1 **Fracture energies at the rupture nucleation points of large strike-slip earthquakes**
2 **on the Xianshuihe fault, southwestern China**

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10

11 **Abstract**

12 Earthquake cycles along a pure strike-slip fault were numerically simulated using
13 a rate- and state-dependent friction law to obtain the fracture energies at the
14 rupture nucleation points. In the model, deep aseismic slip is imposed on the fault,
15 which generates recurrent earthquakes in the shallower velocity-weakening friction
16 region. The fracture energy at the rupture nucleation point for each simulated
17 earthquake was calculated using the relation between shear stress and slip, which
18 indicates slip-weakening behavior. The simulation results show that the relation
19 between the fracture energy at the nucleation point and other source parameters is
20 consistent with a theoretical approach based on fracture mechanics, in that an
21 earthquake occurs when the energy release rate at the tip of the aseismic slip zone
22 first exceeds the fracture energy. Because the energy release rate is proportional to

the square of the amount of deep aseismic slip during the interseismic period, which can be estimated from the recurrence interval of earthquakes and the deep aseismic slip rate, the fracture energies for strike-slip earthquakes can be calculated. Using this result, we estimated the fracture energies at the nucleation points of large earthquakes on selected segments of the Xianshuihe fault, southwestern China. We find that the estimated fracture energies at the rupture nucleation points are generally smaller than the values of average fracture energy for developed ruptures as estimated in previous studies, suggesting that the fracture energy tends to increase with the rupture propagation distance.

Keywords: fracture energy, earthquake cycle, friction, strike slip, fault zone

1. Introduction

Fracture energy is an important parameter in earthquake mechanics, because it is the energy required to allow a rupture to develop and it is associated with the onset of rupture. The ratio of the fracture energy to the available elastic strain energy determines the rupture velocity (Andrews, 2005). The fracture energy can be more stably inferred than other source parameters such as the critical slip-weakening distance (Ide, 2002; Tinti et al., 2005; Abercrombie and Rice, 2005). In the slip-weakening model of friction (e.g., Ida, 1972; Andrews, 1976), the shear stress at a point of a fault decreases from a peak value τ_p to the dynamic frictional stress τ_d with ongoing slip, as illustrated in Fig. 1. The slip distance required to reach τ_d is the critical slip-weakening distance D_c , and the area enclosed between the slip-weakening curve and the dynamic friction stress is the seismological fracture energy $\mathcal{G}_c$.

The fracture energy $\mathcal{G}_c$ of earthquake faulting has been estimated using crack models (Rudnicki, 1980; Tse et al., 1985; Li, 1987) and is often considered to be a scale-independent material constant. However, in reality this is not the case. The fracture energies estimated from field observations are much larger than the values obtained from laboratory measurements (Rudnicki, 1980; Atkinson, 1984; Ohnaka, 2003). For real earthquakes, the measured stress–slip relation is complicated and uncertain because of difficulty in reproducing high-frequency seismic waves. Guatteri and Spudich (2000) showed that waveform inversion of synthetic strong-motion-data set cannot uniquely resolve both strength excess, $\tau_p - \tau_0$ and slip-weakening

64 distance, D_c , because of the trade-off between them, but they found that the
 65 fracture energy can be relatively stably estimated. In addition, possible complicated
 66 friction mechanisms also cause the stress evolution to be more complicated
 67 compared to the ‘classic’ slip-weakening law illustrated in Fig. 1 (Tinti et al., 2005).
 68 Fracture energy also refers to an integrated mesoscopic source parameter
 69 incorporating surface energy, energy loss due to heat, off-fault yielding,
 70 micro-cracking and other dissipative processes around the crack tip (Mai et al.,
 71 2006).

72 Recent modeling and observational studies have demonstrated the dependence
 73 of $\mathcal{G}_c$ on other source parameters. Guatteri et al. (2004) discussed an empirical
 74 linear equation for $\mathcal{G}_c$ in terms of the stress intensity factor. Tinti et al. (2005)
 75 imaged the dynamic traction evolution for several earthquakes using different
 76 kinematic models, and concluded that fracture energy is strongly correlated with the
 77 corresponding slip distribution, primarily caused by different values of D_c and by
 78 variations in stress drop. They also discovered that normal, thrust and strike-slip
 79 earthquakes display the same scaling of fracture energy with seismic moment, in
 80 accordance with the scaling relation proposed by Rice et al. (2005). Abercrombie and
 81 Rice (2005) calculated $\mathcal{G}_c$ for a few recent earthquakes and concluded that $\mathcal{G}_c$
 82 increases with slip. They showed that $\mathcal{G}_c$ is not a constitutive property of a location
 83 on a fault, but rather depends on the dynamic process as the fracture arrives at a
 84 particular point and imposes a limit on slip velocity, also known as velocity
 85 toughening. Mai et al. (2006) calculated a set of spontaneous dynamic rupture

models of earthquakes to estimate the distributions of $\mathcal{G}_c$ on fault planes, and concluded that fault-averaged and maximum $\mathcal{G}_c$ increase with increasing magnitude and that $\mathcal{G}_c$ increases with stress drop and distance from each point to the hypocenter. Kato (2012) simulated earthquake cycles in a subduction zone and demonstrated that $\mathcal{G}_c$ at the rupture nucleation point is proportional to the square of the amount of slip in the deep aseismic zone during the preceding interseismic period; This finding is consistent with the view of that $\mathcal{G}_c$ can be estimated from the recurrence interval of earthquakes and the relative plate velocity, and that fracture energy tends to increase with earthquake magnitude.

In the present study, earthquake fracture energies at rupture nucleation points are estimated from earthquake cycle simulations along a pure strike-slip fault computed using a rate- and state-dependent friction law. To investigate the conditions for initiation of earthquake rupture, $\mathcal{G}_c$ at the rupture nucleation point is an important parameter. In estimating the fracture energy at this particular point our aim is to extend the relation between fracture energy and slip for interseismic periods in deeper portions of the fault, as reported by Kato (2012). We attempt to use this relation to estimate fracture energies for real strike-slip earthquakes on the Xianshuihe fault, southwestern China, for which cycles of large ($M \geq 7$) earthquakes have been estimated using historical and geological data (Allen et al., 1991; Wen et al., 2008). Finally, we compare the estimated $\mathcal{G}_c$ values with other estimates obtained in previous studies. The remainder of the paper is organized as follows. We derive theoretical relations based on fracture mechanics and our simulation method.

We present simulation results, and **estimate** the fracture energies at the rupture nucleation points of large earthquakes on selected segments of the Xianshuihe fault. **We further discuss the uncertainties in our method of estimating fracture energy, and conclude with a summary of our findings.**

2. Theory

We idealize a strike-slip fault as a shear crack in a two-dimensional elastic half-space, in which the shallower seismogenic portion of a fault is locked, as shown in Fig. 2a. The displacement in the deep area is imposed by large-scale stable sliding at a velocity V_s . In this case, the distributions of slip and shear stress on the fault are idealized as shown in Fig. 2b.

According to Kato (2012), the accumulated aseismic slip before a large earthquake is nearly equal to $V_s T_r$, where T_r is the recurrence interval of large earthquakes in the shallow seismogenic portion. The shear stress is concentrated at the edge of the locked zone, point T in Fig. 2, and can be expressed using the stress intensity factor K (Broberg, 1999), which is expected to be proportional to the slip occurring within the deeper aseismic zone:

$$K = f_s(G, z_{se}, z_{cr})V_s T_r, \quad (1)$$

where f_s is a function of the rigidity G , the **width z_{se}** of the seismogenic zone, and the **width z_{cr}** of the transitional aseismic slip zone, as shown in Fig. 2. **Note that f_s will be obtained through numerical simulations in the present study.** The energy release rate $\mathcal{G}$ at the tip of the aseismic slip zone is given by:

$$\mathcal{G} = \frac{1}{2G} K^2, \quad (2)$$

for the antiplane shear case (Broberg, 1999). Earthquake rupture may be expected to occur when the energy release rate $\mathcal{G}$ equals the fracture energy $\mathcal{G}_c$ at the rupture nucleation point:

$$\mathcal{G}_c = \frac{1}{2G} f_s^2 V_s^2 T_r^2. \quad (3)$$

This equation suggests that the fracture energy can be estimated from the stable sliding velocity at depth and the recurrence interval of large earthquakes provided that f_s is known (Kato, 2012).

It is worth noting that equation 1 is valid only when the process zone width, in which aseismic sliding occurs within the seismogenic zone, is sufficiently small compared to the locked zone width, due to the small-scale yielding condition (Broberg, 1999).

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2.1. Simulation method

We conducted numerical simulations of earthquakes for a pure strike-slip using a two-dimensional model of a uniform elastic half-space (Fig. 3). The fault at depths shallower than 70 km is divided into a number of cells. The shear stress τ_i at the center of the i th cell is given by:

$$\tau_i = \Sigma K_{ij} (V_s t - u_j) - \frac{G}{2\beta} \frac{du_i}{dt}, \quad (4)$$

where u_j is the amount of slip at the j th cell, $G = 30$ GPa, and the S-wave velocity β is 3.27 km/s. All material parameters are thus depth-independent. K_{ij} is the shear stress at the center of the i th cell caused by unit uniform slip at the j th cell obtained from dislocation theory (e.g., Hirth and Lothe, 1982). The second term on the

right-hand side of equation 4 represents radiation damping for the approximate calculation during seismic slip. Deep stable sliding at a rate $V_s = 0.015$ m/yr is assumed to occur at the fault at depths greater than 70 km, and the frictional stress τ at shallower depths is assumed to obey the composite rate- and state-dependent friction law (Kato and Tullis, 2003):

$$\begin{aligned} \tau &= \mu \sigma_n^{eff}, \\ \mu &= \mu_0 + a \ln\left(\frac{V}{V_*}\right) + b \ln\left(\frac{\theta V_*}{L}\right), \\ \frac{d\theta}{dt} &= \exp\left(\frac{-V}{V_c}\right) - \left(\frac{\theta V}{L}\right) \ln\left(\frac{\theta V}{L}\right), \end{aligned} \quad (5)$$

where μ is the friction coefficient, σ_n^{eff} is the effective normal stress, which is the difference between the normal stress applied to the fault and the pore-fluid pressure, θ is the state variable, a , b and L are friction parameters, and $V_c = 0.01$ $\mu\text{m/s}$. μ_0 and V_* are the reference friction coefficient and velocity, assumed to be 0.6 and 10^{-6} m/s, respectively; The values of μ_0 and V_* can be taken arbitrarily, because the change of them does not affect the results. Further details of the significance of the parameters used and the simulation method are provided in Kato and Tullis (2001) and Kato (2012).

Fig. 3 shows the depth dependence of parameters a , b , and $(a - b)$. Seismic slip may nucleate in the depth interval where $(a - b) < 0$, because the frictional stress will decrease with increasing slip velocity, Ruina (1983).

It is assumed that σ_n^{eff} remains constant at depths below 5 km. Five cases of constant σ_n^{eff} are examined, namely for 50, 100, 200, 300 and 400 MPa. In each case σ_n^{eff} linearly increases within a 5-km depth from zero to the constant value.

174 Cases with different values of σ_n^{eff} are also simulated with different values of the
 175 characteristic slip distance L , which is assumed to be independent of depth.

176 The assumed value of $V_s = 0.015$ m/yr for the deep stable sliding velocity is
 177 approximately equal to the estimated value for the Xianshuihe fault (Allen et al.,
 178 1991; King et al., 1997). Kato (2012) conducted numerical simulations of earthquake
 179 cycles with different velocities of deep stable sliding for a dip-slip fault, and found
 180 that the stable sliding velocity has little effect on the relation between the amount of
 181 deep aseismic slip and the fracture energy at the rupture nucleation point.
 182 Accordingly, for simplicity we do not vary V_s in this study.

183 To solve the problem in the continuum limit it is necessary to prevent discrete
 184 cells from failing independently of neighbouring cells. This is guaranteed if their size
 185 h is a small fraction of a critical size, which is proportional to L/σ_n^{eff} (Rice, 1993;
 186 Lapusta et al., 2000). The maximum number of cells in the present study is 4640, and
 187 the cell size is always much smaller than the critical size. The initial condition is
 188 steady-state sliding at a velocity of $0.1 V_s$. The simulation results for the first few
 189 cycles are not considered in our analysis because they are affected by the artificial
 190 initial conditions.

191

192 **3. Simulation results**

193 In each of the numerical simulations, large shallow earthquakes occur
 194 repeatedly at a constant recurrence interval, driven by deep steady sliding. As Fig. 4
 195 shown, the first two simulated earthquake cycles are affected by the artificial initial

condition. Earthquake cycles after the third event are almost same. Shear stress is plotted against slip distance (Fig. 5), and the fracture energy at the nucleation point for each simulated earthquake is calculated by:

$$\mathcal{G}_c = \int (\tau - \tau_d) du, \quad (6)$$

where τ_d is the dynamic friction stress and the nucleation point is defined as the point at which the slip velocity first exceeds 0.01 m/s. The critical slip-weakening distance D_c is defined as the amount of slip from the peak shear stress to reach a constant value after seismic slip occurs.

We used different values of σ_n^{eff} and L to simulate earthquakes, and then computed the $\mathcal{G}_c$ values for further statistical analysis.

The simulation results (Fig. 6) show that the fracture energy $\mathcal{G}_c$ is linearly related to the product of L and σ_n^{eff} , as indicated by the fitted equation in Fig. 6. This result is consistent with previous experimental observations (e.g., Okubo and Dieterich, 1981). The fracture energy is expected to be proportional to breakdown stress drop $\Delta\tau_b (= \tau_p - \tau_d)$ and critical slip-weakening distance D_c (Fig. 1), and $\Delta\tau_b = (\mu_s - \mu_d)\sigma_n^{eff}$, where μ_s and μ_d , the static and dynamic friction coefficients, respectively, are nearly constant, and D_c is proportional to L (Bizzarri and Cocco, 2003). The following relation can thus be obtained (Kato, 2012):

$$\mathcal{G}_c \propto \sigma_n^{eff} L. \quad (7)$$

From equations (3) and (7), we expect that the recurrence interval T_r is approximately proportional to the square root of the product of L and σ_n^{eff} :

$$T_r \propto \sqrt{\sigma_n^{eff} L}. \quad (8)$$

218 In this analysis we assume that the process zone width is sufficiently smaller than the
 219 seismogenic zone width, as explained in section 2. Simulation data approximately
 220 obey equation 8 except for simulated earthquakes nucleated at relatively shallow
 221 depths, as shown in Fig. 7, which is in good agreement with a previous study of a
 222 dip-slip fault (Kato, 2012) and is qualitatively consistent with many previous
 223 simulation results (Tse and Rice, 1986; Stuart, 1988).

224 Simulated earthquakes nucleated in the shallower part of the seismogenic zone
 225 when L is larger or σ_n^{eff} is smaller. For these conditions, the recurrence interval
 226 does not fit the relation well, therefore the regression relation in Fig. 7 was obtained
 227 for simulated earthquakes with nucleation depths below 17.5 km. The assumption
 228 that the process zone width is sufficiently smaller than the width of the locked zone
 229 may be violated for earthquakes nucleated at shallow depths, because the
 230 process-zone width is regarded as the distance from the deeper end of the
 231 seismogenic zone to the seismic rupture nucleation point, where preseismic creep
 232 takes place. It therefore follows that equation 1 based on linear fracture mechanics
 233 may not be applicable. Furthermore, it is clear from Fig. 7 that for $\sigma_n^{eff} = 300$ MPa
 234 and 400 MPa, there are gaps in the recurrence interval data at $L \sim 0.04$ m and 0.05
 235 m, respectively. Similar gaps can also be observed in Kato (2012), but they are not
 236 that obvious. In this study, the data beyond the gaps were not used in the
 237 equation-fitting.

238 The fracture energy may theoretically be expected to have a clear relation with V_s
 239 and T_r as expressed by equation 3. The simulation results fit this equation well, as

illustrated in Fig. 8. In this figure and in the regression procedure, data for earthquakes nucleated shallower than 17.5 km are not considered, because the ratio of the process zone width to the seismogenic width is large, the theoretical assumption is invalid and simulation results significantly deviate from (8).

. The fitted equation is:

$$\mathcal{G}_c = 0.0176 V_s^2 T_r^2, \quad (9)$$

where $\mathcal{G}_c$ is measured in MJ/m² and $V_s T_r$ in m.

The coefficient in this equation differs from that in the subduction case (Kato, 2012). From equation 3, the coefficient of $V_s^2 T_r^2$ for equation 9 is $\frac{1}{2G} f_s^2$, where f_s is a function of G , z_{se} and z_{cr} . In the subduction case, the coefficient is $\frac{1-\nu}{2G} f_d^2$, where f_d is a function of G , z_{se} , z_{cr} , Poisson's ratio ν , and the dip angle of the plate boundary Φ . Thus, the equations are not identical and the simulated equation 8 is most applicable for pure strike-slip faults with a seismogenic zone width of 30 km.

Because of differences between the width of the seismogenic portions of different faults, the fracture energies must be corrected for the seismogenic zone width z_{se} . Kato (2012) suggested that $\mathcal{G}_c$ is inversely proportional to z_{se} from dimensional analysis, and confirmed this for a dip-slip fault using numerical simulations. Assuming that the same dependency on z_{se} can be applied to strike-slip faults, we obtained:

$$\mathcal{G}_c = \frac{G}{2z_{se}} f_s'^2 V_s^2 T_r^2, \quad (10)$$

where f_s' is a function of z_{se} and z_{cr} , and it is not the same as f_s in

equation 1. To construct a relation between $\mathcal{G}_c$ and z_{se} , numerical simulations were conducted with different values of z_{se} , varied by extending or shortening the width of the segment where the value of $(a - b)$ has a minimum value of -0.001 (see Fig. 3). z_{se} is defined as the width from the surface of the fault to the deeper edge of the region where $(a - b) < 0$. Note that aseismic sliding in the shallow velocity-strengthening region ($a - b > 0$) is small and its effect on stress concentration may be ignored.

Simulations were conducted using various values of z_{se} between 15 and 40 km and various values of σ_n^{eff} and L under a constant deep stable sliding velocity $V_s = 0.015$ m/yr.

The regression equation was fitted as shown in Fig. 9, where $V_s^2 T_r^2 / z_{se}$ is in mm:

$$\mathcal{G}_c = 0.45 V_s^2 T_r^2 / z_{se}. \quad (11)$$

Note that Kato (2012) obtained the relation $\mathcal{G}_c = 0.57 V_s^2 T_r^2 / z_{se}$ for a dip-slip fault with a dip angle of 15° . The coefficients for the two cases are similar when the effect of z_{se} is taken into consideration. The differences in the values of the coefficient between the two examples result from differences in the geometry of the two fault types. We note that the distance from the free surface to the deeper end of the locked zone is shorter for the dip-slip fault for the same value of z_{se} . This may cause larger stress concentrations at the dip-slip fault as a result of the greater effect of the free surface.

3.1 Estimation of fracture energy at the rupture nucleation point

284 Using equation 11, we estimated G_c at the rupture nucleation points of large
 285 strike-slip earthquakes along the Xianshuihe fault, southwestern China, which is
 286 located along the eastern margin of the Tibetan plateau and which has generated
 287 many $M \geq 7$ earthquakes. Fig. 10a (Jiang et al., 2015) shows the geometry and
 288 segmentation of the Xianshuihe fault. Jiang et al. (2015) omitted the northeastern
 289 and southwestern branches and simplified the fault system to a strip. Fig. 10b (Wen
 290 et al, 2008) shows the spatial-temporal pattern of ruptures on the Xianshuihe fault. It
 291 can be estimated from Fig. 10b that the recurrences of each segment are from about
 292 one hundred years to hundreds of years. Following Jiang et al. (2015), we divided the
 293 fault system into six segments (numbered from north to south) based on the rupture
 294 areas of large earthquakes in each segment estimated from geological data and
 295 historical documents (Wen et al., 2008). This segmentation model is a simplification
 296 of those proposed by Wen (2000) and Wen et al. (2008). In Table 1, the average
 297 magnitude M of repeated large earthquakes, the recurrence interval T_r of the
 298 earthquakes, and the long-term average slip rate, which is assumed to be equal to V_s ,
 299 are shown for each segment. These values were obtained from Jiang et al. (2015),
 300 who compiled values of M and T_r from a number of previous studies and
 301 determined V_s from geodetic data and modeling deformation accounting for
 302 viscoelasticity. Note that large uncertainties are included in the estimates of M and
 303 T_r because of the noncharacteristic behavior of the earthquake recurrence pattern
 304 and the sparsity of the available data. Li et al. (2015) determined the
 305 three-dimensional structure of the seismic P-wave velocity and aftershock

distribution of the 2014 Mw5.9 Kanding earthquake in segment 5 of the Xianshuihe fault, using data from the local seismic network, and found that most aftershocks occurred at depths of 8–15 km **while** the hypocenter of the Mw5.9 mainshock was located near the base of the aftershock area. Similar results for the focal depths of the 2014 Kanding earthquake and its aftershocks were obtained by Yi et al. (2015). From analysis of GPS data, Wang et al. (2008) estimated the locking depth of the Xianshuihe fault to be 15–17 km, which is approximately consistent with the seismogenic depths estimated from the distribution of the aftershocks of the 2014 Kanding earthquake. The fact that the shallower part of the fault is locked supports the assumption in the present model that shear stress is concentrated at the base of the shallow seismic portion of the fault. Following these results, we used $Z_{se} = 15$ km to estimate G_c at the rupture nucleation points. In addition, the focal depth of the mainshock of the 2014 Kanding earthquake was located near the deeper edge of the aftershock area, indicating that the assumption of small-scale yielding in the present model is more or less satisfied. On the basis of this information and given that the hypocenters of large earthquakes are usually located near the deeper parts of aftershock areas (Das and Scholz, 1983; Sanders, 1990; **Mai et al, 2005**), we **consider** assumption **as** satisfied, although the focal depths of past $M \geq 7$ earthquakes along the Xianshuihe fault are not well determined because of the lack of a local seismic network.

The estimated values of G_c at the rupture nucleation points for large earthquakes in segments 1 to 6 of the Xianshuihe fault are listed in Table 1. The

328 estimated $\mathcal{G}_c$ values range from 0.02 to 0.4 MJ/m².

329 Although these estimated values of $\mathcal{G}_c$ may include large errors as will be
 330 discussed in the next section, we consider that the order-of-magnitude estimates of
 331 $\mathcal{G}_c$ at the rupture nucleation points are meaningful. The estimated $\mathcal{G}_c$ values of
 332 0.02–0.4 MJ/m² for $M \geq 7$ strike-slip earthquakes on the Xianshuihe fault are
 333 generally smaller than the average $\mathcal{G}_c$ values over the fault plane for earthquakes of
 334 similar magnitude estimated in previous studies using either the difference between
 335 the released strain energy and the radiated seismic wave energy or using models of
 336 the rupture process using seismic waveform data (e.g., Abercrombie and Rice, 2005;
 337 Tinti et al., 2005; Mai et al., 2006; Rice, 2006). According to Mai et al. (2006), the
 338 fracture energy increases with distance from the hypocenter. This is consistent with
 339 the present finding of smaller values of $\mathcal{G}_c$ at rupture nucleation points. A similar
 340 finding of smaller $\mathcal{G}_c$ values at the rupture nucleation point was obtained for
 341 interplate earthquakes in subduction zones (Kato, 2012). A possible cause of the
 342 increase of $\mathcal{G}_c$ with increasing rupture propagation distance is the increase of
 343 secondary ruptures and inelastic deformation near the crack tip for well-developed
 344 ruptures, which is consistent with the theoretical model of Andrews (2005).

345 The estimated $\mathcal{G}_c$ values for the six segments of the Xianshuihe fault indicate
 346 that $\mathcal{G}_c$ tends to increase with increasing M , although there are large uncertainties
 347 in the estimation and the variation of M is small. Moreover, the estimated $\mathcal{G}_c$ value
 348 of $M \geq 7.5$ earthquakes in segment 6 on this intraplate fault is similar to the
 349 estimated values of 0.1–1 MJ/m² for magnitude ~8 interplate earthquakes along

the Nankai trough, southwestern Japan (Kato, 2012). This may indicate that values of G_c at the rupture nucleation points of similar-magnitude earthquakes are similar, regardless of fault type. To confirm this, an analysis of large numbers of earthquakes is required, which will be undertaken in future work.

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355 4. Discussion

There are considerable uncertainties in the estimates of fracture energies at the nucleation points based on seismic parameters such as M and T_r , V_s , z_{se} , as well as the limits in the simulation model. Periodic recurrence of characteristic earthquakes is assumed in the present model. However, the recurrence pattern of past large earthquakes in this fault system is not simple (Allen et al., 1991; Wen, 2000; Wen et al., 2008). For instance, there have been active periods during which large earthquakes successively occurred in some segments. There is significant variation of T_r . The values of M and T_r are estimated from a small number of data points for each segment because only few earthquakes are expected to occur on each segment due to low slip rates. M is estimated from the length of the rupture trace and the amount of slip obtained from geological data, which may include large errors.

The long-term slip rate V_s in the fault zone is estimated from geological and geodetic data, as compiled by Jiang et al. (2015). However, the estimated rates vary significantly. Moreover, aseismic creep may occur partly on shallower parts of the fault system (Jiang et al., 2015). This is not taken into consideration in the present

372 model.

373 The source areas of past $M \geq 7$ earthquakes are not known precisely, and,
374 accordingly, the z_{se} value is assumed on the basis of the distribution of recent
375 smaller earthquakes. Moreover, the validity of the assumption that the seismic
376 rupture nucleates near the deeper edge of the seismic slip zone for Xianshuihe fault
377 cannot be confirmed from the data for $M \geq 7$ earthquakes. Because there is no
378 record of $M \geq 7$ earthquakes on the Xianshuihe fault.

379 The model is a simplification in that the heterogeneous structure of the fault
380 zone is not taken into consideration. The real fault is likely to experience more
381 complicated stress concentration and rupture processes.

382 The heterogeneity of frictional parameters was not considered in the present
383 simulation, and, accordingly, only characteristic earthquakes that break the entire
384 seismogenic depths are reproduced. In the real fault, a rupture may nucleate in a
385 relatively weak region and subsequently propagate to stronger regions, as described
386 in cascade-rupture models (Ellsworth and Beroza, 1995; Kilb and Gomberg, 1999).
387 Assuming heterogeneous distribution of characteristic slip distance L , Hillers et al.
388 (2006, 2007) conducted numerical simulations of earthquake cycles with a
389 rate-and-state friction and obtained frequency distribution of earthquake size similar
390 to the Gutenberg-Richter law. They pointed out that simulated earthquakes tend to
391 be nucleated in regions of smaller L , and therefore smaller fracture energy. Mai et
392 al. (2005) found that the earthquake nucleation points are often located near or
393 within the regions of large coseismic slip from many finite source models. The

394 estimated $\mathcal{G}_c$ values in the present study may not be those at the exact points of
 395 rupture nucleation, but instead may represent the values at relatively strong points
 396 that control large earthquakes near the nucleation points.

397

398 5. Conclusions

399 We have **used** a model of a vertical strike-slip fault, in which shear stress is
 400 concentrated in the upper locked portion of the fault as a result of deep stable sliding,
 401 to analyze the rupture **nucleation** conditions. **We** conducted numerical simulations of
 402 earthquake cycles using a rate- and state-dependent friction law to obtain the
 403 relation between the fracture energy at the rupture nucleation point and the amount
 404 of aseismic slip in the deeper part of the fault, which can be estimated from the
 405 product of the deep stable sliding velocity and the recurrence interval of shallow
 406 large earthquakes. Using this relation, we estimated the fracture energies at the
 407 rupture nucleation points of large strike-slip earthquakes on the Xianshuihe fault,
 408 southwestern China. The estimated fracture energies at the rupture nucleation
 409 points are smaller than those for developed ruptures of earthquakes with similar
 410 magnitudes reported elsewhere in the literature. A similar result was obtained by
 411 Kato (2012) for large interplate earthquakes at subduction zone: these results
 412 support the hypothesis that the local fracture energy on a fault increases with
 413 rupture propagation distance due to the variations in the dynamic rupture processes
 414 at the crack tip with scale (e.g., Mai et al., 2006). The estimated fracture energies at
 415 the rupture nucleation points of $M \geq 7$ intraplate earthquakes on six segments of the

416 Xianshuihe fault appear to increase with increasing M , and the fracture energy for an
417 $M \geq 7.5$ earthquake in the southernmost segment is similar to the estimated value
418 for a magnitude ~ 8 interplate earthquake along the Nankai trough subduction zone,
419 Japan. This dependence of the fracture energy at the rupture nucleation point on
420 earthquake magnitude and fault type (interplate or intraplate) may be useful for
421 understanding the dynamic rupture processes of earthquakes.

422

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553 Figure Caption

554 Figure 1. An illustration of the 'classic' linear slip-weakening law

555 Figure 2. (a) An idealized model of a strike-slip fault that is locked above point T, but
 556 in the deeper part stable sliding takes place with slip velocity V_s . (b) Distribution of
 557 shear stress (red) and slip (blue) prior to an earthquake in the shallow part. The deep
 558 part is the steady sliding zone with velocity V_s . The transitional creep portion (the
 559 process zone) is present between these two zones. Before an earthquake it is
 560 assumed that no slip occurs in the shallow zone and that the accumulated slip in the
 561 deep zone is $V_s T_r$.

562 Figure 3. The simulation model and distributions of parameters with depth. Values of
 563 a and b are given at depths of 0, 10, 25, 40 and 70 km, and are linearly interpolated
 564 at other depths. The parameter $(a - b)$ is negative at depths of 5–30 km.

565 Figure 4. Simulation results when parameters $\sigma_n^{eff} = 400$ MPa, $L = 0.04$ m. (a)
 566 Cumulative slip evolution. Lines are drawn every 100 years during interseismic period
 567 with solid line, and every 3 seconds during seismic period with dash line. Stars are
 568 rupture nucleation points for different events. (b)-(d) Evolution of slip velocity, shear
 569 stress and the relation between dislocation and shear stress at the rupture
 570 nucleation point for the third earthquake.

571 Figure 5. Shear stress versus slip distance at the seismic rupture nucleation point for
 572 $\sigma_n^{eff} = 300$ MPa and $L = 0.025$ m. The gray area denotes the fracture energy, τ_p is
 573 the peak shear stress, τ_d is the dynamic friction stress and D_c is the critical
 574 slip-weakening distance.

575 Figure 6. Fracture energy $\mathcal{G}_c$ at the rupture nucleation point of simulated

earthquakes plotted against the product of the characteristic slip distance L and the effective normal stress σ_n^{eff} . The solid line represents the regression relation $\mathcal{G}_c = 0.106\sigma_n^{eff}L$ determined by a least-squares method.

Figure 7. Recurrence interval T_r versus characteristic slip distance L for various values of effective normal stress σ_n^{eff} . Solid curves denote the regression relation $T_r = 159\sqrt{\sigma_n^{eff}L}$ determined by a least-squares method. All data are shown, but only data for earthquakes nucleated deeper than 17.5 km are used to determine the fitted curves.

Figure 8. Fracture energy $\mathcal{G}_c$ versus $V_s T_r$ for simulated earthquakes. The solid curve is the fitted relation $\mathcal{G}_c = 0.0176V_s^2 T_r^2$ determined by a least-squares method. Only data for earthquakes nucleated deeper than 17.5 km are plotted.

Figure 9. Simulated fracture energy $\mathcal{G}_c$ at the seismic rupture nucleation point versus $V_s^2 T_r^2 / z_{se}$ for $L = 0.01, 0.02$ and 0.05 m. The solid line is the fitted relation determined by a least-squares method.

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Figure 10. Segmentation and seismicity of Xianshuihe fault system. (a) Earthquake rupture segment model of the Xianshuihe fault system. Red stars are the last earthquakes that occurred on each segments. The rupture ranges of these earthquakes are outlined by green dashed ellipses. (Jiang et al., 2015). (b) A spatial-temporal pattern of the rupture history of $M > 6$ earthquakes of the Xianshuihe fault system. Vertical lines or dashed lines are earthquake ruptures. Horizontal dot-lines show rupture segmentation. (Wen et al., 2008).

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602 Table caption

603 Table 1. Earthquake parameters for six segments of the Xianshuihe fault, southwestern

604 China. The magnitude M and recurrence interval T_r of large earthquakes and the long-term slip605 rate V_s , are taken from Jiang et al. (2015). The fracture energy G_c at the rupture nucleation point

606 was estimated in the present study.

Figure1

Figure2

(a)

(b)

Figure3

Figure4

Figure5

Figure6

Figure7

Figure8

Figure9

Figure10

Fault segment	M	T_r (yr)	V_s (m/yr)	$\mathcal{G}_c$ (MJ/m ²)
Xianshuihe fault (segment 1)	7.5	170	0.01	0.09
Xianshuihe fault (segment 2)	7.5	170	0.008	0.06
Xianshuihe fault (segment 3)	7.0	110	0.0078	0.02
Xianshuihe fault (segment 4)	7.0	170	0.007	0.04
Xianshuihe fault (segment 5)	7.0	230	0.007	0.08
Xianshuihe fault (segment 6)	≥ 7.5	340	0.011	0.4

Table 1. Earthquake parameters for six segments of the Xianshuihe fault, southwestern China. The magnitude M and recurrence interval T_r of large earthquakes and the long-term slip rate V_s , are taken from Jiang et al. (2015). The fracture energy $\mathcal{G}_c$ at the rupture nucleation point was estimated in the present study.

Graphical Abstract (for review)

Fault segment	M	T(yr)	V(m/yr)	$\mathcal{G}$ (MJ/m ²)
Xianshuihe fault(segment 1)	7.5	170	0.01	0.09
Xianshuihe fault(segment 2)	7.5	170	0.008	0.06
Xianshuihe fault(segment 3)	7.0	170	0.0078	0.02
Xianshuihe fault(segment 4)	7.0	170	0.007	0.04
Xianshuihe fault(segment 5)	7.0	170	0.007	0.08
Xianshuihe fault(segment 6)	≥ 7.5	170	0.01 1	0.4