Quaternary rupture behavior of the Karakoram Fault and its relation to the dynamics of the continental lithosphere, NW Himalaya–western Tibet

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Abstract: The Karakoram Fault is a major Tibet-bounding strike-slip system that partitions strain between the compressional regime of the NW Himalaya and the translational and extensional fault systems of Tibet[Searle, et al., 2011]. Although geodetic observations suggest that the fault is currently locked[Wright, et al., 2004], high millennial slip rate estimates infer a dominant role in continental deformation models[Loveless and Meade, 2011].

We examine all Quaternary data available for the Karakoram Fault and attempt to explain the temporal and spatial variability of fault slip rate. We show that Karakoram fault slip rate has been modulated by transient seismicity triggered by the activity associated with subduction of the Indian plate beneath Tibet.

Our model has implications for the understanding of stress transfer between large fault systems and their interaction with lithosphere deformation. We suggest that whilst the long-term deformation of Tibet may be modelled as partially viscous medium, the slip rates of major faults may vary by one order of magnitude during the Quaternary. Our analysis may resolve the frequently observed discrepancy between millennial and decadal records of fault slip rates.

15 **Abstract**

16 The Karakoram Fault is a major strike-slip system that partitions strain between the
17 compressional regime of the NW Himalaya and the translational and extensional fault
18 systems of Western Tibet. Although seismic and geodetic observations suggest that the
19 fault is currently locked, high millennial slip rate infer a dominant role in the deformation
20 of Western Tibet. We examine all Quaternary data available for the Karakoram Fault and
21 attempt to explain the temporal and spatial variability of fault slip rate. We show that
22 Karakoram fault stress level could be modulated by Coulomb Stress changes associated
23 with varying seismicity on the subducting Indian plate beneath Western Tibet. Our model
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26 deformation of Tibet may be modelled as partially viscous medium, the slip rates of
27 major faults may vary by one order of magnitude during the Quaternary. Our analysis
28 may resolve the frequently observed discrepancy between millennial and decadal records
29 of fault slip rates.

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32 Introduction

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34 Models that define how continents actively deform continue to polarise the Earth
35 Science community between two end member views (Thatcher, 2009). At one end of the
36 spectrum are those that argue deformation must be distributed throughout the continental
37 lithosphere e.g. (England and Houseman, 1986; England and Molnar, 1990; Houseman
38 and England, 1986b), which implies that continents can be modelled as a visco-elastic
39 continuum with faults reflecting the near-surface expression of deformation which is
40 distributed at depth. In this context, mantle or lithospheric flow may contribute or control
41 accumulation of stress in the upper crust (Houseman and England, 1986a). The
42 hypothesis of distributed deformation contrasts markedly with the opposing view that
43 deformation is purely elastic and localised along major lithospheric-scale faults which
44 separate crustal blocks e.g. (Avouac and Tapponnier, 1993; Tapponier et al., 2001;
45 Tapponnier and Molnar, 1976; Tapponnier et al., 1982). In this model, deformation
46 between block-bounding faults is limited, with the outcome that a small number of large
47 faults must accommodate most of the stress generated by the relative motions plate
48 motion. Other authors have attempted to reconcile these contrasting views by modelling
49 deformation across a collage of microplates e.g. (Loveless and Meade, 2011; Meade and
50 Hager, 2005; Thatcher, 2007).

51 Regardless of the model for continental deformation, a central tenet of each is to
52 ascribe a role and significance to major faults within an actively deforming zone. Much
53 of this debate has evolved through contrasting studies of how deformation is
54 accommodated across the Himalaya-Tibet orogen. By viewing Tibet as a rigid block, the
55 right-lateral Karakoram and left-lateral Altyn-Tagh faults (Figure 1a) are viewed as
56 largely responsible for the lateral extrusion of Tibet to the east and hence must have large

offsets and fast slip-rates. Conversely, these faults are seen as playing a minor role in the continuum model, which predicts low slip-rates, small offsets and limited continental extrusion. These contrasting models remain polarised in part due to the apparent disparity between modelled millennial and decadal slip-rates for these faults. This may be explained by the fact that none of the current models explore the influence of short- or long-term variability in slip rate for an individual fault, both of which are investigated here.

For the Altyn-Tagh Fault (ATF), millennial slip rates (SR) have previously been reported as a factor of three greater than inter-seismic geodetic estimates (Meriaux et al., 2005; Mériaux et al., 2004). However, after a careful reassessment of river bed mapping and data reanalysis, recent work along the central ATF (Cowgill et al., 2009; Gold et al., 2009; Gold and Cowgill, 2011) appears to reconcile long and short term estimates by determining a slip of 11 ± 2 mm/yr since 4-6 kyr, in agreement with geodetic, paleoseismic, and geologic measurements. However, for the Karakoram Fault (KF) slip-rate datasets are more controversial, due in part to the exposure of the fault zone and the numerous studies utilising differing techniques. Unlike the Altyn Tagh in northern Tibet, the Karakoram displays extreme topographic differences and offset of lithologic units spanning the Miocene to Pleistocene (Murphy et al., 2010; Murphy et al., 2000; Murphy et al., 2002; Searle et al., 2010; Searle et al., 2011; Searle and Phillips, 2007; Streule et al., 2009; Zhang et al., 2011). Consequently, published slip rates that range from 0 to 30 mm/yr (Figure 1b) have been derived from U-Pb (Phillips et al., 2004; Searle et al., 2010; Streule et al., 2009; Valli et al., 2008; Wang et al., 2013; Wang et al., 2012), ^{39}Ar - ^{40}Ar (Searle and Phillips, 2007; Searle et al., 1998; Valli et al., 2007) and ^{10}Be dating techniques along mid- to southern- sections of the fault (Brown et al., 2002; Chevalier, 2006; Chevalier et al., 2005a; Chevalier et al., 2012; Chevalier et al., 2004) in addition to InSAR swaths (Wang and Wright, 2012; Wright et al., 2004) and a limited GPS velocity

field (Banerjee and Burgmann, 2002; Jade et al., 2004; Jade et al., 2011; Zhang et al., 2004). The diversity of slip rates estimates may be the consequence of various geophysical processes involving various time-scales; interseismic motion might be more visible for techniques sampling at greater depth (GPS or InSAR; Figure 1b).

Following re-analysis of published datasets (Table 1) that define the Quaternary to recent slip rate history of the Karakoram Fault (Brown et al., 2002; Brown et al., 2003; Chevalier, 2006; Chevalier et al., 2005a; Chevalier et al., 2004), we investigate the seismic behavior of the KF fault since the Middle Pleistocene, its present lack of seismicity and the apparent absence of Pleistocene offset toward its northern termination. We propose that the kinematic history of the Karakoram Fault is controlled largely by the interplay between Indian plate motion and the associated seismicity along its subducting plane in the NW Himalaya. Using this model, we are able to reconcile the spatial and temporal variability in published slip-rates and offsets along the length of the Karakoram Fault and are subsequently able to better define the role and significance of the fault in models of continental deformation.

The Quaternary Rupture History of the Karakoram Fault

Regardless of the deformation model to which one may subscribe the total amount of strain generated by the collision between India and Eurasia must be accommodated over various temporal and spatial scales. According to recent continental geodetic observations (DeMets et al., 2010), the collisional motion between India and Eurasia (33 mm/yr; orientated at N16°) is perpendicular to the strike of the collision zone (29 mm/yr; N45°). As the Karakoram Fault is one of the longest strike slip faults in western Tibet, the

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106 remaining lateral vector of 14 mm/yr, orientated at N135°, must be at least partially
107 accommodated along this structure during episodes of seismicity. Nevertheless, evidence
108 from InSAR analysis(Wang and Wright, 2012; Wright et al., 2004), coupled with
109 geomorphic evidence and a lack of significant seismicity along the fault (Figure 1.a), has
110 led some to suggest that segments of the Karakoram fault are no longer active
111 e.g.(Robinson, 2009b).

112 Utilizing the GPS velocity field available for the Tibetan plateau(Zhang et al.,
113 2004) we determine that the present large scale strain-rate field for the Karakoram Fault
114 is dominated by strain generated by India/Eurasia motion across the collision zone,
115 providing a shear strain rate of $\sim 10^{-7}$ and a compressional strain rate limited to $\sim 10^{-8}$,
116 oriented toward N45° (i.e. placing the Karakoram Fault currently under compression).
117 The orientation of maximal strain rate is aligned with the SKS shear wave splitting
118 orientation ($\sim$ N60°)(Herquel and Tapponnier, 2005; Jade et al., 2004), roughly
119 perpendicular to the fault. This may imply that crust and lithosphere are decoupled and/or
120 the mantle is infinitely strained (Chamberlain et al., submitted; Houlié et al., submitted;
121 Houlié and Stern, 2012; Molnar, 1999). Interestingly, orientation of the fast axis of shear
122 wave splitting is similar to the principal stress orientation (σ_H) inferred from
123 microseismicity in this region (Zhu and Shi, 2011), which supports the hypothesis of
124 decoupling in the lithosphere. Whilst GPS data for this area is available, the network
125 distribution is insufficient to compute a high-resolution strain-rate map of western Tibet.

126 Previous studies of the Karakoram Fault suggest that estimates of Quaternary slip
127 rate imply secular variations in fault motion(Chevalier et al., 2005a). This hypothesis is
128 based upon the measurement of *in situ* cosmogenic isotope production within quartz
129 cobbles taken from Quaternary landform features offset by the Karakoram Fault. By
130 deriving both a surface age and a displacement, Chevalier et al. (2005,2012) conclude

131 that the millennial slip rate of the Karakoram Fault is an order of magnitude greater than
132 that determined by InSAR analysis(Wright et al., 2004). This may suggest that slip along
133 the fault may have changed markedly in recent times. However, the Chevalier et al.
134 (2005) study was contested on the basis that exposure ages were strongly influenced by
135 postdepositional processes and hence, for a scattered dataset, only the oldest boulder ages
136 can be used to conservatively assess surface age(Brown et al., 2005).

137 To obtain a slip rate (*SR*), commonly the average age for each surface is divided
138 by the corresponding fault offset to obtain a local fault slip rate. Completing this task for
139 the various age/offset datasets allows us to resolve varying slip rates for different
140 segments of a fault. Definition of each fault segment used here (central, south-central and
141 south, Figures 1 and Table 1) is the same as adopted in published datasets chevalier
142 (Brown, 2002; Brown et al., 2005; Chevalier, 2006; Chevalier et al., 2005b; Chevalier et
143 al., 2004). For the Karakoram fault we compute a *SR* for each fault segment where the
144 oldest age is adopted for each segment. This allows us to check the precision of the age
145 computation if the data sampled are close in both time and space.

146 By independently computing the slip rate for different segments of the Karakoram
147 Fault (Figure 1), we find that slip rates are uniform in time (as suggested by (Chevalier et
148 al., 2012) for the entire KF) and space, with up to 3 mm/yr of difference (Figure 2a).
149 However, the *SR* time-series is not exempt from artificial variation. Indeed, older slip
150 rates depend on the relative age of the available terraces in a same area. Longer time gaps
151 will generate larger slip rates because each offset represents the accumulated seismic
152 deformation (non-linear of time) over the measured period.

153 Below, we define a new measure termed „Instantaneous Slip Rate’ which delimits
154 slip between observational/sampling periods and provides a history of millennial slip

variability unlike the time-averaged slip rates discussed above and provides an insight into the possible dynamics of the NW Himalaya-West Tibetan lithosphere.

Defining 'Instantaneous Slip Rates' (ISR) from Geologic or Geomorphic Studies

Slip rates determined by geological or surface dating techniques are essentially a long-term time-integrated averaged rate, i.e. a surface age and offset are determined and $SR = \frac{age}{\sum d_i}$. Conversely, geodetic techniques define slip rates that are 'time-stamped' at the middle of the data collection period. Geodetic slip rates could be compared to very short-term slip rates provided by e.g. cosmogenic exposure dating. However, geodetic slip rates cannot be compared directly to slip estimates derived from Pleistocene or older surface ages because the latter is the ratio of all cumulative offsets accrued since the dated surface was formed. Below, we explore a method to determine the variability of fault slip rate between two periods of interest and interrogate constraints on the relative timing of past events.

Let d be the offset, the sum of all the offsets accumulated over a period of time delimited by times t_1 and t_2 :

$$d = \int_{t_1}^{t_2} SR dt = \sum_{i=1}^n (SR_i \times t_i) \quad \text{Eq. (1)}$$

Since d is a cumulative value it does not reflect the variability of displacement through time. SR is a measure of the seismicity that actually occurred since an age time. For a geomorphic surface offset (d_{cosmo}) of known age derived from e.g. cosmogenic exposure dating ($\text{age}_{\text{cosmo}}$), then:

$$d_{cosmo} = SR \cdot age_{cosmo} \quad \text{Eq. (2)}$$

For Equation 2, SR cannot be compared with geodetic techniques because it is derived by measuring a cumulative surface offset and a surface age, which predates the absolute timing of an initial rupture and thus provides a *minimum* value of slip. SR_{min} and d_{cosmo} are not time-stamped because age_{cosmo} defines a stabilization age for the offset surface. Assuming the age distribution to be scattered on a surface, age_{cosmo} would be the oldest age on that surface.

Instead of defining the slip rate SR by using the age of the sample and accumulated offset we propose a method to time-stamp each sample. We thus move away from the representations of slip rate described by Equations 1 and 2, and instead define an 'Instantaneous Slip Rate', ISR , which is computed by using the slip-rate defined over a period of time delimited by time t_1 and t_2 , e.g.:

$$ISR_{2-1} = \frac{d_{cosmo2} - d_{cosmo1}}{age_2 - age_1} \quad \text{Eq. (3)}$$

Where ISR fractional uncertainty is defined by:

$$\frac{\partial ISR_{2-1}}{|ISR_{2-1}|} = \frac{\partial age_1}{|age_1|} + \frac{\partial age_2}{|age_2|} + \frac{\partial d_{cosmo1}}{|d_{cosmo1}|} + \frac{\partial d_{cosmo2}}{|d_{cosmo2}|} \quad \text{Eq. (4)}$$

Based on the published KF cosmogenic dataset (Brown, 2002; Chevalier et al., 2005, Chevalier et al., 2012), which includes all *known* field uncertainties and relates to the instantaneous behavior of the fault, the calculation of ISR uncertainties vary from 51% to 150%.

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200 Importantly, *ISR* tells us that the Karakoram Fault slip rate behavior changed
201 dramatically at ~50 kyr, displaying a marked decrease in seismic activity from 5 ± 1
202 mm/yr to 0 ± 2 mm/yr (Figure 2). The magnitude in this change of slip rate cannot be
203 explained by the effect of glacial unloading (Hetzel and Hampel, 2005) associated with
204 the last period of deglaciation in the area (Owen et al., 2008).

205 Given the current low slip rate it is necessary to consider where strain may be
206 accommodated across the region. The pattern of seismicity in western Tibet (Figure 1)
207 does not suggest that any major fault system is currently offloading the Karakoram Fault.
208 Below, we explore a mechanism that may explain the suggested decrease in seismicity
209 since 50Kyr and discuss stress accumulation across the region.

210

211 **Stress level history along the Karakoram Fault: influence of the Himalayan frontal**
212 **thrust system (HTF)**

213

214 In order to generate an earthquake along a strike-slip fault, three conditions are
215 necessary: (1) the fault needs to be stress-loaded, (2) the principal stress axes σ should be
216 of different amplitudes ($\sigma_1 > \sigma_2 > \sigma_3$, where σ_1 and σ_2 are the principal components of
217 horizontal stress and σ_3 the vertical stress), and (3) the stress axes must be oriented
218 appropriately (i.e. σ_1 not parallel to strike). Since the stress axes orientations are not
219 known, we assume that the Karakoram Fault strain and stress axes (related to India-
220 Eurasia collision) are aligned, as suggested by our comparison of the GPS strain field,
221 the fast polarization of SKS seismic waves and the local stress principal axes (above).
222 This is expected, as diverging stress and strain axes would suggest the recent occurrence
223 of a large seismic event. In such a case, the seismicity level should be higher than it is at
224 present. The low level of seismicity observed along the Karakoram Fault suggests that the

accumulated stress must be distributed across the collision zone. If we assume that (1) the load of the fault has been sustained by a constant northward motion of India over the last 1 Myr, and (2) the Karakoram Fault accumulates only 30 to 50% of this stress generated by the continental collision in western Tibet, then the long-term slip-rate of Karakoram Fault would be 5 ± 3 mm/yr. At the present collision rate, the stress accumulated should be able to generate a seismic sequence containing at least one Mw8.0 (~2 meters of slip) every 1 kyr.

We know little about the stress accumulated along the Karakoram Fault, but as the strain rate field is dominated by shear it is reasonable to assume that the stress components are different. In order for the fault to slip what is required is a process that can (1) change the background stress field, (2) sustain stress axes of different amplitudes, at least temporarily, and (3) overcome the background stress field. We propose that such conditions are created following a significant earthquake or earthquake sequence occurring along the subducting Indian plate, south of the Karakoram Fault.

Below, we test whether a single major event along the Indo-Asian collision zone in the NW Himalaya may alter the stress level along the KF. In the Supplementary Materials we also explore the effect of an earthquake sequence of Mw8.0 events. For both cases we assume that the KF strain field can be deconvoluted into steady-state (regional long-term) and transient (local short-term) strain components:

$$\epsilon_{ij}^{KF}(t) = \dot{\epsilon}_{ij} \times \Delta t - \sum_{i=1}^n \Delta \epsilon_{ij}^{HFT} \times \delta(t_i) \quad \text{Eq. (5)}$$

The first term corresponds to the shortening between India and Eurasia since the beginning of the seismic cycle (or since the lowest strain value). The second term represents the seismic strain change for a single earthquake or a sequence of n events along the subducting plane (denoted as HFT in Eq.5). Both terms should balance on the

very long term: at the end of seismic cycle (when most of the stress is released after a major thrust event), $e_{ij}^{KF}(t)$ is minimal. *A-priori* we can assume that over a seismic cycle, the stress is entirely released by the seismicity along the subducting plane. This would imply that the magnitude of the transferred stress is constant along the Karakoram Fault.

It has been shown that for large events ($M > 8$), the coseismic (Ghimire et al., 2008; Lei et al., 2011; Uchida et al., 2009) and postseismic (Uchida et al., 2009) Coulomb stress changes may effect crustal stress levels thousands of kilometers away from the seismic source.

For a single earthquake, we calculate the Coulomb stress changes in a purely elastic medium (Figure 3) and the strain fields generated by various sized earthquakes rupturing along the collision zone in the NW Himalaya (Table S1). In order for a subduction-related earthquake to pre-condition the Karakoram Fault for a future seismic event, the temporary stress axis rotation needs to be of the order $> 20^\circ$ counter-clockwise. In order to define the length and mean slip of characteristic events we utilize a scaling law (Wells and Coppersmith, 1994) for each characteristic event (Table S1). We assume the dip angle along the subducting plane was equal to 16° for all events.

Figure 3a shows the stress changes in the elastic surrounding medium induced along Karakoram Fault by a seismic event ($M_w \sim 8.0$) rupturing a segment of the NW Himalaya subduction zone. *A-priori*, we would expect any seismic event to unload the stress along the Karakoram Fault and to inhibit seismicity. We find that if this assumption is confirmed, in limited areas, the shear and normal stress changes are respectively increased and decreased, which encourages triggering or promotes a future earthquake along the KF (Figure 3a, 3b). We also confirm that a strain of 10^{-7} may be imposed along the KF (Figure 3b) and that, over a short time window, would allow the triggering of an large mainshock along KF.

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274 In order to test whether the strain accumulated along KF could be sustained over a
275 long sequence of seismic events, we compute the stress change associated with a spatially
276 randomized distribution of seismicity along the subduction zone, we show that a small
277 rupture gap along the thrust front can preserve stress accumulated along the KF and that
278 at the edges of the rupture zone, the transient strain field $\Delta\epsilon_{ij}$ is misaligned with the
279 strain-rate field $\dot{\epsilon}_{ij}$ which, as stated above, is a requirement for an earthquake to happen
280 along the Karakoram Fault.

281 The location along the Karakoram Fault at which stress changes from negative
282 (inhibiting slip) to positive (promoting slip) is a function of the location of the seismic
283 event along the collision zone: the strain transition will occur toward the southern end of
284 the Karakoram Fault if the subduction-related earthquake moves to the southeast.
285 Regardless of the location of the subduction-related seismic event, under the present
286 boundary conditions, the northern segment of the Karakoram Fault is always inhibited
287 with regard seismic loading and may explain the observation that no Quaternary offsets
288 are evident on the northern section of the KF(Robinson, 2009a; Robinson, 2009b). If the
289 subduction-related rupture event is located further south along the collision zone, then the
290 lateral extent of inhibited slip increases toward the southern end of the fault.

291

292

Conclusions

We define the Quaternary rupture behaviour of the Karakoram Fault by derivation of the 'Instantaneous Slip Rate' history. We suggest that the KF likely experiences high variations in seismic activity over millennial (or shorter) time scales and that it is in a period of quiescence. We demonstrate that the KF rupture history may be modulated by seismic activity along the subducting Indian plate to the southwest. The relative position of the KF and the subducting plate results in the northern segment of the Karakoram Fault remaining inhibited to dextral slip, whilst slip is promoted toward the southern segment of the fault. This may explain why such slip variability is observed along the length of the fault and why the northern termination lacks evidence of Quaternary offset. We suggest that the structural features of western Tibet need not be linked to the deep lithosphere as proposed for the dynamics of southern Tibet (Copley et al., 2011) and that the level of seismicity is mostly due to the adjustment of stress across large scale fault systems, the lateral relative plate motions being mostly accommodated along KF. We therefore suggest that KF is not deeply rooted in the mantle lithosphere as suggested for other large continental strike slip faults (Polet and Kanamori, 2002).

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Figure 1a: Tectonic setting of the Karakoram Fault, western Tibet. Seismicity derived from Centroid Moment Tensor(Dziewonski et al., 1981) (all earthquakes available are plotted) and ANSS catalogues ($M>3$ since May, 21, 1962) demonstrate a very low level of stress accumulation in this region. KF - Karakoram Fault; ATF – Altyn Tagh Fault. Locations 1-4 represent the cosmogenic exposure dating sites of Chevalier et al. (2004, 2005, 2006) [1) and 2) South site, 3) South-central site] and Brown et al. (2004) [4) Central site in Ladakh]. See text for discussion.

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Figure 1b: Comparison between slip rates derived from Quaternary and geodetic studies for the Karakoram Fault (1σ error bars). We plot each solution for its appropriate depth. This Figure demonstrates that the previous slip-rate estimates (Chevalier, 2006; Chevalier et al., 2005a; Chevalier et al., 2004) exhibit sufficient dispersion such that they overlap with slip estimates derived by late Quaternary (Brown et al., 2002) or geodetic (Wright et al., 2004) studies. The plotted error bars for all studies are compatible for those derived from other well-studied faults.

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Figure 2a: Slip-rate (SR) estimates along the southern Karakoram Fault for the last 200 kyr for individual sites. SR suggests that different KF segments are expressing various levels of seismic activity and that stress was accumulated in areas between south-central and south segments over the period 50-100kyr. Central segment shows a constant decrease of slip rates since 20kyr.

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Figure 2b: *ISR* Time Series for the last 200 kyr for the South-central, South and Central segments of the southern Karakoram fault. All KF segments experienced a decrease of

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523 seismicity since at least 10kyr with a peak of seismic activity occurring between 10kyr
524 (central segment) and 100kyr (south segment). We suggest differential strain
525 accumulated between segments over time and that stress was transferred between
526 segments over large time periods.

527

528 **Figure 3a:** Stress changes induced by a M8.0 along the Himalayan Front Thrust (HTF).
529 The KF is indicated by a wide blue line. In this model, the seismic rupture intersect with
530 the surface. The values presented on this Figure have been computed using the Coulomb
531 3.3 package(Toda and Stein, 2002) and interpolated using a spline interpolation Generic
532 Mapping tool function surface (with a spacing of 100 km)(Wessel and Smith, 1991). See
533 Figure S1 of Supplementary Materials to see the strain pattern associated with this event.

534

535 **Figure 3b:** Cross-section of stress field changes along KF (see Figure 3a for a map
536 view). We find that while the normal stress is increased and the shear stress is decreased
537 in some areas of KF, the opposite behavior can be made in some other areas. We suggest
538 these locations are the possible starting point for triggered events along KF.

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			Age		Offse			ISR unc.		
			unc.		t unc.			(%)		
			(1σ,	Offset	(m)	SR				
	Area	Age (ky)	ky)	(m)		(m/y)	Time (ky)	ISR (m/y)		Segment
			NA		0.01					
	Central	0.010		0?		0	0	0.0000		Ladakh
			2		0.1				71	
	Central	3.022		2		0.0007	1.516	0.0028		Ladakh
			7		5				56	
	Central	16.050		40		0.0025	9.536	0.0024		Ladakh
			7		15					
	South	13.449		80		0.0059	NA	NA		La Zhi Tang
			4		15					
	South	14.190		80		0.0056	13.820	0.0000		La Zhi Tang
			11		15					
	South	16.334		80		0.0049	15.262	0.0000		La Zhi Tang
			17		18				63	
	South	35.049		118		0.0034	25.691	0.0020		Menshi
			9		10				22	
	South	51.118		220		0.0043	43.084	0.0063		La Zhi Tang
			26		30				33	
	South	97.468		430		0.0044	74.293	0.0045		Menshi
			50		30				50	
	South	116.203		430		0.0037	106.836	0.0000		Menshi
	South		9		10					
	Central	35.599		220		0.0067	NA	NA		Manikala
	South	139.376	25	1520	50	0.0112	87.488	0.0128	21	Manikala

	Central							
	South	69	50				37	
	Central	207.032	1520	0.0080	173.204	0.0015		Manikala

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544 **Table 1:** Ages and offsets published in the literature (Brown et al., 2002; Chevalier et al.,
545 2005a; Chevalier et al., 2012), SR and ISR presented in this study. ISR values for the
546 ages 13449 yr and 35599 could not be computed because of lack of the reference value.
547 We adopt an arbitrary value of 5% for the 1σ uncertainty of offsets. For the La Zhi Tang
548 terraces (south KF) where various ages are available for a same offset value, we use the
549 oldest age to compute ISR between $\sim 16\text{kyr}$ and $\sim 25\text{kyr}$.

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Figure 1a
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Figure 1b
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Figure 2a
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Figure 2b
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Figure3a
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Figure 3b

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Quaternary Rupture Behavior of the Karakoram Fault and its relation to the dynamics of the continental lithosphere, NW Himalaya-West Tibet

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SUPPORTING MATERIALS

A. Randomized computation of the Coulomb stress change along Karakoram fault.

We use Coulomb3.3[Toda and Stein, 2002] to compute the shear, normal and Coulomb stress changes along the KF generated by a sequence of earthquakes occurring along the subducting Indian plate. We simulate the behaviour of the two faults by using two discontinuities separated by 300 km (along the Y axis presented in Figure 3). We randomly place earthquakes of constant magnitude (Mw8.0 for a constant slip of 11 meters on a fault plane of 100 km x 12 km) along the subducting plate. We neglect any earthquake of smaller magnitude. This assumption is supported by the observation of earthquake of limited size (Loma Prieta, Parkfield, San Simeon, Coalinga). However, as observed in the nature, we do not allow for two consecutive earthquakes to happen within 120 km (Figure S2).

We computed stress changes (Figure S3) for a sequence of earthquakes. We find that if the subduction zone is seismically active, the normal stress along the KF will be increasing while the shear stress will tend to decrease locally making them unlikely

25 candidates for future rupture planes. We then analysed whether the evolution of the stress
26 changes along the KF during the sequence. We suggest that for some locations, the shear
27 stress can be increased even for times that are late in the seismic sequence. We then
28 confirm the model presented for a single event (see main text) and for short-term
29 interaction between the two structures.

30 The second observation is that because the subduction zone stops at $X=-500$ km,
31 the stress field along the KF for $X<-600$ km is not affected by the subduction activity.
32 This implies that the triggering of an event is unlikely but also that the stress accumulated
33 in that section of KF can remain high for a long time.

41 **B. Figures and Tables.**

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44 **Figure S1.** Exy strain induced by a M8.0 along the subducting plate. We contoured a
45 selection of values ($\pm 10^{-7}$, $\pm 10^{-6}$, 0 , $\pm 10^{-5}$ and $\pm 2 \cdot 10^{-5}$ strain).

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50 **Figure S2.** Position of the ruptured areas for the seismic sequence. KF is symbolized by a
 51 blue line at $Y = 100$ km. The Himalyan trust front is indicated by the green line at $Y = -$
 52 200 km. The black lines indicated the projection of the fault planes with the surface.

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56 **Figure S3:** Coulomb, shear and normal stress changes associated with a seismic
 57 sequence. We find that even with distant seismicity the KF stress state is affected by a

58 seismic sequence along HTF. This suggests that whenever the subduction zone is active,
59 the Karakoram Fault would not be able to slide/slip.

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66 **Figure S4:** Same as Figure 3b for the long-term term randomized seismic sequence.

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69 **Figure S5:** Accumulated strain generated by long-term seismic activity along HTF.

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Mw	Slip Patch		Max. depth, km	Slip, m
	L, km	W, km		
7	48.97	15.48	10.07	1.55
7.25	68.78	18.62	12.10	2.18
7.5	96.60	22.38	14.55	3.07
7.75	135.67	26.91	17.50	4.31
8	190.54	32.35	21.04	6.06
8.25	267.60	38.90	25.29	8.51
8.5	375.83	46.77	30.41	11.96

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74 **Table S1:** Parameters for simulated earthquakes along the collisional zone in the NW
75 Himalaya. Slip, and source geometry parameters were computed. The magnitude of an
76 earthquake is function of both Length (L) and Width (W) of the ruptured fault
77 segment [*Wells and Coppersmith*, 1994]. We computed slip and source geometry
78 parameters for events that could affect the KF area.

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