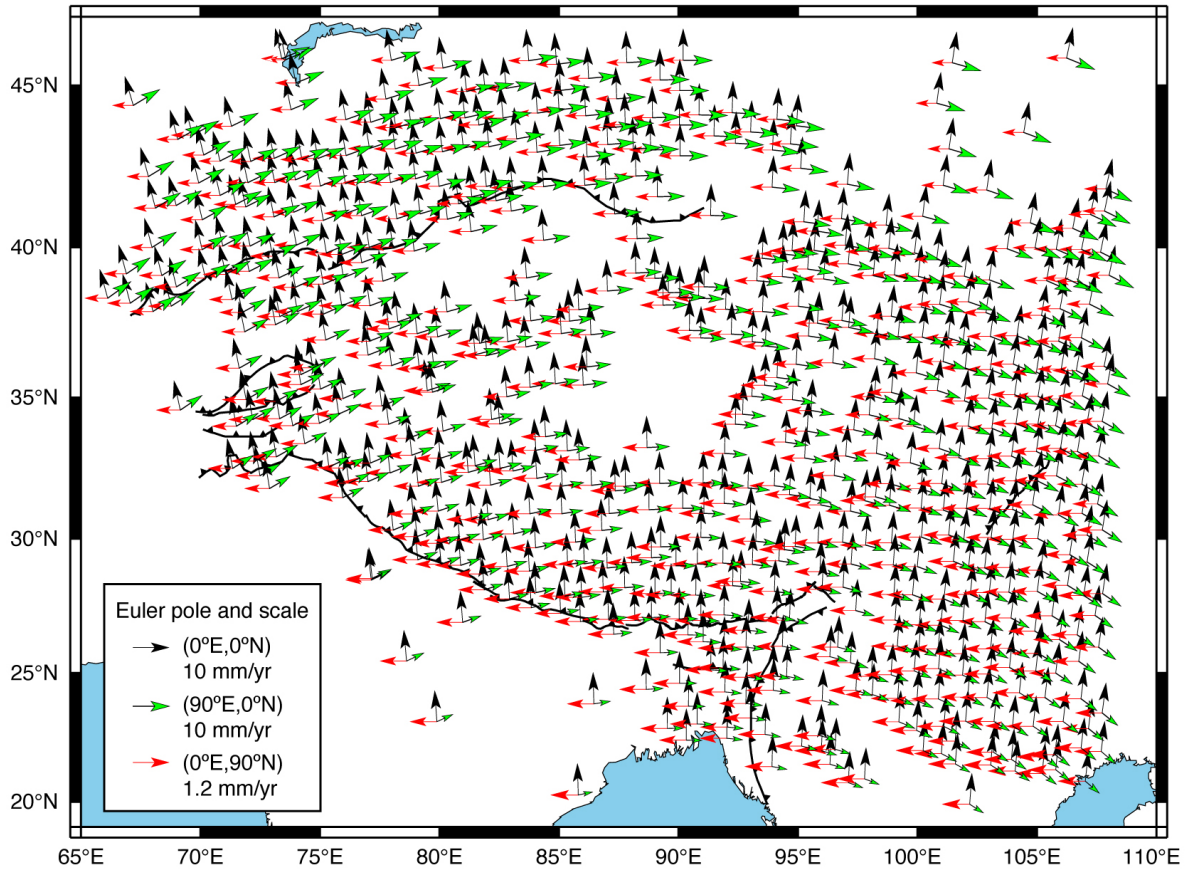


Figure S1: Velocity field caused by rigid-body rotation about three independent Euler poles. A linear combination of these velocity field captures the rotation about an arbitrary Euler pole.

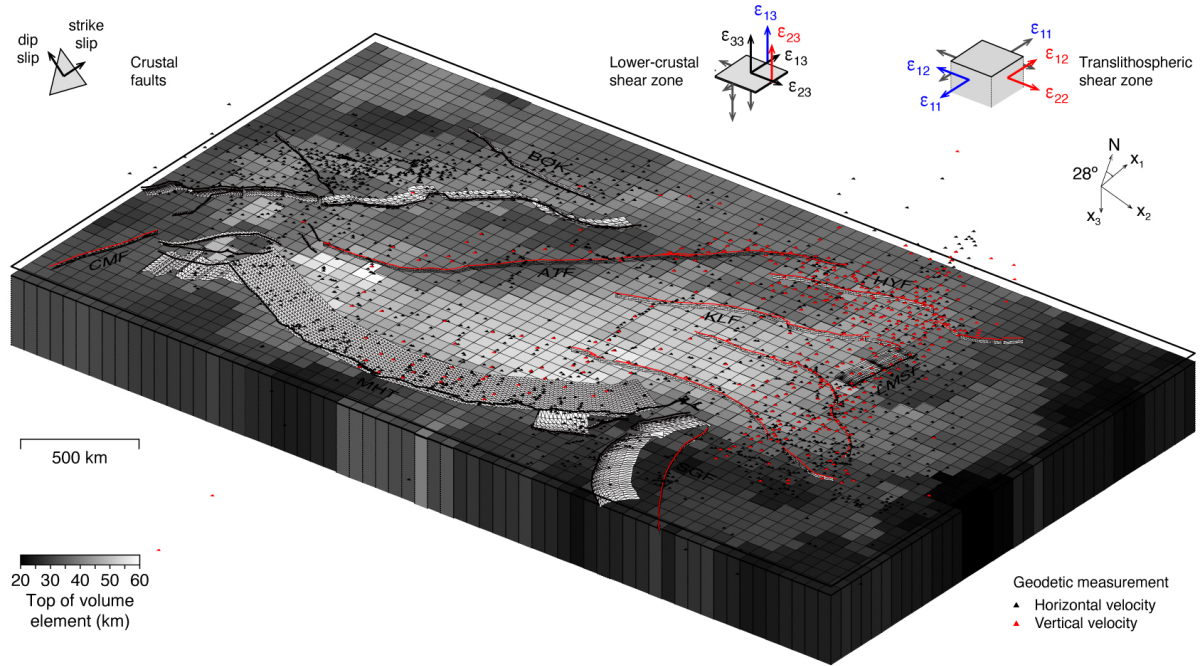


Figure S2: Structural model of the lithosphere surrounding the Tibetan plateau using a mesh of volume and surface elements. The finite volume elements are confined to the lower crust, defined by CRUST1.0 (1) and capture possible thickening, thinning, and vertical shear within the lower crust. The semi-infinite elements extrude down from the top of the lower crust and deform in pure shear. Long alignments of pure shear produce trans-lithospheric shear zones deforming in simple shear. We use a mesh of triangle surface elements to represent fault slip on the ATF, IBFB, BOK, CMF, HYF, JLF, KKF, KLF, KRF, LMSF, MPT, MHT, RRF, SGF, STSF, TFF, Shillong, and several thrust faults in Pamir. The triangles represent GNSS stations measuring vertical (red triangles) and horizontal (black triangles) velocity components. Each surface element has 2 degrees of freedom for the strike-slip and dip-slip component of velocity. The volume elements have 5 degrees of freedom, as the trace of the plastic strain-rate tensor is zero to prevent net volume change.

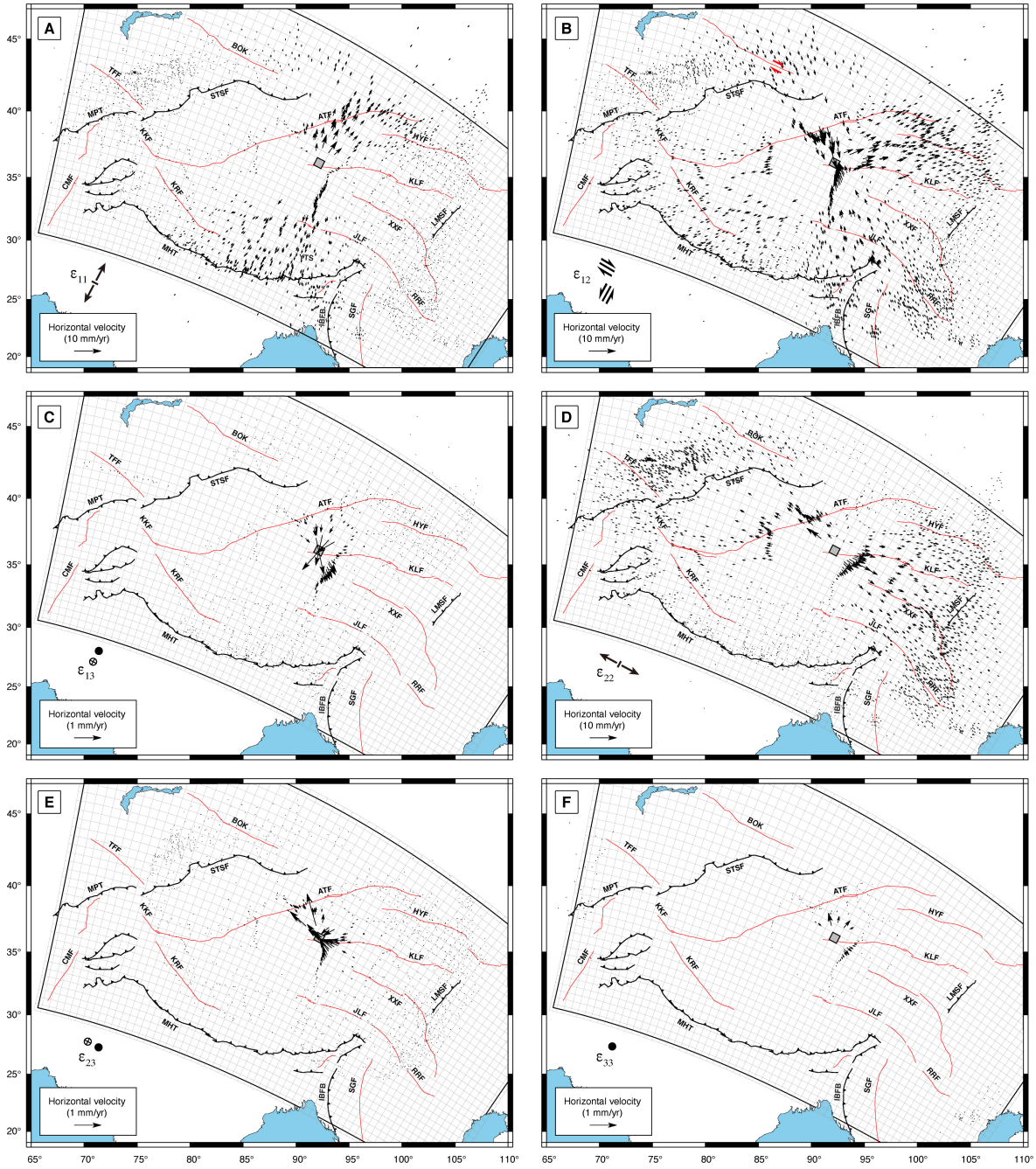


Figure S3: Green's function for the horizontal velocity evaluated at the GNSS observation points. A) Horizontal velocity field (black arrows) occasioned by uniaxial latitudinal plastic strain-rate of 1 microstrain per year uniformly distributed within a semi-infinite element located near the center of the domain (gray square with black contour). B) Velocity field for uniformly distributed horizontal pure shear within a near-central semi-infinite volume element. C, E) Horizontal velocity field caused by vertical plastic shear within a finite volume element confined in the lower crust. D) Same as A for longitudinal uniaxial plastic strain-rate confined within a semi-infinite volume element. F) Same as $\tilde{\epsilon}$ and E for uniaxial vertical plastic strain-rate confined within a lower-crust volume element. For each panel, the orientation of the non-zero plastic strain-rate is indicated with a diagram.

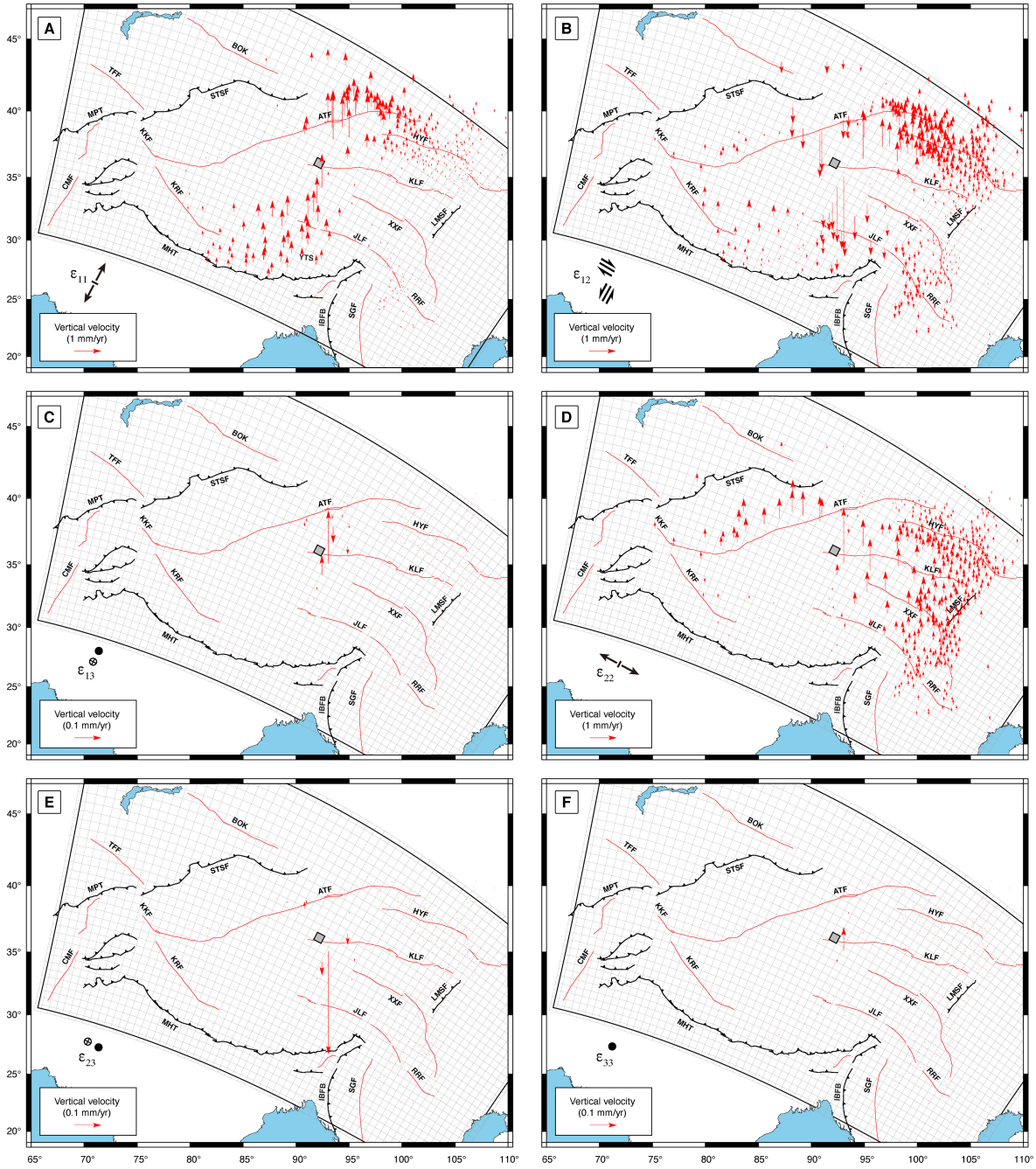


Figure S4: Green's function for the vertical velocity evaluated at the GNSS observation points. A) Vertical velocity field (red arrows) occasioned by uniaxial latitudinal plastic strain-rate of 1 microstrain per year uniformly distributed within a semi-infinite element located near the center of the domain (gray square with black contour). B) Vertical velocity field for uniformly distributed horizontal pure shear within a near-central semi-infinite volume element. C, E) Vertical velocity field caused by vertical plastic shear within a finite volume element confined in the lower crust. D) Same as A for longitudinal uniaxial plastic strain-rate confined within a semi-infinite volume element. F) Same as C and E for uniaxial vertical plastic strain-rate confined within a lower-crust volume element. For each panel, the orientation of the non-zero plastic strain-rate is indicated with a diagram.

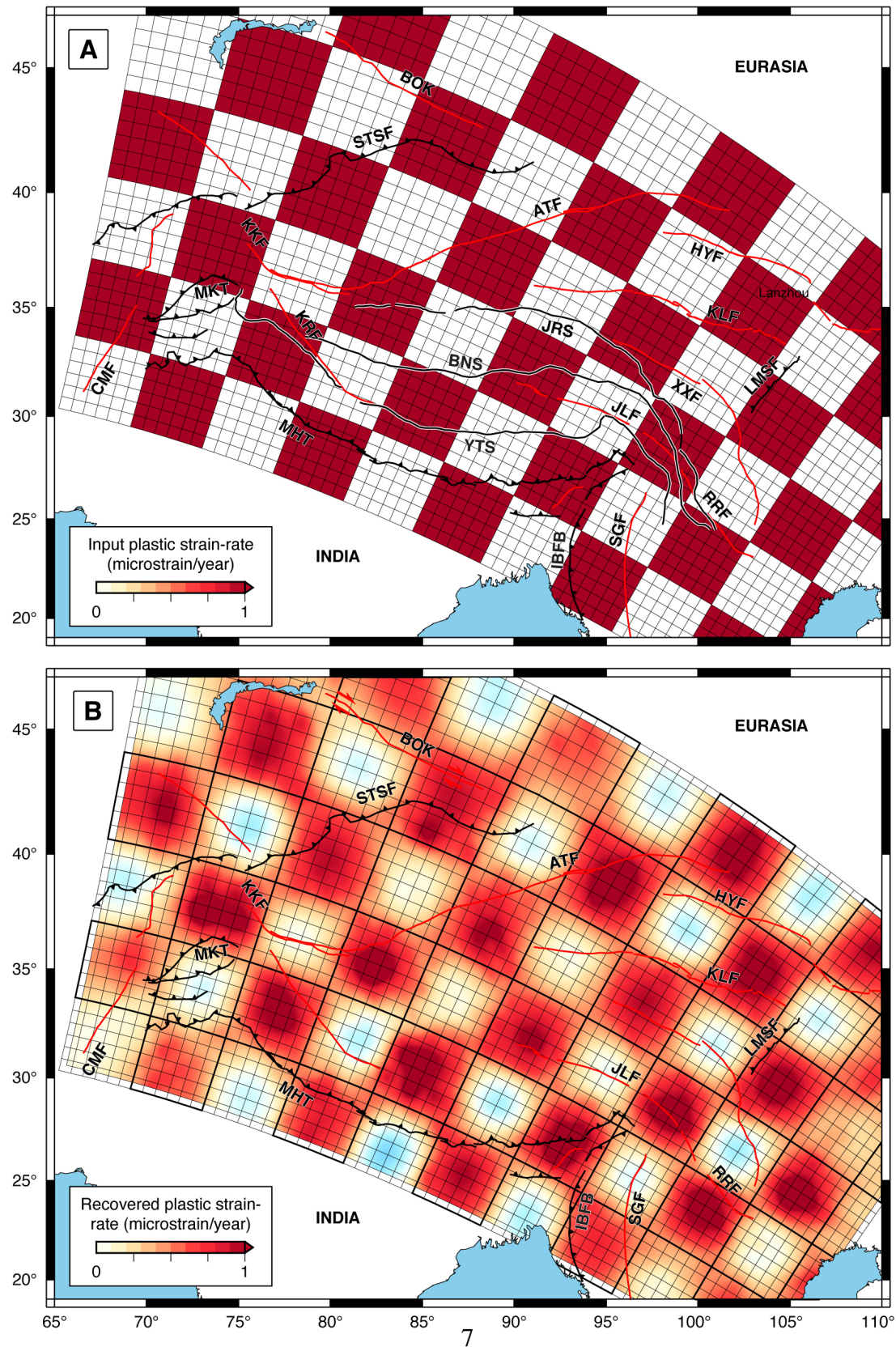


Figure S5: Checkerboard test. A) Input model for the checkerboard test. The amplitude corresponds to uniaxial, longitudinal plastic strain-rate. B) Recovered model obtained by inverting synthetic data with noise from the target model using regularized least squares.

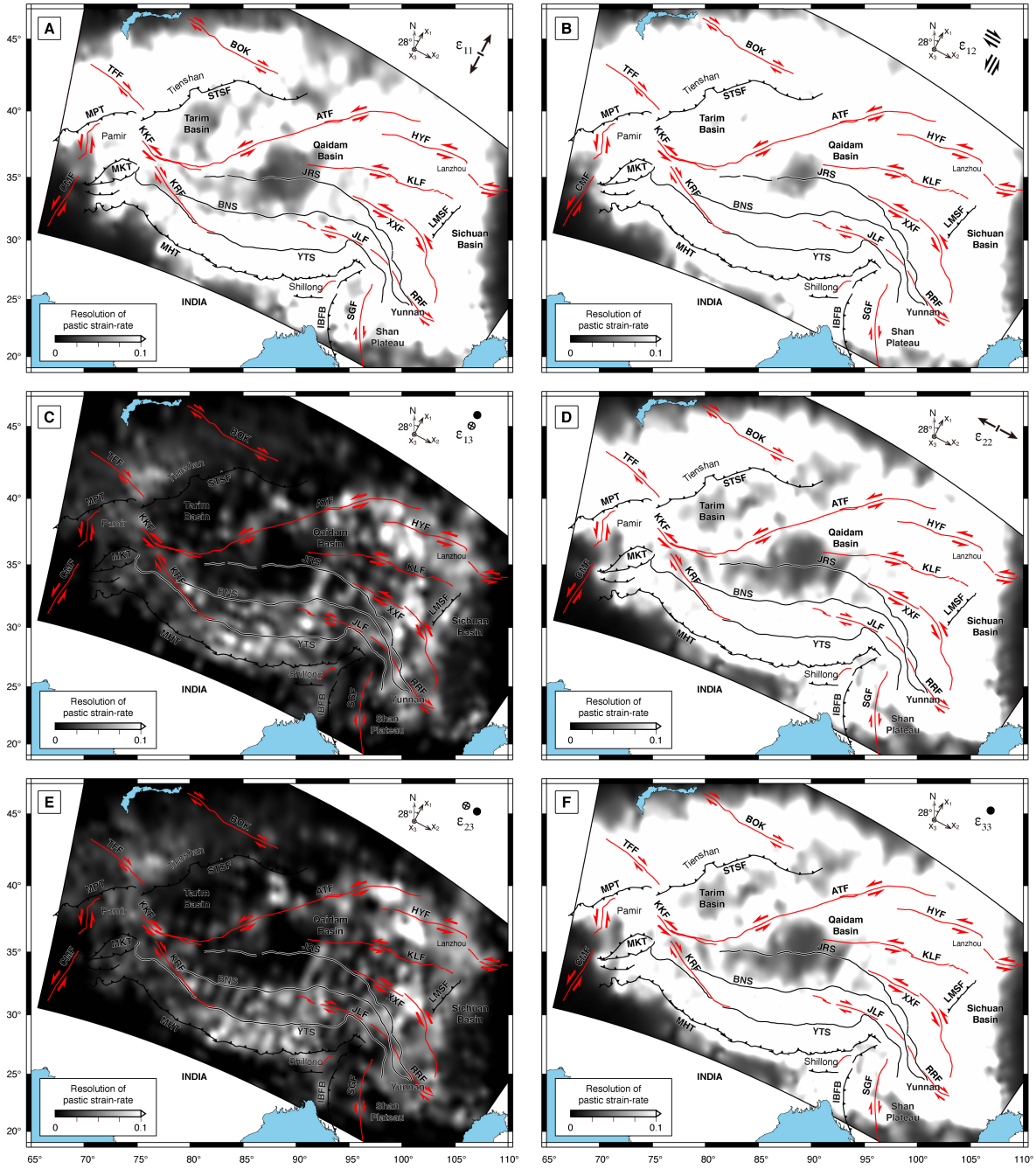


Figure S6: Diagonal of the resolution matrix for individual strain-rate components. A) Resolution for the latitudinal plastic strain-rate. B) Same for the horizontal pure shear component of plastic strain-rate. C, E) Resolution of vertical shear for volume elements confined to the lower crust. D) Resolution for longitudinal plastic strain-rate. F) Resolution of vertical plastic strain-rate within volume elements confined to the lower crust. The resolution is poor for every component south of the MHT and of the west Himalayan syntaxis.

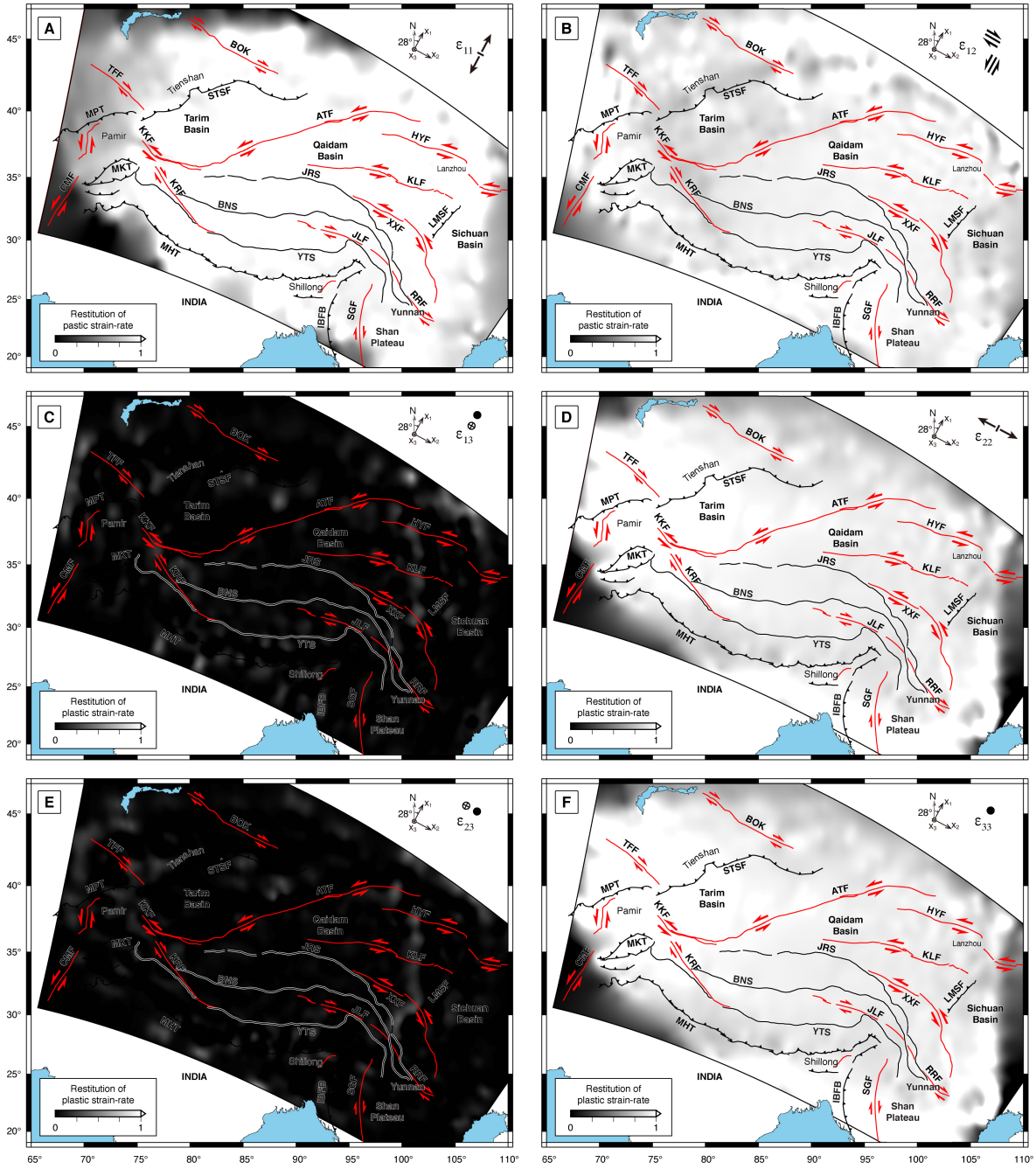


Figure S7: Restitution index for the six components of the plastic strain-rate tensor, built from the summed row of the resolution matrix, reflecting recovery of a single strain component from the entire observation network. A) Restitution for the latitudinal plastic strain-rate. B) Same for the horizontal pure shear component of plastic strain-rate. C, E) Restitution of vertical shear for volume elements confined to the lower crust. D) Restitution for longitudinal plastic strain-rate. F) Restitution of vertical plastic strain-rate within volume elements confined to the lower crust. The restitution is poor for every component south of the MHT and of the west Himalayan syntaxis.

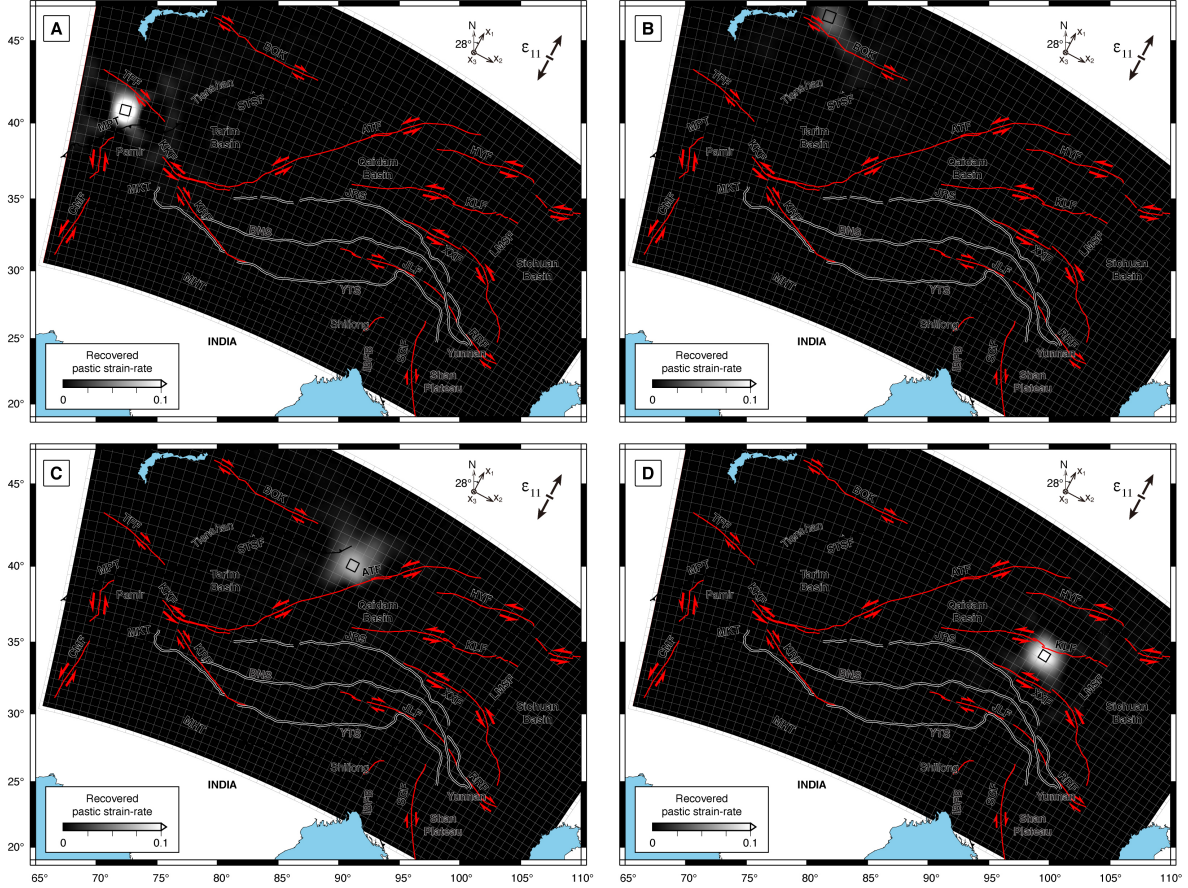


Figure S8: Recovery of spike models with unit latitudinal extension in various regions, corresponding to a column of the resolution matrix. A) Column 200 of the resolution matrix, showing the plastic strain-rate at that location (bold rectangle) near the MPT smeared throughout neighboring regions. B) Column 500 for the strain-rate near the BOK at the poorly resolved northern boundary of the model. C) Column 1000 for the strain-rate north of the ATF. D) Column 1500 for the strain-rate near the KLF. The spatial filtering of the recovered models is consistent with a variable spatial resolution of $1 - 3^\circ$, commensurate with the size of 3 to 6 adjacent volume elements.

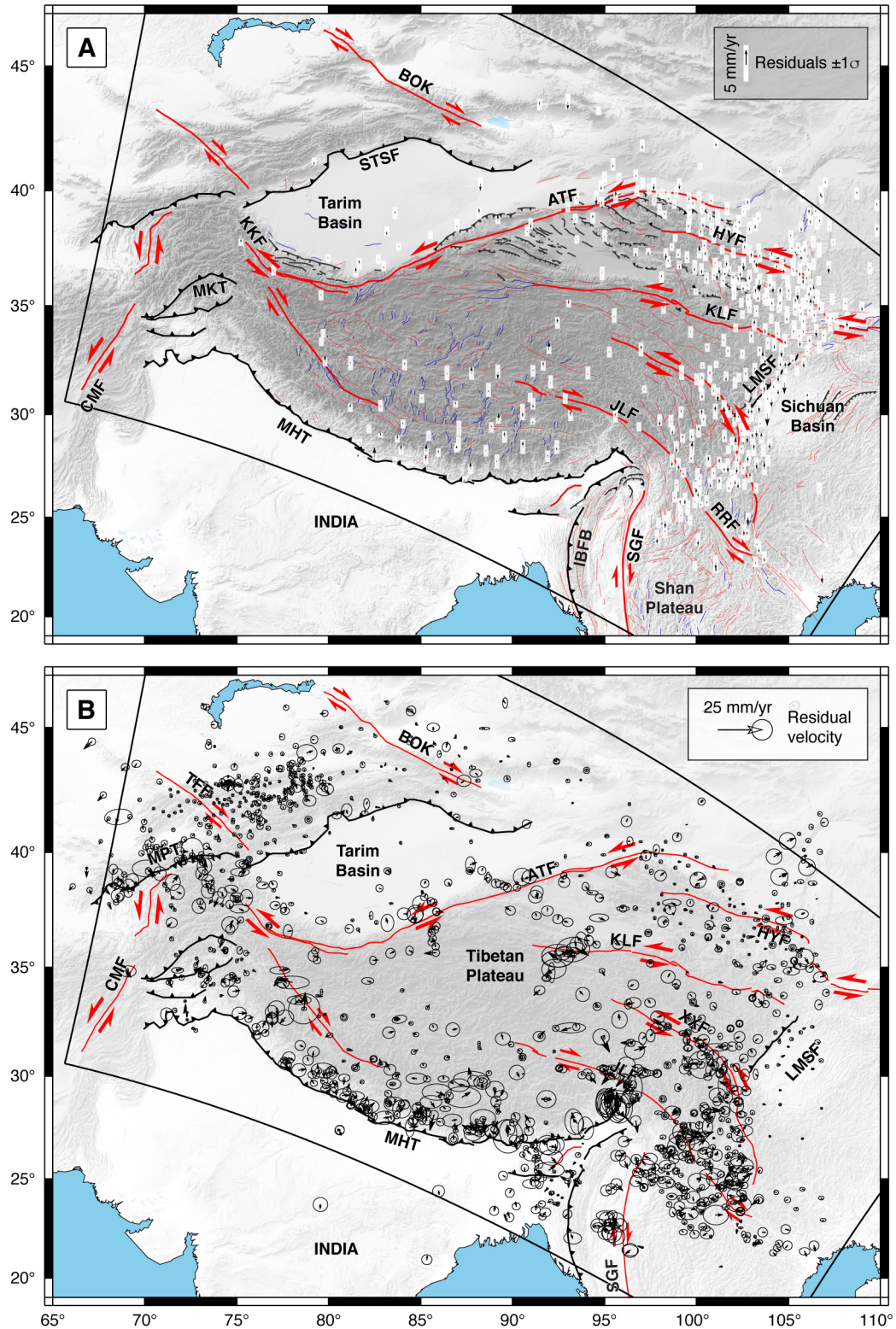


Figure S9: Residual velocity. A) Modeling residuals (arrows) for vertical GNSS data, with a mean of 1.4 mm/yr relative to the observation uncertainties (white bar). B) Residuals (arrows) for horizontal data, with a mean of 0.93 mm/yr relative to uncertainties (ellipses). The variance reduction of the kinematic model is 88.2%, with a reduced chi-square of 1.48. The shallow fault motion represents only 1% of the variance reduction.

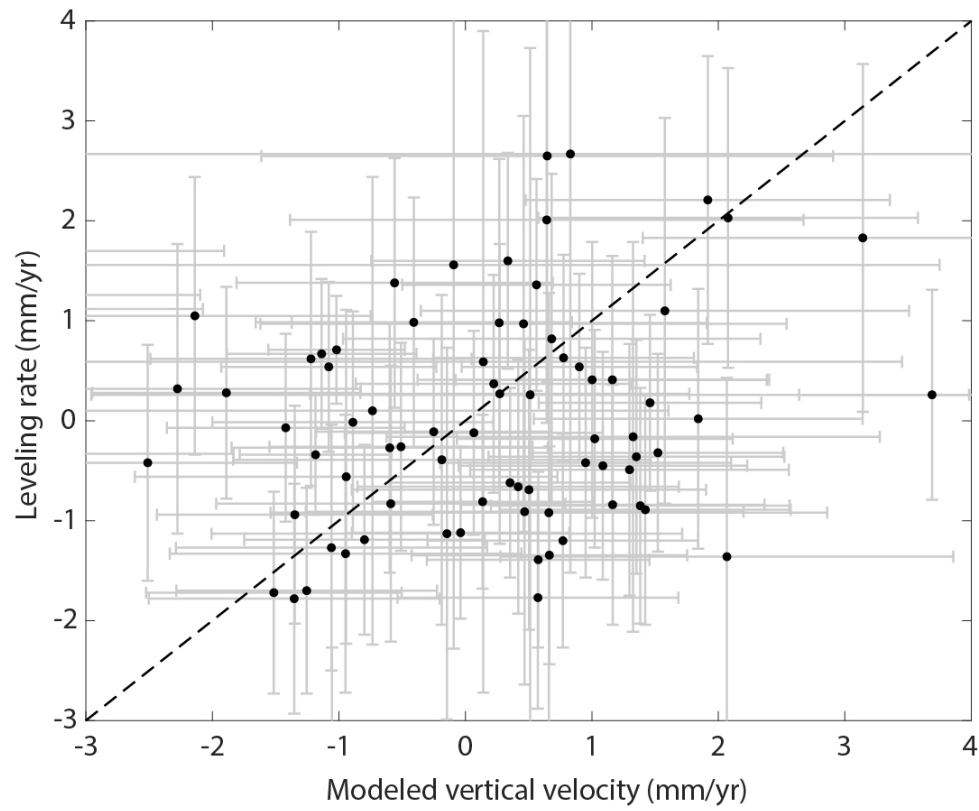


Figure S10: Comparison about the modeled vertical velocities in this study with the leveling data of (1). The error bars represent measurement uncertainties of the leveling data.

Supplementary References

1. Yanqiang Wu, Zhijiang Zheng, Jianliang Nie, Liu Chang, Guangli Su, Haiquan Yin, Hongbao Liang, Yajin Pang, Changyun Chen, Zaisen Jiang, and Wanjun Bo. High-Precision Vertical Movement and Three-Dimensional Deformation Pattern of the Tibetan Plateau. *Journal of Geophysical Research: Solid Earth*, 127(4):e2021JB023202, 2022.