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► **To cite this version:**

E. Calais, L. Dong, M. Wang, Z. Shen, Mathilde Vergnolle. Continental deformation in Asia from a combined GPS solution. *Geophysical Research Letters*, 2006, 33, pp.L24319. 10.1029/2006GL028433 . hal-00195570

**HAL Id: hal-00195570**

**<https://hal.science/hal-00195570>**

Submitted on 11 Dec 2007

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# Continental Deformation in Asia from a Combined GPS Solution

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After decades of research on continental tectonics, there is still no consensus on the mode of deformation of continents or on the forces that drive their deformation. In Asia the debate opposes edge-driven block models, requiring a strong lithosphere with strain localized on faults, to buoyancy-driven continuous models, requiring a viscous lithosphere with pervasive strain. Discriminating between these models requires continent-wide estimates of lithospheric strain rates. Previous efforts have relied on the resampling of heterogeneous geodetic and Quaternary faulting data sets using interpolation techniques. We present a new velocity field based on the rigorous combination of geodetic solutions with relatively homogeneous station spacing, avoiding technique-dependent biases inherent to interpolation methods. We find (1) unresolvable strain rates ( $< 3 \times 10^9$ /yr) over a large part of Asia, with current motions well-described by block or microplate rotations, and (2) internal strain, possibly continuous, limited to high-elevation areas.

## 1. Introduction

Geodetic measurements at sites located far enough away from active plate boundaries show that horizontal surface motions on most of our planet can be described by simple rotations of a limited number of rigid plates, as predicted by plate tectonics (*e.g.*, Argus and Heflin, 1995). In deforming continents such as Asia or the Western U.S., however, the ability of plate tectonic concepts to describe horizontal motions is still questioned (Thatcher, 2003). Indeed, observations and models of actively deforming continents such as Asia<sup>1</sup> have led to two opposing interpretations. For some, continental lithosphere deforms as a mosaic of rigid lithospheric blocks bounded by fast-slipping faults affecting the entire thickness of the lithosphere. In that view, deformation is solely driven by boundary forces due to the India-Eurasia collision (*e.g.*, Tapponnier et al., 1982; Peltzer and Tapponnier, 1988; Peltzer and Saucier, 1996). For others, deformation is

44 pervasive and continents can be treated as a continu-  
45 ously deforming viscous medium where faults play a mi-  
46 nor role. In that view, deformation is driven for a large  
47 part by buoyancy forces resulting from crustal thickening  
48 in response to the India-Eurasia collision (*e.g.*, England  
49 and Houseman, 1986; Houseman and England, 1993).

50 In some instances, space geodetic studies have pro-  
51 vided insight into this debate. For instance, GPS mea-  
52 surements show that the central part of the Altyn Tagh  
53 fault accumulates strain at a rate of 9 mm/yr (Bendick et  
54 al., 2000; Shen et al., 2001; Wallace et al., 2004), incon-  
55 sistent with edge-driven block models that require slip  
56 rates at least a factor of two larger (Peltzer and Saucier,  
57 1996). Geodetic measurements of the eastward velocity  
58 of south China at 8 to 10 mm/yr (*e.g.*, Wang et al., 2001)  
59 match block models and continuous deformation models  
60 equally well (Peltzer and Saucier, 1996; Molnar and Gip-  
61 son, 1996) but proved wrong early models of extrusion  
62 that required at least 10-15 mm/yr of eastward motion  
63 of south China (Avouac and Tapponnier, 1993). At a  
64 continent-wide scale, Flesch et al. (2001), used an inter-  
65 polated velocity field derived from heterogeneous GPS  
66 data and Quaternary fault slip rates to show that large  
67 parts of Asia undergo little internal deformation and that  
68 gravitational potential energy (GPE) contributes up to  
69 50% to the force balance. England and Molnar (2005),  
70 using similar data but a different spatial resampling tech-  
71 nique, argue that continuous deformation dominates.

72 Here, we combine geodetic solutions in Asia to produce  
73 a new velocity field with continent-wide coverage and rel-  
74 atively homogeneous station spacing, removing the need  
75 for spatial resampling, necessarily model-dependent. The  
76 kinematic analysis of this continent-wide data set shows  
77 unresolvable strain rates over a large part of Asia, while  
78 significant strain rates, possibly associated with continu-  
79 ous deformation, are limited to the high-elevation areas  
80 of the Himalaya, Tibet, Pamir-Tien Shan, and Western  
81 Mongolia.

## 2. GPS data

82 In order to obtain a geodetically consistent velocity  
83 field covering Asia, we combined three GPS solutions.  
84 The first one covers Mongolia, the Baikal rift zone, and  
85 the Russian Altay. It contains 110 survey sites, of which  
86 64 have been observed at least 3 times from 1994 to  
87 2004, and 3 continuous stations. The second one includes  
88 83 stations in China measured between 1998 and 2005,  
89 of which 27 became continuous in 1999. The 56 other  
90 are measured annually, with 10 observation-days per site  
91 each year. The third one includes 41 sites in Southeast  
92 Asia with data spanning from 1991 to 2002 (Socquet et  
93 al., 2006). Although Socquet et al.'s (2006) original solu-  
94 tion contains 191 sites, those located within active plate  
95 boundary zones in eastern Indonesia (Sulawesi, Timor,  
96 Irian Jaya) and the Philipines were not considered here.

97 For the first two data sets, we processed the pseudor-  
98 ange and phase GPS data single-day solutions, together  
99 with 16 reference stations of the International GPS Ser-  
100 vice (IGS) to serve as ties with the International Terres-  
101 trial Reference Frame (ITRF). Details on the data pro-  
102 cessing procedure can be found in Wang et al. (2003)  
103 and Calais et al. (2003) and are not repeated here. The  
104 resulting least squares adjustment vector and its cor-  
105 responding variance-covariance matrix for station posi-  
106 tions and orbital elements estimated for each indepen-  
107 dent daily solution were then combined with global So-

108 lution Independent Exchange format (SINEX) files from  
 109 the IGS daily processing routinely done at Scripps In-  
 110 stitution of Oceanography (<http://sopac.ucsd.edu>) into  
 111 a single, unconstrained, global solution using the com-  
 112 bination method described in Dong et al. (1998). The  
 113 velocity error model includes a  $2 \text{ mm}/\sqrt{\text{yr}}$  random walk  
 114 component to account for colored noise in GPS uncertain-  
 115 ties. We imposed the reference frame by minimizing the  
 116 position and velocity deviations of 25 core IGS stations  
 117 with respect to the ITRF2000 (Altamimi et al., 2002)  
 118 while estimating an orientation and translation (and their  
 119 rate-of-change) transformation (12 parameters). These  
 120 25 reference stations, globally distributed, were chosen  
 121 for having velocity uncertainties less than  $2 \text{ mm}/\text{yr}$  on the  
 122 horizontal and  $5 \text{ mm}/\text{yr}$  on the vertical components in the  
 123 ITRF2000 definition. The post-fit  $\sqrt{\text{weighted root-mean-}}$   
 124  $\text{square (WRMS)}$  of the reference frame stabilization is  
 125  $2.0 \text{ mm}$  in position and  $0.6 \text{ mm}/\text{yr}$  in velocity. We then  
 126 combined the resulting solution with that of Socquet al.  
 127 (2006) for Southeast Asia, by estimating a 7-parameter  
 128 transformation (translation, rotation, and scale) based  
 129 on 12 IGS stations common to the two solutions. The  
 130 WRMS of the velocity differences at the common sites is  
 131  $1.2 \text{ mm}/\text{yr}$ .

132 We mapped the resulting velocities (in ITRF2000)  
 133 into a Eurasia-fixed frame by minimizing velocities at  
 134 15 sites distributed across the Eurasian plate (YAKT,  
 135 IRKT, KSTU, ARTU, ZWEN, GLSV, GRAZ, WSRT,  
 136 POTS, WTZR, KOSG, CAGL, NRIL, NVSK, VILL),  
 137 while propagating the variance of the ITRF2000-Eurasia  
 138 angular velocity to the individual site velocities. These 15  
 139 reference sites are chosen to cover the entire stable part of  
 140 the Eurasian plate and are located away from areas po-  
 141 tentially affected by tectonic deformation or significant  
 142 glacial isostatic adjustment effects (Calais et al., 2003).  
 143 The resulting GPS velocity field describes horizontal sur-  
 144 face motions at 188 sites in Asia with a precision ranging  
 145 from  $0.5$  to  $3.5 \text{ mm}/\text{yr}$  (Figure 1<sup>2</sup>). In the following, we  
 146 discard from the interpretation sites with velocity uncer-  
 147 tainties larger than  $1.5 \text{ mm}/\text{yr}$ . These sites, mostly lo-  
 148 cated in the Mongolia-Altay-Baikal area, are consistently  
 149 campaign sites with less than 3 observations epochs.

### 3. Velocity field

150 The combined GPS velocity field (Figure 1) and veloc-  
 151 ity profiles (Figure 2) illustrate the known convergence  
 152 between India and the Tarim basin, the eastward mo-  
 153 tion of Tibet and south China and the clockwise rota-  
 154 tion of eastern Tibet around the eastern Himalayan syn-  
 155 taxis. Convergence between India and Eurasia occur at  
 156  $38 \text{ mm}/\text{yr}$  (from velocities at sites Bangalore and Hy-  
 157 derabad in southern India), consistent with GPS-derived  
 158 plate motion parameters for India (Paul et al., 2001;  
 159 Sella et al., 2002). The western velocity profile (Fig-  
 160 ure 2A) shows consistent NNE-directed azimuths with  
 161 velocity magnitudes steadily decreasing northward, in-  
 162 dicative of NNE-SSW shortening. About  $20 \text{ mm}/\text{yr}$  of  
 163 the total shortening is accommodated in the Himalayas,  
 164 as previously reported by Bilham et al. (1997), while  
 165 the remaining  $17 \text{ mm}/\text{yr}$  are distributed from Tibet to  
 166 the Siberian platform, mostly taken up in the Tien Shan  
 167 ( $17 \text{ mm}/\text{yr}$  in the west, decreasing eastward to less than  
 168  $10 \text{ mm}/\text{yr}$ ).

169 On the central profile (Figure 2B), horizontal veloci-  
 170 ties show a more complex pattern, with about  $20 \text{ mm}/\text{yr}$   
 171 of shortening accommodated in the Hymalayas and Ti-

172 bet, but no shortening north of the Qilin Shan. This  
 173 NNE-SSW shortening is accompanied, in Tibet, by up to  
 174 17 mm/yr of ESE-ward motion. North of the Qilin Shan,  
 175 across western Mongolia and all the way to the Baikal rift  
 176 zone velocities are directed ESE-ward at 3 to 5 mm/yr.

177 On the eastern profile (Figure 2C), horizontal motions  
 178 are mostly directed to the east or southeast, with a steady  
 179 increase in magnitude from 0 to about 9 mm/yr from  
 180 north to south across north and south China. This con-  
 181 sistent pattern of east- to southeastward motions from  
 182 eastern Mongolia, north China, and south China, is a  
 183 striking feature of this velocity field and had not yet been  
 184 documented at that scale.

185 To separate block rotations from distributed strain, we  
 186 attempt to describe the horizontal velocity field in terms  
 187 of rotations of non-deforming blocks or microplates. To  
 188 do so, we use the trace of major active faults in Asia  
 189 (Figure 1) to divide the velocity field into 6 subsets of  
 190 sites, representing the following blocks: North China  
 191 (or “Amurian plate” of Zonenshain and Zavostin, 1981),  
 192 South China, Sunda (*e.g.*, Chamot-Rooke and Le Pichon,  
 193 1999; Bock et al., 2003), Tarim basin, Qaidam basin, and  
 194 Central Tibet. In Tibet, we limit our analysis to two  
 195 blocks, Qaidam and Central Tibet, bounded by the Al-  
 196 tyn Tagh, Kunlun, and Jiali faults (Chen et al., 2004)  
 197 because the low density of sites in our solution does not  
 198 provide the resolution necessary to investigate kinematics  
 199 at smaller spatial scales. Also, we omit GPS sites located  
 200 within actively deforming structures in the Himalayas,  
 201 the Tien Shan, western Mongolia (Altay and Gobi Altay),  
 202 Eastern Tibet (Karakorum and Pamir), Western Tibet  
 203 (Longmen Shan), and in the Ordos, possibly affected by  
 204 non-secular deformation processes on these active tec-  
 205 tonic structures (*e.g.*, interseismic strain accumulation or  
 206 postseismic deformation). For the same reason, we omit  
 207 sites located within 500 km of the Andaman-Sumatra-  
 208 Java subduction, where elastic loading effects are signif-  
 209 icant (Chamot-Rooke and Le Pichon, 1999). We then  
 210 solve for block angular rotations with respect to Eurasia  
 211 by inverting the model that relates horizontal site veloci-  
 212 ties to plate angular velocity. Table 1 shows the resulting  
 213 angular rotations and corresponding statistics, while Fig-  
 214 ure 1 (bottom) shows residual velocities after subtracting  
 215 the estimated rotations.

216 The fit to a block rotation is good for most site sub-  
 217 sets, with reduced chi-squared close to unity, except for  
 218 the Qaidam and Central Tibet subsets. The fit in Ti-  
 219 bet is not improved by considering Qaidam and Central  
 220 Tibet as a single block, consistent with previous reports  
 221 of block motions and internal deformation from denser  
 222 GPS measurements in Tibet (Chen et al., 2004). The fit  
 223 to a rigid rotation is particularly good for South China,  
 224 with a weighted velocity residual RMS of 0.4 mm/yr. For  
 225 North China, the resulting angular velocity is consistent  
 226 with a recent estimate by Apel et al. (2006), based on a  
 227 similar dataset. It is significantly different from previous  
 228 estimates from Kreemer et al. (2003), Sella et al. (2003),  
 229 and Prawirodirdjo and Bock (2004), but those were con-  
 230 strained by 3 sites only. The rotation poles for North and  
 231 South China are located in eastern Siberia and associated  
 232 with a counter-clockwise rotation with respect to Eurasia.  
 233 The linear gradient in eastward velocities from north to  
 234 south on Profile C (Figure 2) and the lack of offset at the  
 235 boundary between North and South China may suggest  
 236 that they constitute a single plate. We tested the sig-  
 237 nificance of the  $\chi^2$  decrease from a solution where North  
 238 and South China are treated as a single block to a solu-  
 239 tion where they are treated as two separate blocks using

240 an F-test (Stein and Gordon, 1984). The F-statistics,  
 241 defined as  $(\chi^2_{1plate} - \chi^2_{2plates}/3)/(\chi^2_{2plates}/72)$  is 2.3, im-  
 242 plying that the  $\chi^2$  decrease is significant at the 92% level.  
 243 The data is therefore better fit by a splitting North and  
 244 South China into two separate plates, although not at a  
 245 very high significance level.

246 Our rotation pole for Sunda is located southwest of  
 247 Australia, with a clockwise rotation with respect to Eura-  
 248 sia. These parameters differ significantly from those of  
 249 Chamot-Rooke and Le Pichon (1999), possibly because  
 250 of different definition of the Eurasia frame. They also  
 251 differ from those of Bock et al. (2003), but these authors  
 252 considered Sunda and South China as a single block. Us-  
 253 ing a F-test, we find that the  $\chi^2$  decrease when splitting  
 254 Sunda and South China compared to treating them as a  
 255 single block is significant at the 99.9% confidence level,  
 256 indicating that our data is fit significantly better by a  
 257 two-plate model.

#### 4. Strain distribution

258 The above analysis in terms of block rotations is lim-  
 259 ited by the a priori choice of block boundaries and site  
 260 subsets. An alternative approach consists of calculating  
 261 horizontal strain rates over the study area. To do so, we  
 262 discretize the study area using a Delaunay triangulation  
 263 and calculate, for each triangle, the strain rate tensor  
 264 with its covariance matrix, its level of significance, the  
 265 principal strain rates, and the second invariant of the  
 266 strain rate tensor – or effective strain rate – given by  
 267  $\dot{E} = \sqrt{(\dot{\epsilon}_{ij}\dot{\epsilon}_{ij})}/2$ , where  $\dot{\epsilon}_{ij}$  are the components of the  
 268 strain rate tensor and summing over repeated subscripts  
 269 applies.

270 The resulting maps (Figure 3) show that strain rates  
 271 are significant at the 95% confidence in the Himalayas,  
 272 Tibet, Pamir-Tien Shan, Altay and Gobi Altay, with  
 273 principal compressional axis consistent with shortening  
 274 perpendicular to these structures. Within Tibet, princi-  
 275 pal strains show a combination of NNE-SSW compres-  
 276 sion and WNW-ESE extension, consistent with previ-  
 277 ous results (Wang et al., 2001; Zhang et al., 2004) and  
 278 geologic observations of widespread extension on NS-  
 279 trending normal faults in Tibet (*e.g.*, **Armijo et al.,**  
 280 **1986**; Yin et al., 1999; Kapp and Gunn, 2004). Strain  
 281 rates are also significant in the Baikal rift zone and di-  
 282 rectly west and southwest of it in the Hovsgol, Darkhat,  
 283 and Busingol grabens, with extensional maximum princi-  
 284 pal strain perpendicular to the major normal faults.  
 285 Effective strain rates in all these regions are larger than  
 286  $3 \times 10^{-9}$ /yr and reach maximum values of  $2-3 \times 10^{-8}$ /yr  
 287 in the Himalayas, Burma, and along the eastern edge of  
 288 the Tibetan plateau.

289 Strain rates are not significant at the 95% confidence  
 290 level in the rest of Asia (including the Tarim basin, cen-  
 291 tral and eastern Mongolia, north and south China, and  
 292 Sunda). These regions also show effective strain rates less  
 293 than  $3 \times 10^{-9}$ /yr, which corresponds to the current pre-  
 294 cision level of the GPS data set (average triangle dimension  
 295  $\sim 300$  km, velocity precision  $\sim 1$  mm/yr). These regions  
 296 of unresolvable strain rate, at the current precision of  
 297 the GPS data, are consistent with the major blocks or  
 298 microplates defined above. Strain rates in a significant  
 299 part of Asia (about 60% of the area considered in this  
 300 study) are therefore comparable to stable plate interiors  
 301 (less than  $3 \times 10^{-9}$ /yr) and not resolvable at the current  
 302 precision level of GPS measurements in Asia.

303 Our findings contrast with England and Molnar's

304 (2005) conclusion that continuous deformation dominates  
 305 in Asia, while block-like motions are restricted to the  
 306 Tarim basin and small portions of north and south China.  
 307 The difference likely results from England and Molnar's  
 308 modeling approach, which resamples heterogeneous GPS  
 309 data sets and Quaternary fault slip rates over a coarse  
 310 triangular grid with linear shape functions. Our results  
 311 match Flesch et al.'s (2001) interpolated kinematic model  
 312 better, which however does not fit the observed east to  
 313 southeastward velocities in Mongolia and North China.  
 314 However, we do find, like Flesch et al. (2001) and Eng-  
 315 land and Molnar (2005), a radial pattern in principal  
 316 compressional strain rate directions around Tibet aligned  
 317 with gradients of gravitational potential energy, an argu-  
 318 ment used by England and Molnar (2005) to support the  
 319 idea that buoyancy forces play a significant role in driving  
 320 present-day deformation in Asia.

## 5. Conclusion

321 The debate on continental deformation in Asia opposes  
 322 edge-driven block models, requiring a strong lithosphere  
 323 with strain localized on faults, to buoyancy-driven con-  
 324 tinuous models, requiring a viscous lithosphere with per-  
 325 vasive strain. As shown here, block- or plate-like mo-  
 326 tions appear to provide an accurate kinematic descrip-  
 327 tion of surface deformation for most of Asia. Similar  
 328 conclusions have been drawn at a smaller scale for Ti-  
 329 bet (Thatcher, 2005) and the Western U.S. (*e.g.*, Meade  
 330 and Hager, 2005). Although these results apparently fa-  
 331 vor block models, they do not rebut continuous deforma-  
 332 tion models, provided that significant lateral variations in  
 333 lithospheric strength exist. This is supported by results  
 334 from Flesch et al. (2001), who show that vertically aver-  
 335 aged effective viscosity in Asia varies laterally by up to  
 336 3 orders of magnitude. The GPS velocity field presented  
 337 here does not resolve, by itself, the debate on continental  
 338 deformation but provides new quantitative information  
 339 to validate physical theories on driving forces.

340 **Acknowledgments.** We thank our collaborators in Rus-  
 341 sia (Institute of the Earth Crust, Irkutsk and Institute of  
 342 Geology, Geophysics, and Mineralogy, Novosibirsk, Siberian  
 343 Branch of the Russian Academy of Sciences), Kazakhstan (In-  
 344 stitute for High Temperatures), Mongolia (Research Center for  
 345 Astronomy and Geophysics), for their invaluable contribution  
 346 to the collection and processing of the GPS data. We thank A.  
 347 Socquet and C. Vigny for making their GPS results available  
 348 in advance of publication. Insightful reviews by P. Molnar and  
 349 an anonymous reviewer and discussions with L. Flesch signifi-  
 350 cantly helped improve the manuscript. This work was funded  
 351 by NSF under award EARXXXX, CNRS-INSU (*"Intérieur de*  
 352 *la Terre"* Program).

## Notes

- 353 1. Supplemental Material is available at <ftp://ftp.agu.org/apend/gl/2006GL28433>  
 354 2. See Supplemental materials

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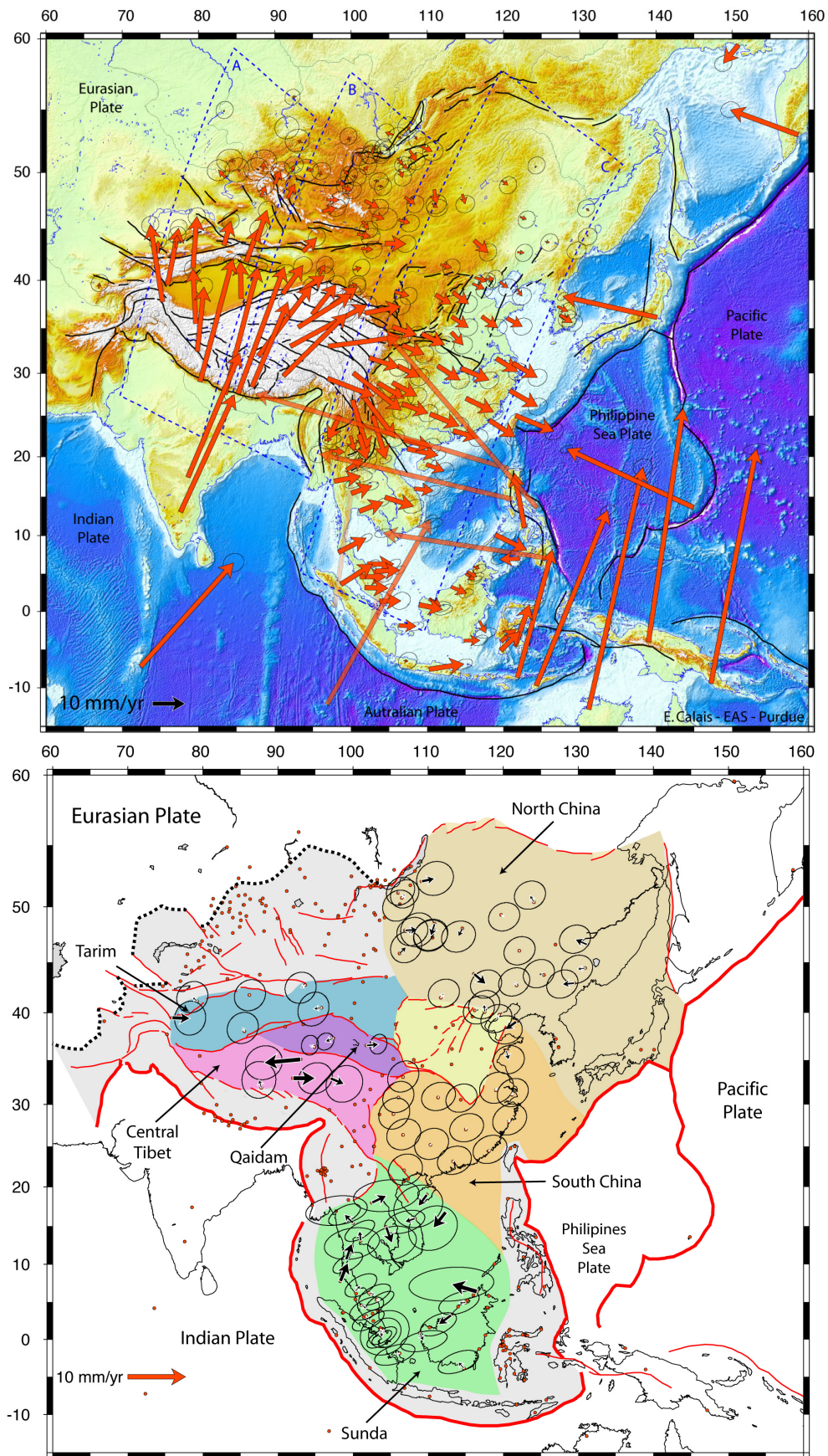
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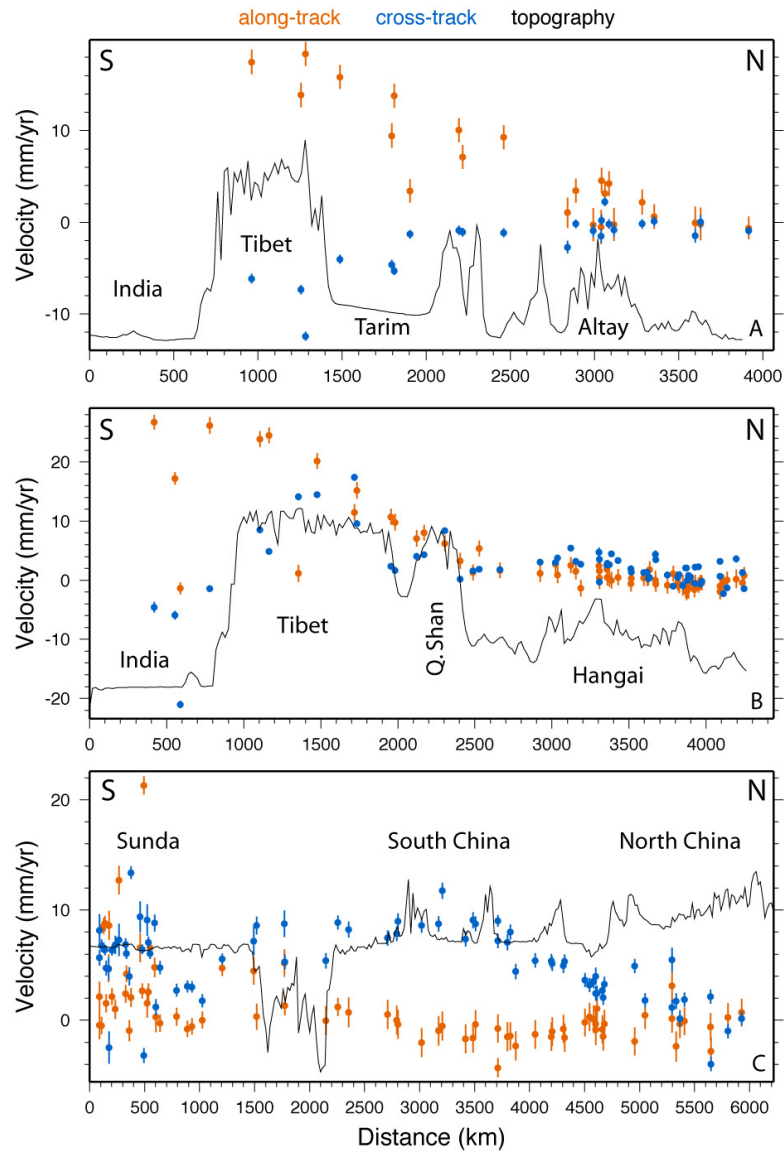
480 M. Vergnolle, Laboratoire de Géophysique Interne et  
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Block	$\chi_r^2$	dof	$\lambda$	$\phi$	$\sigma_{maj}$	$\sigma_{min}$	$\theta$	ang	WRMS
N. China	1.0	43	54.6	135.149	4.6	2.15	27.2	0.079±0.016	0.6
S. China	1.2	29	55.1	127.253	3.3	0.89	63.8	0.110±0.008	0.4
NS China	1.2	75	53.1	127.427	1.7	0.75	61.4	0.111±0.005	0.7
Tarim	1.6	9	-36.9	-79.7	1.6	0.7	25.7	0.438±0.036	0.7
Sunda	1.5	47	44.3	-73.3	16.9	2.5	86.5	0.062±0.011	1.2
Qaidam	9.1	3	-29.2	-76.5	1.5	0.4	60.6	0.570±0.063	2.5
C. Tibet	10.1	5	-22.5	-80.7	1.7	0.4	61.9	0.905±0.084	1.6

**Table 1.** Angular velocities.  $\chi_r^2$  is the chi-squared per degree of freedom (dof).  $\lambda$  and  $\phi$  are the latitude and longitude, respectively, of the Euler pole describing the block rotation with respect to Eurasia (in decimal degrees).  $\sigma_{maj}$  and  $\sigma_{min}$  are the semi-major and semi-minor axes of the pole error ellipse in degrees.  $\theta$  is the direction of the semi-major axis in degrees counterclockwise from East. Ang. is the rotation rate in degrees per Ma. WRMS is the weighted root mean square of residual velocities for each block.

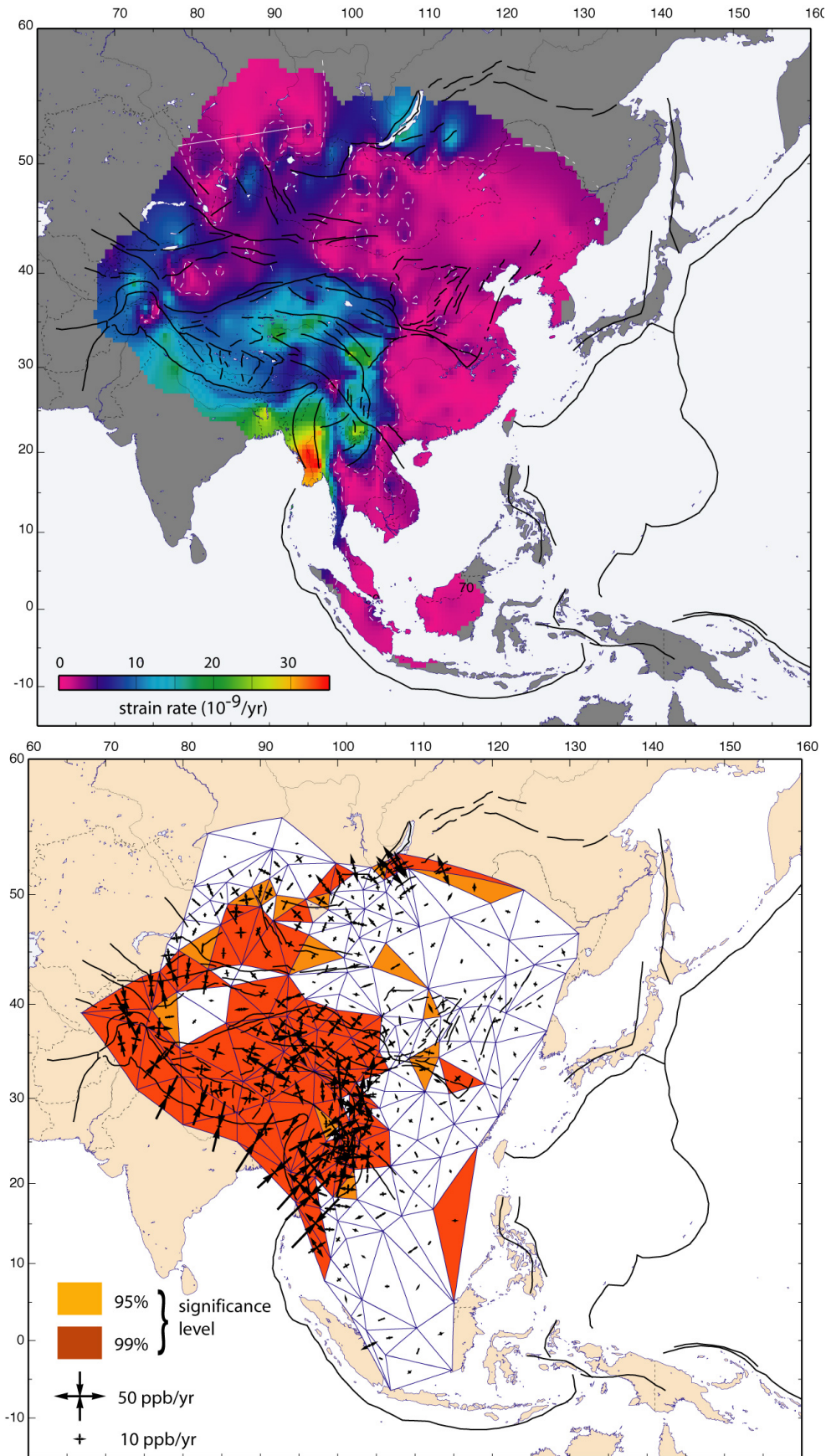


**Figure 1.** Top: Horizontal GPS velocities shown with respect to Eurasia. Large velocities at sites on adjacent plates are shown transparent for a sake of readability. The dashed boxes show the domains included in the 3 profiles (A, B, C) shown on Figure 2. Bottom: Residual velocities after subtracting rigid block rotations (see explanations in text). Dots show the location of all GPS sites. Major blocks used here are shown with color background. White areas were not included in the block analysis. Error ellipses are 95% confidence interval on both figures.



**Figure 2.** Velocity profiles: GPS velocity components projected into profile-parallel (along-track) and profile-perpendicular (cross-track) directions. The profile locations and sites included are shown on Figure 1 (top).





**Figure 3.** Top panel: Second invariant of the strain rate tensor calculated for a Delaunay triangulation (see bottom panel). The white dashed line shows the  $3 \times 10^{-9} \text{ yr}^{-1}$  contour. Bottom panel: Delaunay triangulation of the GPS network shown on Figure 1 with principal axis of the strain rate tensor shown at the centroid of each triangle. Convergent arrows mean contractional strain, divergent arrows mean extensional strain. Yellow and orange triangles show domains where the strain rate tensor is significant at the 95% and 99% confidence level, respectively. White triangles indicate a significance level lower than 95%.