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1 Postseismic deformation following the April 25, 2015 Gorkha earthquake (Nepal): afterslip
2 versus viscous relaxation.

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12

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22

23 Abstract

24

25 The postseismic deformation consecutive to the April 25, 2015 Gorkha earthquake (Mw
26 7.9) is estimated in this paper based on a cGNSS network installed prior to the earthquake and
27 supplemented by 6 cGNSS stations installed after the main shock. Postseismic displacement
28 are obtained from daily time series corrected for interseismic deformation and seasonal
29 variations. The maximum postseismic displacement is found north of the rupture area, where
30 locally it reached 100 mm between the date of the earthquake and late 2016. The postseismic
31 deformation affects the northern part of the rupture area but not the southern part, along the

32 southern part of the Main Himalayan Thrust (MHT). Three hypotheses for the mechanisms
33 controlling postseismic deformation are tested through numerical simulations of the
34 postseismic time series: (i) viscous relaxation, (ii) afterslip, or (iii) a combination of these two
35 mechanisms. We can exclude postseismic deformation controlled by viscous relaxation of a
36 thick deformation zone along the northern and lower flat of the MHT. However, it is impossible
37 to discriminate between postseismic deformation controlled by either afterslip along the MHT
38 (northern part of the rupture zone, crustal ramp, and lower flat of the MHT) or a combination
39 of afterslip along the MHT (northern part of the rupture zone, crustal ramp) and viscous
40 relaxation controlled by a thin (~3-4 km thick) low-viscosity body centered on the lower flat of
41 the MHT. The occurrence of afterslip along the northern part of the upper flat of the MHT and
42 its longitudinal variations have been established thanks to the densification of GNSS network
43 by our team presented in this paper.

44

45 Introduction.

46 The large number of geophysical instruments which recorded the April 25, 2015 Mw
47 7.8 Gorkha earthquake provides a unique opportunity to document better than ever a large
48 Himalayan earthquake. The main instrumental contributors to our understanding of the
49 mainshock include Interferometric synthetic aperture radar (InSAR) investigations as well as
50 teleseismic data (e.g. Avouac et al., 2015, Fan and Shearer, 2015), with also the continuous
51 Global Navigation Satellite System (GNSS) time series (Grandin et al., 2015) and regional
52 seismological records (e.g. Adhikari et al., 2015; Baillard et al., 2017). The deployment of the
53 Nepal GPS Geodetic Network, prior to the earthquake, and its maintenance during the seismic
54 crisis has also allowed to quantifying the early postseismic surface deformation (KKN4 and
55 CHLM stations) consecutive to this large earthquake (Mencin et al., 2016; Gualandi et al.,
56 2016).

57 In addition to being one of the few instrumental Himalayan earthquake, the setting of the 2015
58 earthquake (Fig. 1&2) is appropriate to study the complexity of the seismic cycle in a
59 continental subduction zone. Indeed, the slip deficit along the main Himalayan thrust (MHT),
60 on which the mainshock occurred, is accommodated during various types of earthquakes
61 (Mugnier et al., 2013), that partially contributes to release the elastic strain accumulation
62 (Avouac et al., 2015). This partial release has already been instrumentally measured in several
63 oceanic subduction environments; for example, in the Andean convergent margin, the main slip
64 patch of the 2010 Mw 8.8 earthquake occurred in an area that was highly coupled and had
65 already released slip in 1960 (Melnick et al., 2012; Moreno et al., 2012). However, contrarily
66 to earthquakes ruptures at oceanic subduction zones rarely captured by GNSS network in their
67 whole extend due to their frequent extension offshore, the 2015 Gorkha rupture was surrounded
68 by 12 stations well distributed above and around it. In addition, this permanent network was
69 complemented during the weeks following the main shock, by the deployment of additional
70 permanent or semi-permanent GNSS stations (this paper), this network dedicated to the
71 postseismic deformation has been designed to test the occurrence of afterslip along the upper
72 flat of the MHT in the rupture zone and south of it.

73 These records add some details to the postseismic deformation pattern and give a unique
74 opportunity to study in greater details the mechanism controlling the postseismic deformation
75 associated with the 2015 Gorkha event.

76 Different mechanisms are usually inferred for the postseismic deformation: afterslip or viscous
77 relaxation. In this paper, the Relax software (Barbot et al., 2009) was used to model the
78 postseismic deformation, taking into account the Main Himalayan Thrust geometry, rather well
79 imaged in the region (Nabelek et al., 2009; Duputel et al., 2016) and the coseismic displacement
80 field associated to it. Three postseismic mechanisms were tested: afterslip, viscous relaxation
81 or a combination of these two phenomena. We used a flap-ramp-flat geometry (Elliott et al.,

82 2016) with a southern and upper flat corresponding to the geometry adopted by Grandin et al.
83 (2015) to describe the coseismic slip distribution of the Gorkha earthquake along this flat.

84

85 Geological setting.

86 The structure of the Himalaya results from the underthrusting of the Indian lithosphere
87 along the Main Himalayan Thrust (MHT) beneath the Tibetan Plateau (Argand, 1924). Great
88 earthquakes have episodically ruptured segments of the brittle upper part of the MHT (e.g.
89 Avouac et al., 2001; Mugnier et al., 2013, Bollinger et al., 2014). The Nepal earthquake of April
90 25, 2015 followed a series of great earthquakes in the Central Himalaya (Mugnier et al., 2011,
91 Bollinger et al., 2016): over the last two centuries, the city of Kathmandu was severely damaged
92 in 1833, 1866, and 1934.

93 The April 25, 2015 event (Fig. 1) was the first earthquake on the MHT to be simultaneously
94 recorded by numerous instruments: high-rate GPS (e.g. Avouac et al., 2015), teleseismic waves
95 (e.g. Fan and Shearer, 2015), SAR imaging (e.g. Lindsey et al., 2015), InSAR and teleseismic
96 waves (Grandin et al., 2015), strong-motion recordings (e.g. Bhattarai et al., 2015), and a local
97 seismometer network (Adhikari et al., 2015).

98 The rupture was mainly located to the NW of Kathmandu, at a depth of 13–15 km on a flat
99 portion of the Main Himalayan Thrust (MHT) that dips N–NE at 7–10°. The northern boundary
100 of the main rupture corresponds to the transition towards a steeper crustal ramp. This ramp,
101 which is partly coupled during the interseismic period (Jouanne et al., 2017), was only locally
102 affected by the earthquake (Elliott et al., 2016). The southern boundary of the rupture was near
103 the leading edge of the Lesser Himalaya antiformal duplex (Mugnier et al., 2017) and possibly
104 near the frontal footwall ramp of the upper Nawakot duplex (Hubbard et al., 2016). This rupture
105 was affected by transversal structures: on the western side, a ~20° dipping lateral ramp (Kumar
106 et al., 2017), located beneath the Judi lineament (Mugnier et al., 2017) and already defined by

107 Kayal (2008), separates the main rupture zone from the nucleation area. On the eastern side, a
108 lateral ramp (Mugnier et al., 2017) located beneath the Gaurishankar lineament (Kayal, 2008)
109 illustrated by its seismic signature at depth (Letort et al., 2016, Baillard et al., 2017) separates the
110 April 25, 2015 rupture from the May 12, 2015 (Mw 7.2) rupture.

111

112 Data acquisition and analysis.

113

114 After the April 25 Gorkha earthquake, we installed a GNSS network designed to record
115 postseismic deformation induced by this Mw 7.9 earthquake. We installed four permanent
116 GNSS stations in June 2015 and 11 campaign GNSS stations between June and December 2015.
117 Seven of these stations were measured again in November 2016 (Figs 3 and 4). We analyzed
118 these data together with the continuous GNSS networks established by LDG-DASE, Caltech
119 (www.unavco.org), Central Washington University (<http://www.geodesy.cwu.edu>) and with
120 data from the GNSS sites defined in the ITRF2014 reference frame (Altamimi et al., 2016)
121 (ARTU, BADG,BAKU,BJFS, BJNM, CHUM, CUSV, GUAO, HYDE, IISC, IRKJ, IRKM,
122 KIT3, KUWT, LHAZ, MDVJ, POL2, SGOC, SHAO, TALA, TASH, TCMS, TEHN, TNML,
123 URUM, ZECK) obtained from unavco.

124 The data were analyzed using Bernese 5.2 software (Dach et al., 2016) with absolute antenna
125 phase center offset models, together with precise IGS orbits, Earth rotation parameters, and
126 ocean tidal loading and atmospheric tidal loading estimates. Velocities and time series were
127 estimated in the ITRF2014 reference frame (Altamimi et al., 2016) with discontinuities
128 associated with this reference frame and expressed in terms of the India fixed reference frame
129 by the use of the rotation pole proposed by Ader et al. (2012). This rotation pole, originally
130 proposed to describe the motion of India relative to ITRF2005, accurately describes the India
131 plate motion in the ITRF2014 reference frame, as shown by Jouanne et al. (2017) and as

132 exemplified by the lack of velocity of the cGPS SIM4 station located on the India plate (Fig.
133 3). In any case, any velocity changes introduced by the ITRF2005 / ITRF2014 change are
134 negligible compared to the large postseismic displacements.

135 We followed the resolution strategy with (1) an initial ionosphere-free analysis with calculation
136 of the residuals; (2) a residual analysis; (3) code-based wide-lane ambiguity resolution for all
137 baselines (Melbourne, 1985; Wübbena, 1985), using differential code bias (DCB) files when
138 available and calculation of the ionosphere-free solution with the introduction of resolved
139 Melbourne-Wübbena linear combination ambiguities; (4) phase-based wide-lane (L5)
140 ambiguity resolution for baselines < 200 km and computation of the ionosphere-free solution
141 with the introduction of resolved ambiguities; (5) resolution of the previously unresolved
142 ambiguities for baselines < 2000 km using the quasi ionosphere-free strategy of resolution; (6)
143 direct L1/L2 ambiguity resolution for baselines < 20 km with the introduction of an ionosphere
144 model; (7) calculation of the normal equations; (8) a compatibility test between the daily free
145 solution and ITRF2014 solution, selection of compatible ITRF2014 stations, and (9)
146 transformation of the daily normal equation in the ITRF2014 reference frame with a six-
147 parameter Helmert solution (three translation parameters and three rotation parameters) using
148 the ITRF2014 selected stations. During these steps, site-specific troposphere parameters were
149 estimated every two hours.

150 Normal equations were analyzed simultaneously to determine accurate velocities in the
151 ITRF2014 reference frame with the introduction of ITRF2014 coordinates and velocities.
152 Outliers and new discontinuities were detected using the “Find Outliers and Discontinuities in
153 Time Series” tool in Bernese 5.2 software which estimates annual seasonal fluctuations and
154 reduces, step by step, the discrepancy between the functional model and the time series due to
155 statistical adjustment (Ostini et al., 2008). Bernese 5.2 software underestimates the daily errors
156 because systematic errors or mismodeled parameters are not included in the formal error. We

157 therefore rescaled the formal errors by multiplying them by a factor of 10 to obtain a more
158 realistic estimated error (Hugentobler et al., 2001).

159

160 Results: postseismic displacements at the surface.

161

162 We consider that displacements contain three superimposed signals: interseismic
163 displacements, postseismic displacements, and the seasonal signal associated with loading of
164 the Ganga Plain during the monsoon and its unloading during the dry season (Bettinelli et al.,
165 2008; Fu and Freymueller, 2012; Gualandi et al., 2016). In order to analyze postseismic
166 displacements, we removed the interseismic displacements that were either measured before
167 the Gorkha earthquake for the sites that already existed before this event (BESI, BRN2, CHLM,
168 DAMA, GUMB, KKN4, KLDN, LMJG, NAST, ODRE, RMJT, RMTE, SNDL, SYBC, TPLJ)
169 (Fig. 2; Jouanne et al., 2017) or were estimated using interseismic deformation modeling by
170 Jouanne et al. (2017) for the new GNSS sites (Fig. 3).

171 In order to evaluate the seasonal components, we make the hypothesis that time series
172 are nearly linear during the period beginning 300 days after the 25 April 2015 earthquake. For
173 the period beginning 300 days after the main shock, we have then modeled time series as the
174 consequence of a linear velocity and of seasonal component (eq. 1).

$$175 \quad U(t) = U^*(t-t_{\text{ref}}) + a \cos(2\pi^*(t-t_{\text{ref}})/365) + b \sin(2\pi^*(t-t_{\text{ref}})/365) + c \cos(2\pi^*(t-t_{\text{ref}})/182.5) + \\ 176 \quad d \sin(2\pi^*(t-t_{\text{ref}})/182.5) \quad (\text{eq. 1})$$

177 Where t_{ref} is the first date after the day D_0+300 existing in the time series, D_0 being the date of
178 the main shock, U the velocity, and a , b , c and d are the amplitude of annual and semi-annual
179 signals. In a second step, whole time series are corrected for seasonal signals using these
180 amplitudes.

181

182 The postseismic displacements for the period when most of the GNSS stations were
183 available (between June 24, 2015 and late 2016) are shown (Fig. 4) to compare site
184 displacement measured over the same time span. Postseismic displacements are characterized
185 by the southward displacements of the points north of the Gorkha rupture (CHLM, GUMB,
186 TSM1). The station that recorded the greatest postseismic displacement is CHLM (Fig. 4 and
187 5) located to the north of the rupture, with 40 mm of southward displacement between April 25
188 and June 24, 2015 and 100 mm of southward displacement between June 24, 2015 and late
189 2016. The points located in the northern part of the rupture zone (KKN4, GURJ, BALE) are
190 affected by moderate southward postseismic displacements, whereas the points located at the
191 southern end of the rupture, near to and south of Kathmandu (CHIR, DAMA, NAST and
192 XYAK), are subject to small postseismic displacement. It should be noted that the points at the
193 western part of the rupture (LMJG, GORK and ANBU) are not affected by postseismic
194 displacements whereas the points located several kilometers to the east of the April 25, 2015
195 rupture (CHAR, JIR2, MALU) are affected by significant postseismic displacements reaching
196 35 mm (Fig. 4). Given that these points were installed after the Mw 7.2 main aftershock of May
197 12, 2015, these postseismic displacements could be related to the postseismic deformation
198 induced by this earthquake, but the lack of change in the cumulative postseismic displacements
199 in the CHLM time series indicates, before and after the May 12, 2015 earthquake indicates that
200 this second large earthquake does not induce a significant postseismic deformation.

201 Significant postseismic displacements are therefore restricted to the northern part of the rupture
202 zone and to an area to the north of it (Figs 4, 5, 6 and 7). It is important to note that there are no
203 clear postseismic displacements to the south of the Gorkha earthquake rupture and, like Mencin
204 et al. (2016), we exclude the occurrence of significant afterslip along the southern part of the
205 MHT. Therefore, the slip deficit along the MHT south of Kathmandu is not resorbed
206 aseismically by slip along the MHT from the rupture zone to the MFT where the MHT emerges.

207 The slip deficit could then possibly be resorbed by a future large earthquake between the
208 southern end of the rupture near Kathmandu and the Main Frontal Thrust near the Ganga Plain,
209 as probably happened in the 1866 earthquake (Oldham, 1883; Szeliga et al., 2010), or by a
210 larger earthquake rupturing the locked fault zone from the brittle-ductile transition zone to the
211 surface, in a similar way as in the subduction zones (Melnick et al., 2012; Moreno et al., 2012)
212 or to the 1934 Nepal-Bihar earthquake (e.g. Mugnier et al., 2013).

213 Figures 5, 6 and 7 illustrate the postseismic deformation with the time series for the southern,
214 eastern and vertical components corrected for the interseismic component and the seasonal
215 signal in the India fixed reference frame.

216 Time series of southern component present a progressive decrease in postseismic displacement
217 with time, suggesting progressive dissipation of the stress perturbation induced by the
218 earthquake (Fig. 5). It can be observed that the time series of the eastern components (Fig. 6)
219 presents spatial variations: BALE, CHLM and DNC4 time series indicate significant westward
220 components of postseismic displacements, whereas time series of BHAZ, CHAR, GUMB,
221 JIR2, KKN4 and XBAR do not present this component. This is why we will consider only the
222 southern and vertical time series to simulate postseismic displacements. Time series of vertical
223 component present a progressive decrease in postseismic displacement with time, suggesting
224 progressive dissipation of the stress perturbation induced by the earthquake (Fig. 7). The CHLM
225 time series of the south components presents a jump corresponding to the Mw 7.2 main
226 aftershocks of May 12, whereas the other stations were not significantly affected or were
227 installed too late to record this coseismic displacement. It can be also observed that this second
228 earthquake does not induced a change in the evolution of the postseismic displacement of the
229 CHLM and KKN4 station. This is why we have not consider this earthquake in the numerical
230 simulations.

231

232 Modeling postseismic- displacement.

233 We have chosen to test the origin of the progressive release using three hypotheses with
234 Relax 1.0.7 software (Barbot et al., 2008; Barbot et al., 2009; Barbot and Fialko 2010; Bruhat
235 et al., 2011; Rousset et al., 2012): a postseismic deformation controlled by afterslip, viscous
236 relaxation of the stress perturbation with a linear rheology, and a combination of these two
237 mechanisms.

238 This software computes the displacement and stress due to dislocations and the nonlinear
239 postseismic time-dependent deformation, the latter either controlled by viscous bodies or by
240 rate-strengthening friction faults. This software takes gravity into account and is based on a
241 Fourier-domain elastic Green's function and an equivalent body-force representation of
242 deformation mechanisms. We consider a 512*512*512 grid size model around the relevant
243 faults with 0.7*0.7*0.7 km sampling which corresponds at a 358*358*358 km grid.

244 For this modeling, we use the same MHT geometry as for the pre-earthquake
245 deformation (Jouanne et al., 2017); this geometry also fits with the location of the rupture zone
246 proposed by Grandin et al. (2015) indicated in Figure 2. The geometry of the MHT is formed
247 by a succession of flats and ramps characterized by a large southern flat (95–100 km) dipping
248 7° northward, a crustal ramp dipping 27° northward between 15 and 25 km, and a northern flat
249 dipping 7° northward as illustrated by receiver-function data (Duputel et al., 2016).

250 As postseismic displacements only affected stations north of Kathmandu, if postseismic
251 displacements are controlled by afterslip along the MHT, afterslip did not affect all of the upper
252 flat of the MHT but only its northern parts. If we consider the points BALE, KKN4, and GURJ
253 (Fig. 4 and 5) that are nearly the same distance from the upper flat-ramp connection, it appears
254 that the eastern one (BALE) is affected by greater postseismic displacements than the other two
255 located in the western part of the upper flat of the MHT. We then considered that these surficial
256 variations in displacement reflect afterslip distribution along the MHT. These spatial variations

257 in the time series led us to consider a 25 km-wide western segment and a 40 km-wide eastern
258 segment and the boundary between these two segments coincides with the western edge of the
259 May 12, 2015 rupture and with the Gaurishankar lateral ramp as illustrated in Figure 1. This
260 spatial variation also reflects interseismic coupling variations between the western and eastern
261 parts: the western part was completely locked whereas the eastern part was only partially
262 locked, with a coupling of 0.7 (Fig. 2a) (Jouanne et al., 2017).

263 To test the models, we used a time series that was corrected for interseismic velocities
264 and seasonal components. As postseismic displacements are southward with a lack of E-W
265 components, we have only used the N-S and vertical components of time series.

266 The preferred solutions were selected using the comparison between the observed and
267 simulated time series with the estimation of weighted root mean square WRMS for each
268 simulation (Fig. 9).

269

270 *Viscous relaxation model.*

271 The estimation of coupling during the interseismic period (Betinelli et al., 2006; Ader
272 et al., 2012; Jouanne et al., 2017) suggests ductile behavior along the northern flat of the MHT.
273 We therefore test the hypothesis that postseismic displacements reveal viscous relaxation of the
274 stress perturbation induced by the main shock. Ductile behavior is temperature dependent
275 (Scholz, 1998) and does not occur in the brittle crust. Viscous relaxation is therefore excluded
276 for the upper flat and the ramp characterized by a temperature of less than 375 °C (Robert et
277 al., 2011). Hereafter, we assume that the lower flat accommodates viscous relaxation only.

278 In this simulation, a low viscous body with a linear Maxwell rheology corresponding to the
279 deeper part of the Main Himalayan Thrust is embedded in an elastic half space (Fig. 8a). The
280 parameters to be determined are the viscosity and the thickness of this body. As the indian

281 lithosphere is very thick, 135 km in eastern Nepal (Devi et al., 2011), we do not take into
282 account the asthenosphere viscosity.

283 We chose to explore the following ranges of values: viscosity of the body from 10^{16} to 10^{19}
284 Pa*s and thickness of the body from 0 to 14 km. The WRMS is invariably greater than 17 mm
285 and no solution is clearly favored among the 84 numerical runs performed to determine
286 parameter influence and summarized in Figure 9a.

287

288 *Afterslip model.*

289 If the postseismic displacements are controlled by afterslip induced by the Mw 7.9
290 earthquake of April 25 2015, these displacements can be simulated by progressive release of
291 stress perturbation due to the main shock. We assume that the afterslip occurs (Fig. 8a) along
292 the northern part of the upper flat of the MHT affected by the April 25, 2015 earthquake, along
293 the crustal ramp north of the rupture zone, and along the lower flat north of this ramp.

294 We assign rate-strengthening properties derived from laboratory experiments (Dieterich, 1979;
295 Ruina, 1983, Barbot et al., 2009; Lapusta et al., 2000; Rice & Ben-Zion, 1996) to these three
296 fault segments with:

$$297 \quad V = 2 \dot{\gamma}_0 \sinh \frac{\Delta\tau}{(a-b)\sigma} \quad (\text{eq. 2})$$

298 Where V is the slip velocity on the fault, $\Delta\tau$ is the shear stress perturbation induced by the
299 earthquake that is progressively released by the afterslip, $\dot{\gamma}_0$ is the initial slip velocity and $(a -$
300 $b) \sigma$ is a constitutive parameters with a value of the order of the stress drop during the
301 earthquake, σ being the effective normal stress and $(a - b)$ a frictional parameter.

302 The initial stress perturbation associated with the coseismic slip distributions of April 25, 2015
303 estimated by Grandin et al. (2015), with InSAR and teleseismic waves data (Fig. 2b) is
304 calculated with Relax 1.0.7 software.

305 We explore the parameters space (Fig. 9b, c, d) formed by $\dot{\gamma}_0$ (from 50 to 500 mm/year), and
306 the friction along the relevant planes (from 0.2 to 0.7) for $(a - b)$ σ values of 10 and 22 MPa (22
307 MPa being the stress drop estimated by Denolle et al., 2015). The tests of the $(a - b)$ σ values
308 of 22 and 10 MPa (Fig. 9 c and d) allow us to determine that the best fit for the southern
309 component time series is obtained for the $(a - b)$ σ value of 22 MPa, which is the value of the
310 stress drop estimated by Denolle et al. (2015), a friction ratio of 0.7 and a $\dot{\gamma}_0 = 200$
311 mm/year. The simulation of vertical time series allows to confirm that $\dot{\gamma}_0$ must be larger than
312 150 mm/year (Fig. 9d).

313 We decide to adopt as the better model the solution obtained for 0.7 frictional parameters and
314 a $\dot{\gamma}_0$ value of 200 mm/year.

315

316 *Afterslip and viscous relaxation model.*

317 This simulation takes into account the hypothesis that the northern flat may be a zone affected
318 by ductile deformation (Beaumont et al., 2001), while the upper part of the MHT is probably in
319 a brittle condition as shown by the high coupling of the upper flat and crustal ramp during the
320 interseismic period (Jouanne et al., 2004; Ader et al., 2012; Jouanne et al., 2017).

321 We test the hypothesis of a mixed origin for postseismic deformation (Fig. 8), with viscous
322 relaxation controlled by a deep low-viscosity body centered on the northern MHT flat, as done
323 above, whereas afterslip occurs along the crustal ramp and the northern part of the southern flat.

324 We adopt, as an *a priori* model for the afterslip component, the above model that minimizes
325 the WRMS among the models based solely on afterslip and we explore the following
326 parameters: viscosity of the low-viscosity body (from 10^{16} to 10^{19} Pa.s) and the thickness of
327 this body (1 to 6 km).

328 Among 50 numerical runs performed to determine the parameter influence with the southern
329 time series (Figure 9e), a minimum of 3.2 mm is found for the WRMS (Fig. 9e) linked to a 3-4

330 km thickness for the viscous body and a 10^{16} Pa*s viscosity. The used of vertical component to
331 determine the best solution (Fig. 9 e) is not determining.

332

333 Discussion.

334 *Comparison between the different models.*

335 Comparison of the WRMS for the models performed with the three hypotheses tested
336 (Fig. 9) indicates that the models with only viscous relaxation on the lower flat of the MHT
337 have much higher WRMS and can be excluded (Fig. 9a).

338 The other two models, afterslip alone or afterslip associated with viscous relaxation on the
339 lower flat of the MHT, have respectively WRMS for the southern time series of 3.6 mm for the
340 afterslip model and of 3.2 mm for the mixed model. The use of vertical time series (Fig. 9d and
341 9f) do not help to choose between these two models.

342 The mixed model seems to better simulate the observations than the afterslip only model, but
343 if the Relax software allowed the use of variable friction coefficients along the MHT, it would
344 probably be possible to find a more satisfactory solution with the afterslip model, with probably
345 a lower friction coefficient along the northern flat of the MHT than along the ramp and the
346 southern or upper flat of the MHT.

347 Therefore the numerical modeling approach does not enable us to choose between the two
348 hypotheses – afterslip alone or afterslip combined with viscous relaxation on the lower flat (Fig.
349 9c and 9e and Fig. 10). Nevertheless, it must be underlined that afterslip combined with viscous
350 relaxation on the lower flat allows to simulate the early postseismic displacements as shown on
351 Figure 10 for the CHLM and KKN4 time series which is not the case if we consider the afterslip
352 only model.

353 All the retained simulations indicate (Fig. 9c and d, Fig. 9 e and f, Fig. 11 and 12): (a) moderate
354 afterslip along the ramp; (b) significant afterslip along the northern part of the upper flat; (c)

355 substantial afterslip where the coseismic slip gradient was high: at the upper flat/crustal ramp
356 transition, locally in the rupture area, and near the southern boundary of the rupture. Afterslip
357 along the southern part of the upper flat, to the south of the southern border of the numerical
358 model, has been a priori excluded in our modelling as it has suggested by the near zero
359 postseismic displacement measured in the southern part of the Gorkha earthquake rupture zone.
360 This observation indicates the likely existence of local variations in friction coefficients not
361 taken into account in our model.

362

363 *Afterslip properties along the MHT.*

364 With Relax software it is possible to consider just one single afterslip property (friction
365 ratio and constitutive parameters) for all of the fault segments. As a result, we then considered
366 the same properties for the upper flat, crustal ramp, and lower flat of the MHT. Our preferred
367 model, which provides a good fit with the observed time series (Fig. 7c), was obtained with $\dot{\gamma}_0$
368 = 200 mm/year and a friction of 0.7 for (a-b) $\sigma = 22$ Mpa.

369 A friction coefficient of 0.7 is somewhat higher than the values usually inferred. For
370 example, the friction angle was estimated at 20° for the Indian crust in modeling by Berger et
371 al. (2003). Such high values have nonetheless been found experimentally for numerous rocks
372 (Kulhawi, 1975).

373 The afterslip evolution over time and space of our preferred model indicates that (Fig.
374 11): the lower flat of the MHT is affected by slow large-scale afterslip decreasing over time,
375 whereas the crustal ramp is affected by negligible afterslip without significant lateral variations.
376 The northern part of the upper flat is characterized by local patches of high afterslip; the latter
377 reached 1 m after two years with significant lateral variability and a significant decrease of
378 afterslip evolution between D + 30 days and D + 6 months. The areas of the upper flat affected
379 by significant slip are located close to the flat-ramp transition corresponding to the northern

380 boundary of the rupture. Areas of the upper flat locally affected by significant slip are
381 characterized by a local high coseismic displacement gradient in Grandin et al.'s model (2016)
382 and then by local high deviatoric stress to be released. Locally, slip also occurred southward, in
383 areas near the southern end of the mesh, the upper flat segment of the MHT affected by afterslip.
384 Our modeling suggests changes of width of the upper flat of the MHT affected by afterslip (Fig.
385 11). The distribution of the afterslip reflects the distribution of the coseismic displacement
386 model, the roughness of the afterslip distribution reflects the roughness of the co-seismic
387 displacement model considered at the input of the model. It can therefore be assumed that with
388 a smoother coseismic displacement model, we would also obtain a smoother afterslip model.
389 But we assume that the model roughness considered as input does not affect the conclusions of
390 our models.

391 Our modelling clearly differs from the model proposed by Wang and Fialko, 2018, we
392 allow afterslip along the northern part of the 2015 rupture whereas these authors supposed that
393 no afterslip occurred along the upper flat of the MHT. Our model allows good simulation of
394 time series of points located in the southern part of the area affected by postseismic deformation
395 BALE, BHAZ, GURJ, KKN4, JIR2 and CHAR whereas the model of Wang and Fialko does
396 not allow a good simulation of the time series of JIR2, the points BALE, BHAZ, GURJ and
397 CHAR, installed by our team, being not included in their study. On the contrary, the model of
398 Wang and Fialko presents a better simulation of the CHLM and DCN4 time series. Our model
399 failed to predict accurately the early postseismic deformation of CHLM and failed to well fit
400 the time series of DCN4 and GUMB. We can then propose that rheological properties are
401 different between the upper flat of the MHT and the crustal ramp and the northern flat. As in
402 this study we present a larger number of time series sensitive to the afterslip along the upper
403 flat, we can suppose that our solution reflects mainly the rheological properties of the upper flat

404 whereas the results presented by Wang and Fialko, 2018 reflect mainly the rheological
405 properties along the lower part of the MHT (ramp and northern flat).

406

407 *Viscous relaxation controlled by a low viscosity zone along the lower flat of the MHT.*

408 The time series for the stations located above the rupture zone, or to the south of it, are not
409 correctly simulated by only viscous relaxation controlled by a ductile body centered on the
410 northern flat. In the numerical models where afterslip along the upper flat of the MHT and along
411 the crustal ramp has been introduced, the low-viscosity body (10^{16} Pa.s) has to be thin (close to
412 3-4 km) to minimize the discard between model and data (Fig. 9e). We therefore believe that
413 viscous relaxation controlled by a low-viscosity body cannot alone explain the recorded
414 postseismic deformation and another source of deformation located to the south of the lower
415 flat (i.e. afterslip) is needed. Models combining afterslip and viscous relaxation controlled by a
416 thin, viscous body centered on the lower flat of the MHT better predict early post-seismic
417 displacement (CHLM and KKN4 time series) than models considering only afterslip along the
418 MHT (Fig. 10).

419 The low-viscosity body is a reasonable assumption as it may explain the low coupling
420 along the lower flat documented for the interseismic period (Fig. 2a and 12). Furthermore, the
421 low-viscosity level has been suggested from the interpretation of deep images of the Himalayan
422 crust (e.g. Zhao et al., 1993; Nelson et al., 1996). Since these articles, new seismic experiments
423 demonstrated that the low velocity zones in Tibet is discontinuous, restricted to surfaces with
424 maximum vertical extension of 10 km and maximum horizontal length about 50 km (Hetenyi
425 et al., 2011).

426

427 A channel flow model (Beaumont et al., 2001) was even proposed to describe the evolution of
428 Himalayan tectonics and is based on a very thick ductile zone (more than 10 km thick); so thick

429 that the horizontal velocity depicts a peculiar gradient, with a maximum velocity in the center
430 of the ductile zone. Our results nonetheless suggest that the ductile zone is 3 – 4 km thick
431 beneath the extreme southern part of the Tibetan plateau. Therefore, we suggest that the recent
432 tectonism of the Himalaya is not controlled by channel flow deformation at depth, although our
433 results does not preclude a thicker ductile zone to the north.

434

435 If we assume that postseismic deformation ends after 6 years, our results (Fig. 12) show (1)
436 afterslip or viscous relaxation of a thin body (~3-4 km thick) of low viscosity along the lower
437 flat of the MHT (up to 0.5 m after 6 years) and (2) moderate afterslip along the crustal ramp
438 that extends down-dip from the Gorkha rupture (up to 0.5 m after 6 years) as well as (3) a high-
439 velocity small-scale afterslip (up to 5 m after 6 years for the western segment) along the
440 southern boundary of the upper flat affected by afterslip, and along the upper flat, high-velocity
441 afterslip in areas characterized by a significant coseismic slip gradient during the earthquake
442 (reaching 5.6 m after 6 years in its western part and 3.4 m in its eastern part).

443 This pattern, in which moderate afterslip occurs along the crustal ramp and extends down-dip
444 from the rupture, has also been shown for the postseismic deformation following the 2005
445 Balakot-Bagh earthquake (Jouanne et al., 2011; Wang and Fialko, 2014), for the deformation
446 consecutive to the 1995 Chi-Chi earthquake (Yu et al., 2003; Perfettini and Avouac, 2004), and
447 for the 1995 Jalisco earthquake (Hutton et al., 2001).

448

449 *Importance of afterslip in the seismic cycle.*

450

451 As illustrated in Figure 12, the effects of afterslip consecutive to the Gorkha earthquake remain
452 confined to the northern part of the rupture area, the crustal ramp, and the northern flat of the
453 MHT. The afterslip does not, then, homogenize coseismic slips throughout the rupture area but

454 only and partially in its northern part. Moreover, if we consider that the 1833 and 2015
455 earthquakes have the same rupture area, and if we take the cumulated slip along the MHT during
456 the interseismic period as estimated by Jouanne et al. (2017), then it appears that postseismic
457 displacement along the MHT does not homogenize slip along the MHT between the ductile slip
458 along the northern flat (4 m for 200 years) and the coseismic slip along the northern part of the
459 upper flat.

460

461 Conclusion.

462 The cumulative postseismic velocity field clearly shows a lack of displacements to the
463 south of Kathmandu. Afterslip along the southern part of the rupture area of the Gorkha
464 earthquake and along the southern segment of the MHT, that was unaffected by the main shock,
465 is then clearly excluded. The slip deficit along the southern part of the upper flat of the MHT,
466 between Kathmandu and the Ganga Plain, would probably be transferred along the MHT by an
467 earthquake of large magnitude, as may have been the case after the previous 1833 large
468 earthquake along this segment of the MHT, or by a very large magnitude earthquake affecting
469 the MHT from the ductile zone to the MFT. To the west and east of the Gorkha rupture,
470 postseismic displacements are almost negligible, and afterslip does not affect the upper flat
471 areas of the MHT to the west of the rupture zone.

472 The simulation of the time series using Relax software suggests that the postseismic
473 deformation consecutive to the April 25, 2015 earthquake is controlled by: heterogeneous
474 afterslip along the northern part of the upper flat of the MHT corresponding to the northern part
475 of the rupture; afterslip along the crustal ramp reaching 0.17m after two years; and afterslip
476 reaching 0.20 m after two years or viscous relaxation of a thin (~3-4 km thick) ductile zone
477 along the lower flat of the MHT. Viscous relaxation along a ductile body centered on the lower
478 flat of the MHT alone cannot explain alone the postseismic deformation.

479

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777

778 Captions

779

780 Graphic abstract

781 Example of observed and simulated postseismic time series and test of mechanisms controlling
782 the postseismic deformation, afterslip along the northern part of the upper flat, the ramp and the
783 flower flat of the Main Himalayan Thrust (blue) or a combination of afterslip along the northern
784 part of the upper flat and the ramp of the MHT and a viscous relaxation controlled by a low
785 viscosity body centered on the lower flat of the MHT (red). The simulated time series are
786 respectively drawn in blue and red.

787

788 Figure 1. Location of the Gorkha earthquake along the upper flat of the MHT. Dark purple for
789 ramp geometry; pink, light purple, and green for fully locked, partial coupled, and ductile MHT,
790 respectively; red for rupture zones. The rupture area is bounded by lateral ramps (Mugnier et
791 al., 2017).

792

793 Figure 2. Description of inter and co-seismic deformation used for modeling the post-seismic
794 deformation with Relax software. (a) Coupling along the Main Himalayan Thrust during the

795 interseismic period (before the Gorkha earthquake) (modified from Jouanne et al., 2017) and
796 location of Gorkha earthquake indicated by yellow dash line (Grandin et al, 2015). CR indicates
797 the location of the crustal ramp. (b) Coseismic slip distribution (adapted from Grandin et al.,
798 2015) used as input for our numerical simulation.

799

800 Figure 3. Observed (Jouanne et al., 2017) and simulated interseismic velocities using the model
801 proposed by Jouanne et al. (2017). Velocities are expressed in the India fixed reference frame.

802

803 Figure 4. Postseismic displacements following the Gorkha earthquake for the June 24, 2015–
804 December 2016 period. The recorded displacements are corrected for interseismic
805 displacements.

806 The rupture of the Gorkha earthquake is indicated by a blue line and the rupture of its main
807 aftershocks, on May 12, 2016, is drawn with an orange line. The star indicates the nucleation
808 of the Gorkha earthquake to the west of its rupture. The dashed green lines indicate the location
809 of the Judi lineament (Kayal, 2008) that separates the main rupture zone from the nucleation
810 area (Kumar et al., 2017) and, on the eastern side, the Gaurishankar lineament (Mugnier et al.,
811 2017). Errors ellipses are drawn for a 95% confidence level. GNSS stations installed by our
812 team for this study are indicated in blue and permanent GNSS stations of LDG are indicated in
813 orange.

814

815 Figure 5. Southern components for the cGNSS station displacements, corrected from
816 interseismic velocities and seasonal signals estimated during the period before the main shock
817 or extrapolated for the new stations. The locations of cGNSS stations are indicated in Figure 2.

818

819 Figure 6. Eastern components for the cGNSS station displacements, corrected from interseismic
820 velocities and seasonal signals estimated during the period before the main shock or
821 extrapolated for the new stations. The locations of cGNSS stations are indicated in Figure 2.

822

823 Figure 7. Vertical components for the cGNSS station displacements, corrected from
824 interseismic velocities and seasonal signals estimated during the period before the main shock
825 or extrapolated for the new stations. We present only the time series that seem to be correctly
826 correct for seasonal components. The locations of cGNSS stations are indicated in Figure 2.

827

828 Figure 8. Geometry and rheological properties considered in the numerical simulations of
829 postseismic deformation. (a) Viscous relaxation controlled by a high-fluidity body embedded
830 in a half-space characterized by low fluidity; (b) afterslip along the northern part of the upper
831 flat of the MHT, along the ramp, and along the lower flat of the MHT; and (c) viscous relaxation
832 controlled by a high-fluidity body embedded in a half-space characterized by low fluidity and
833 afterslip along the crustal ramp and along the northern part of the upper flat.

834

835 Figure 9. Search for the best solution, with the plot of the WRMS, for (a) the viscous relaxation
836 hypothesis controlled by a viscous body along the lower flat of the MHT; (b) the afterslip
837 hypothesis with (a-b) $\sigma= 10$ MPA; (c) the afterslip hypothesis with (a-b) $\sigma= 22$ MPA with the
838 southern time series, (d) the afterslip hypothesis with (a-b) $\sigma= 22$ MPA with the vertical time
839 series; (e) afterslip and viscous relaxation controlled by a viscous body along the lower flat of
840 the MHT with the southern time series and (f) afterslip and viscous relaxation controlled by a
841 viscous body along the lower flat of the MHT with the vertical time series .

842

843 Figure 10. Observed and simulated postseismic time series with our preferred afterslip model,
844 the afterslip & viscous relaxation model, and the viscous relaxation model. The simulated time
845 series with our preferred afterslip and afterslip & viscous relaxation models almost always
846 become conflated. Blue curve: afterslip hypothesis, red curve: afterslip and viscous relaxation
847 controlled by a viscous body along the lower flat of the MHT.

848

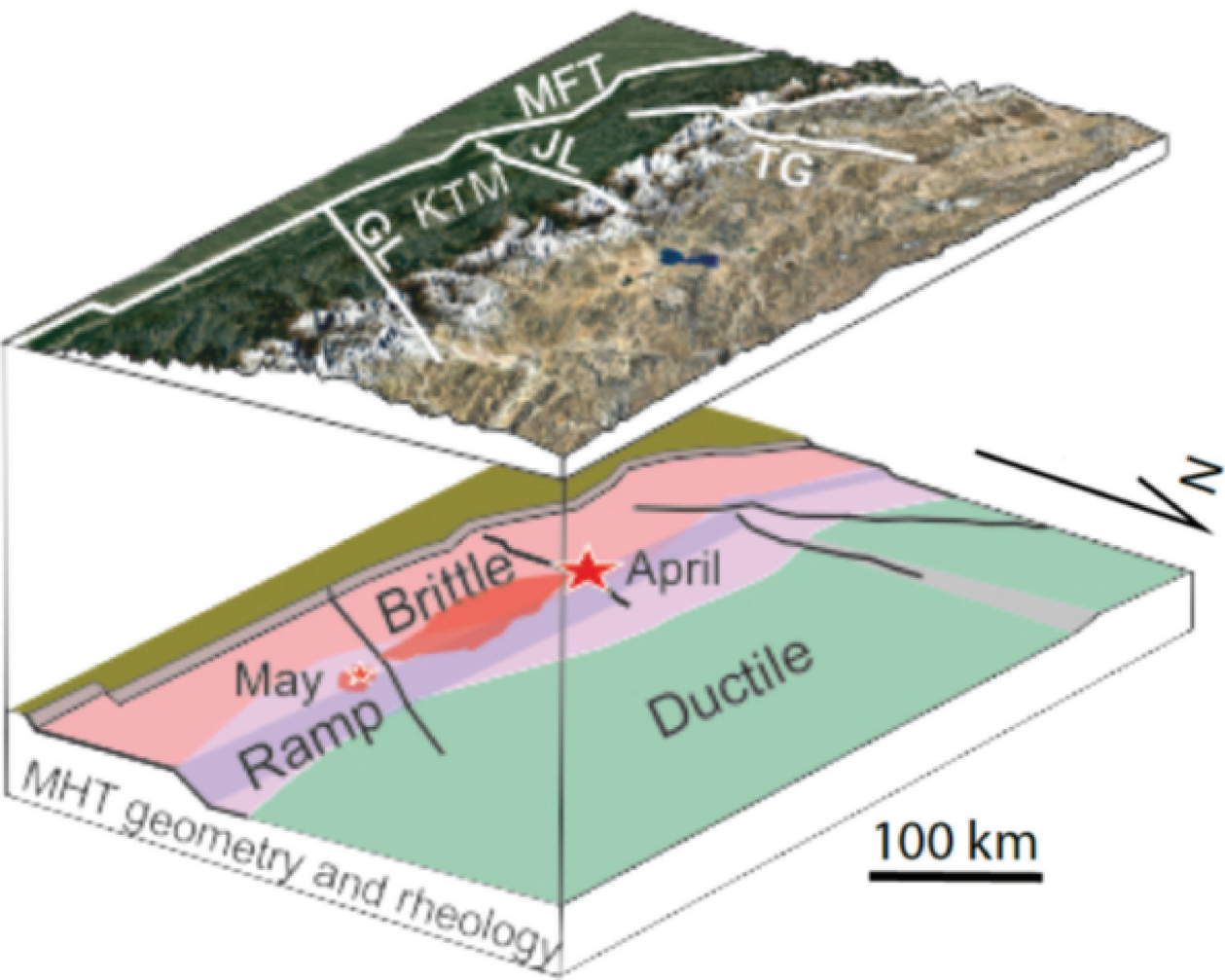
849 Figure 11. (a) Evolution of slip over time and space, predicted by our preferred afterslip model,
850 expressed for selected dates. The locations of the permanent GNSS stations used to constrain
851 our modeling are indicated by circles, (b) zoom of afterslip distribution after two years.

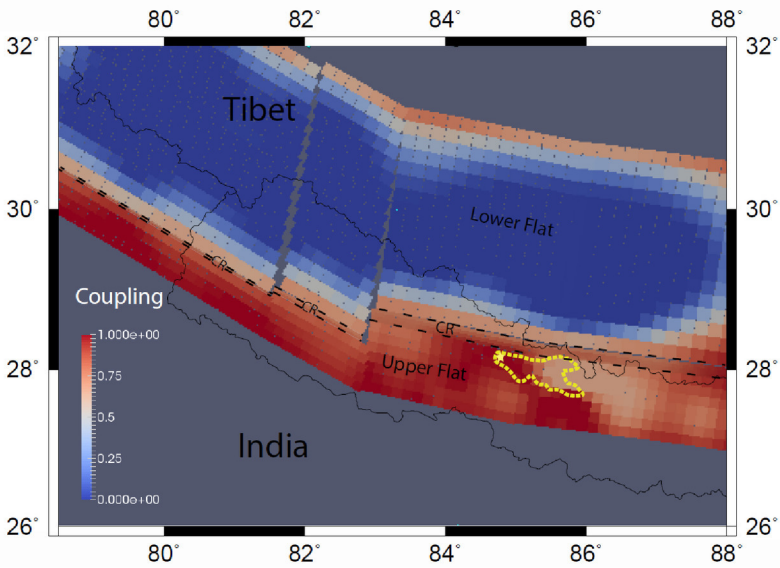
852

853 Fig. 12. Comparison between interseismic slip rate, seismic slip, and after-slip predicted after
854 6 years, supposed to be the end of postseismic deformation, along the Main Himalayan Thrust.
855 See Fig. 9 for location of the cross section.

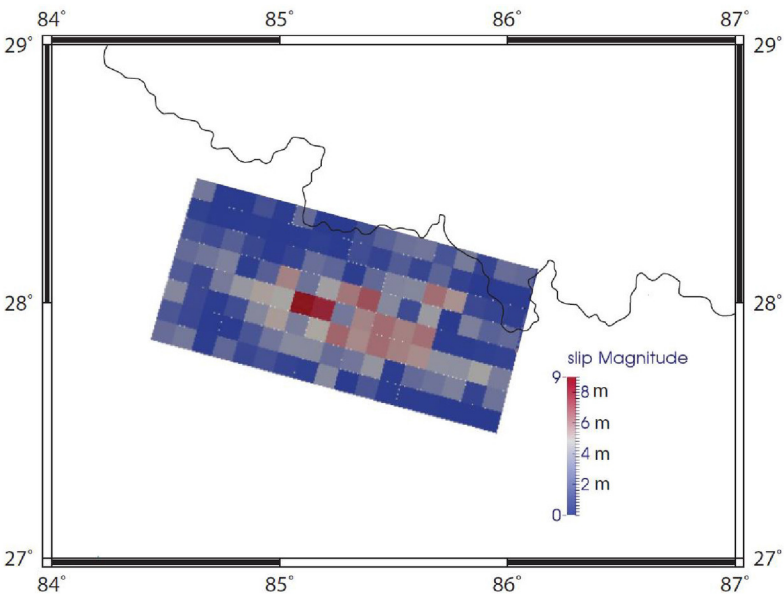
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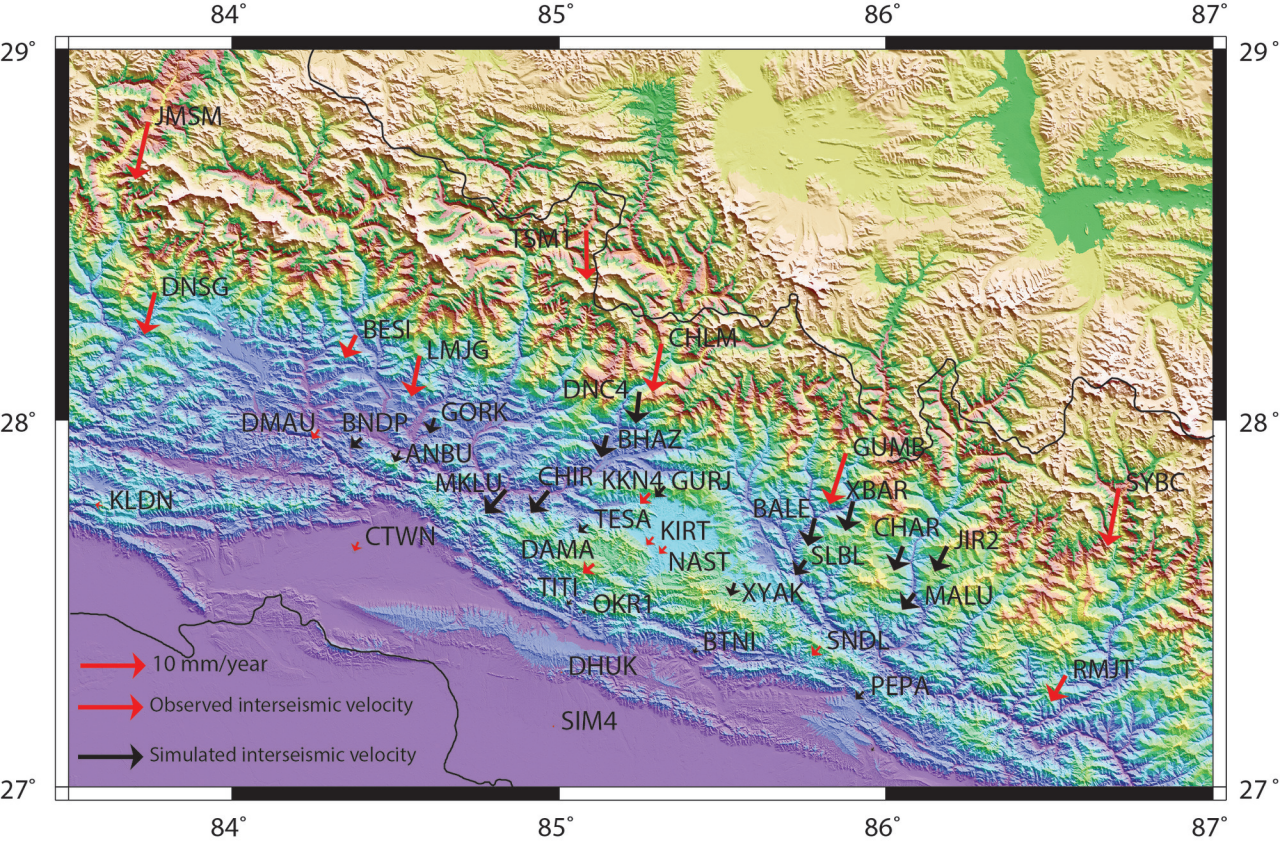


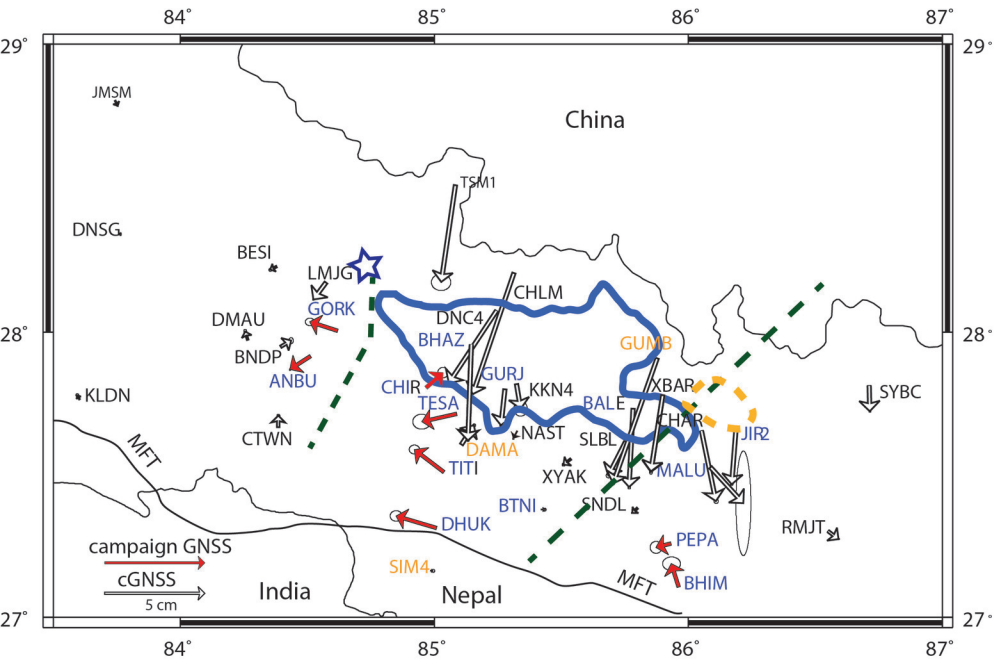


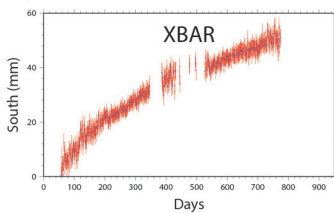
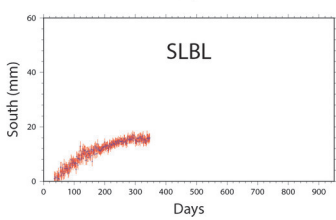
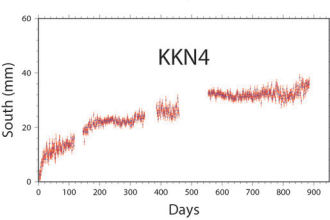
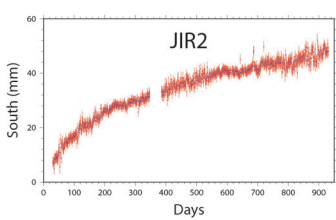
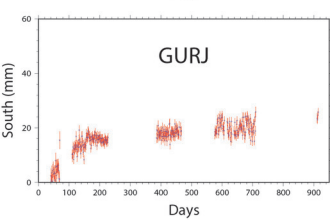
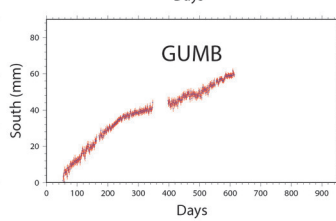
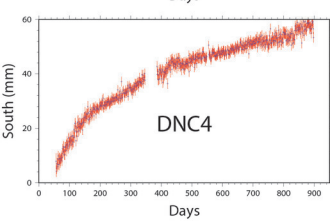
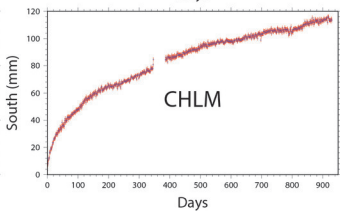
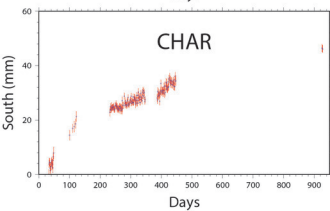
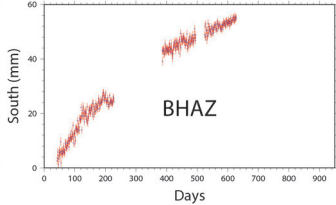
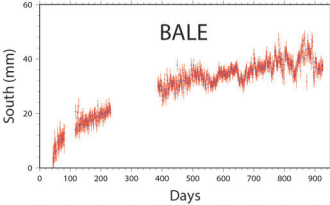
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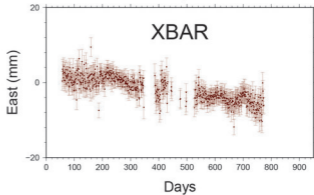
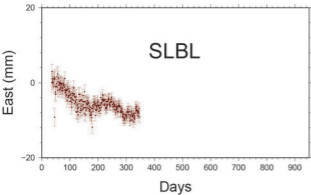
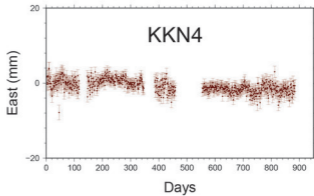
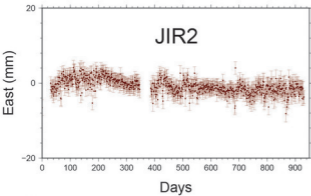
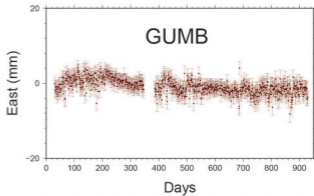
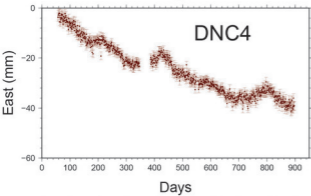
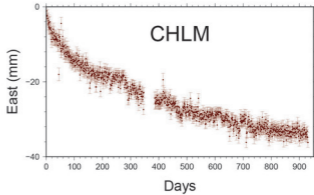
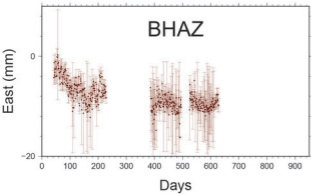
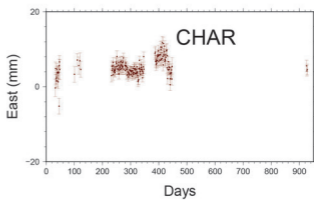
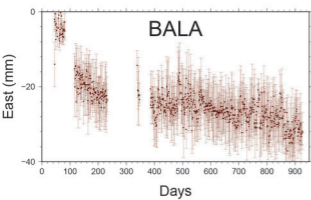


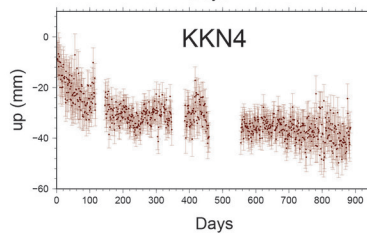
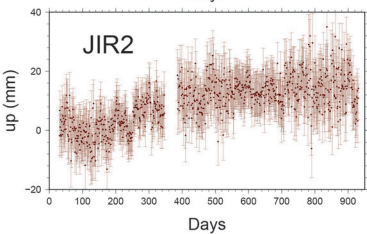
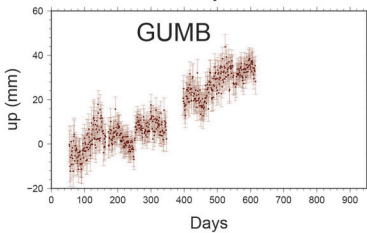
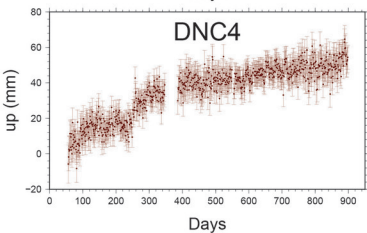
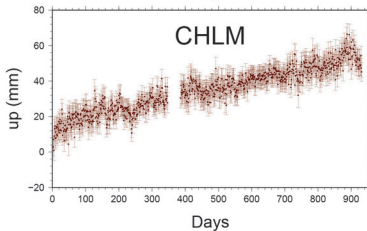
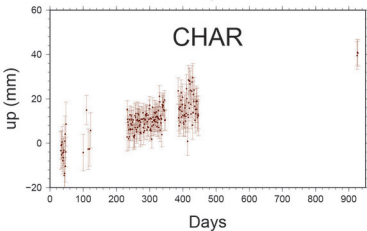
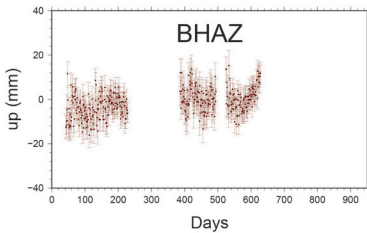
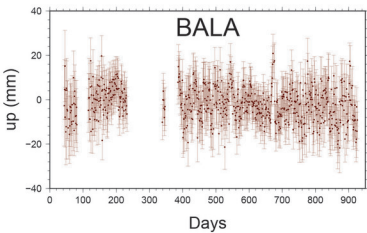
(b)

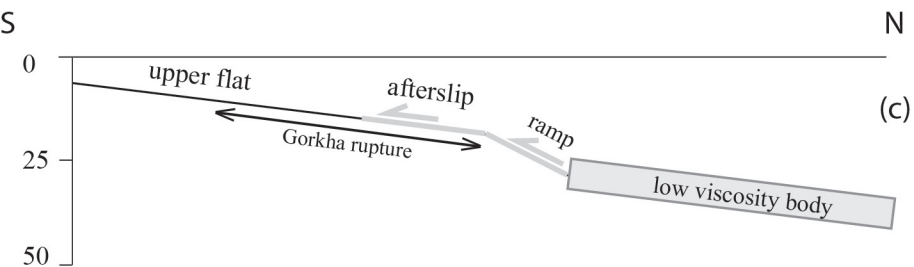
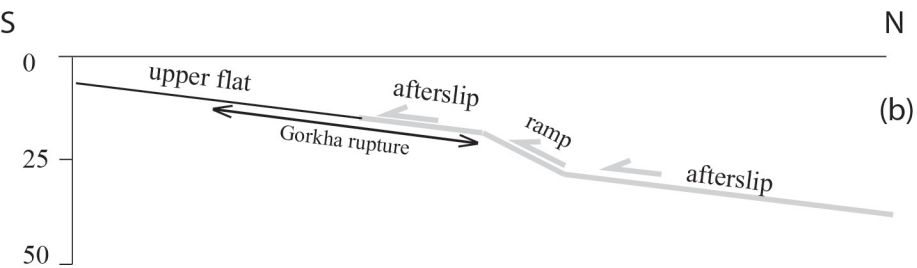
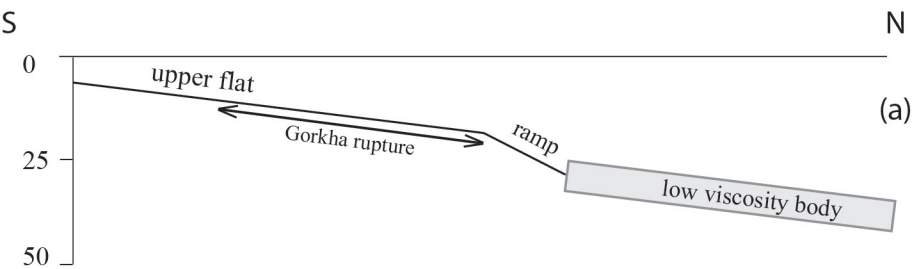




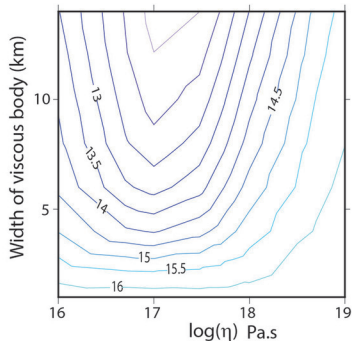




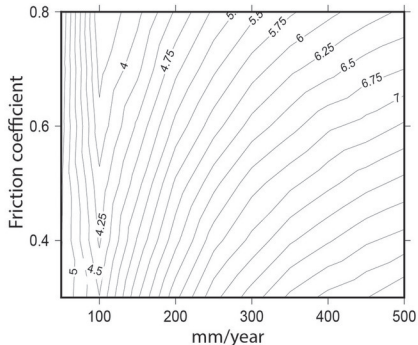




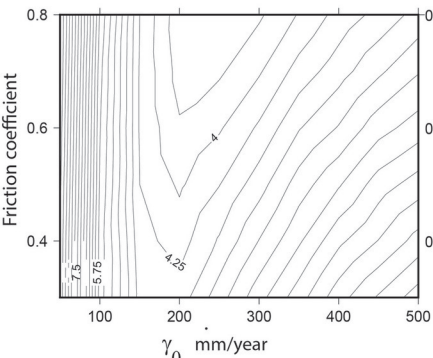
Viscous relaxation (a)



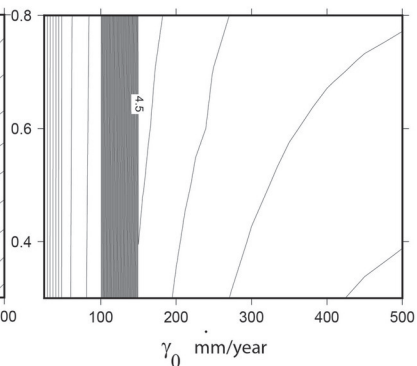
Afterslip 10 MPA (b)



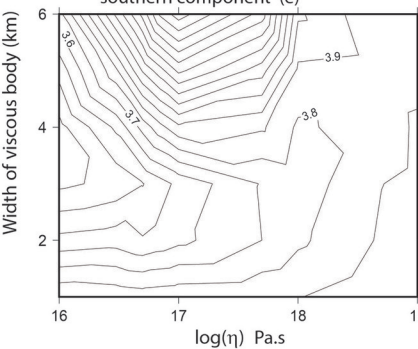
Afterslip 20 MPA southern component (c)



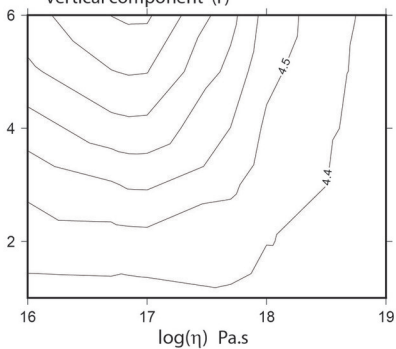
Afterslip 20 MPA vertical component (d)

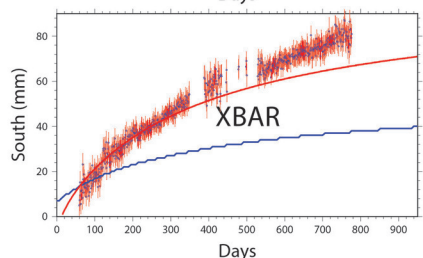
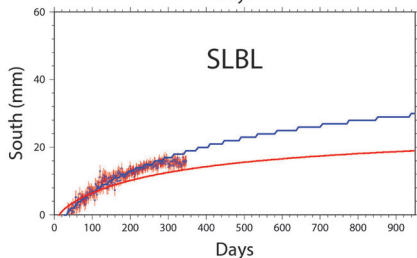
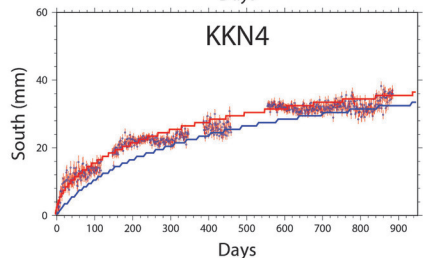
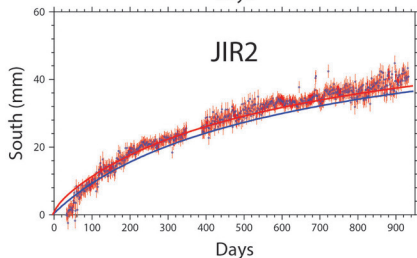
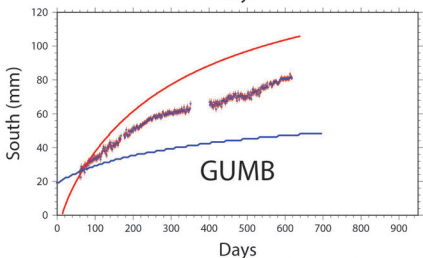
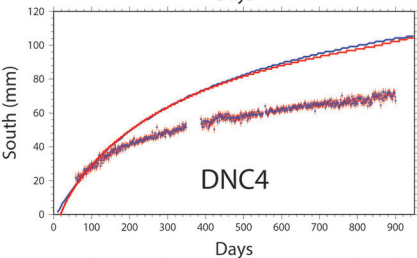
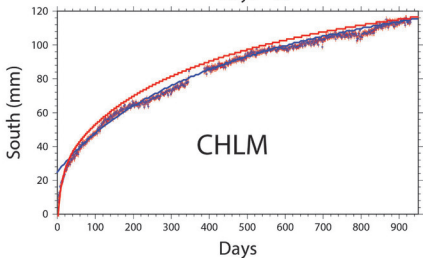
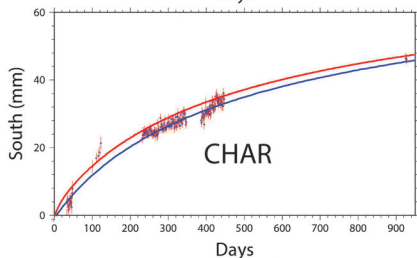
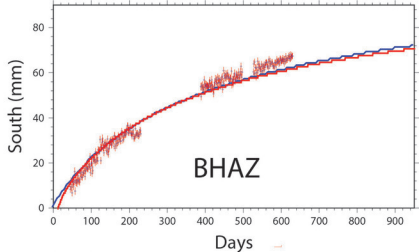
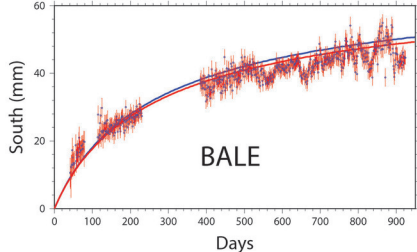


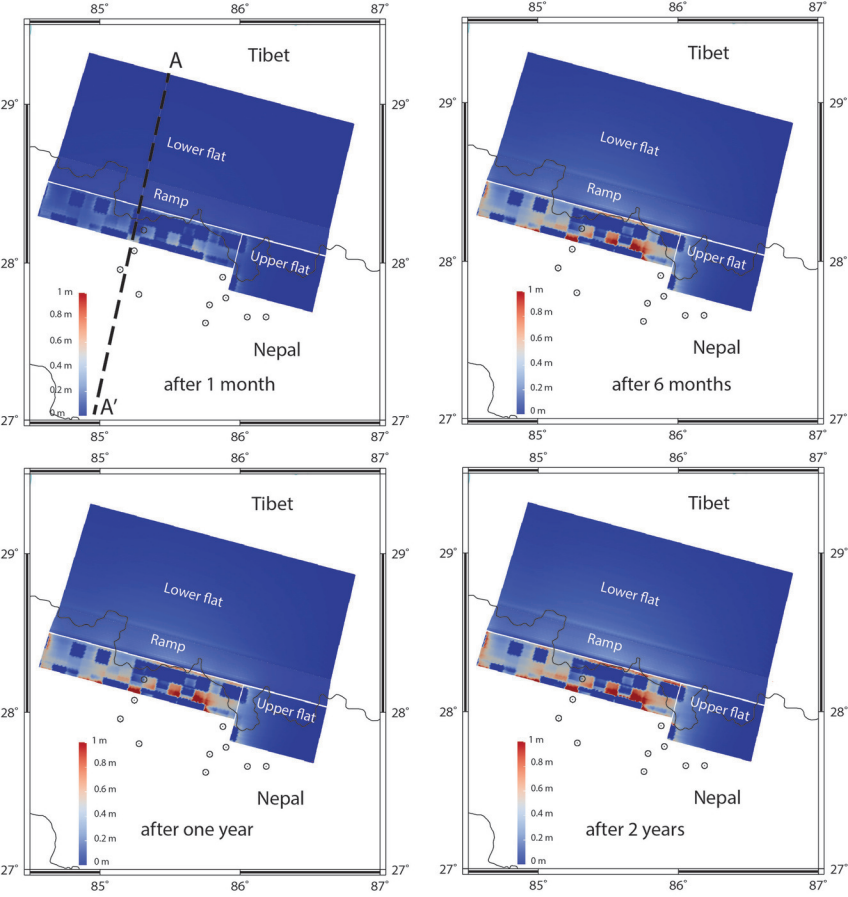
Afterslip and viscous relaxation southern component (e)



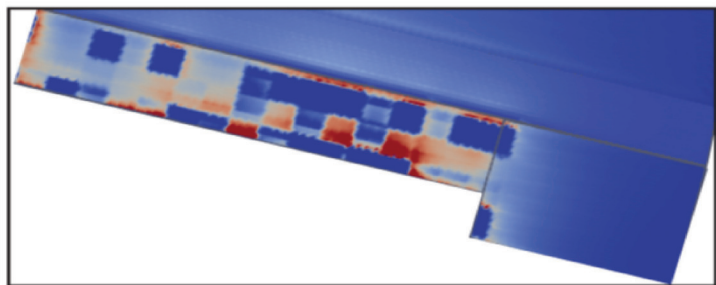
Afterslip and viscous relaxation vertical component (f)



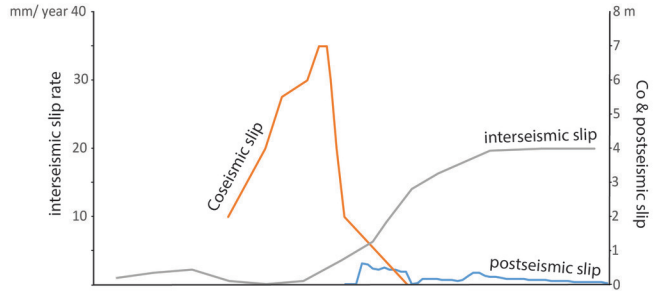




(a)



(b)



50 km

