Implication of fault interaction to seismic hazard assessment in Sichuan-Yunnan provinces of southeastern China*

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Abstract

Coulomb stress changes associated with the strong earthquakes that occurred since 1904 in Sichuan and Yunnan provinces of China are investigated. The study area comprises the most active seismic fault zones in the Chinese mainland and suffers from both strong and frequent events. The tectonic regime of this rhombic-shaped area is affected by the eastern extrusion of the Tibetan highland due to the collision of Eurasian Plate against the Indian lithospheric block along the Himalayan convergent zone. This movement is accommodated on major strike-slip intraplate fault zones that strike in an E-W direction. The gradual 90° clockwise rotation of the faults in the study area contributes to the complexity of the stress field. The seismic hazard assessment in this region is attempted by calculating the change of the Coulomb Failure Function (ΔCFF) arising from both the coseismic slip of strong events ($M_s \geq 6.5$) and the stress built-up by continuous tectonic loading on major regional faults. At every step of the stress evolutionary model an examination of possible triggering of each next strong event is made and the model finally puts in evidence the fault segments that apt to fail in an impending strong event, thus providing future seismic hazard evaluation.

Key words: strong earthquakes; fault segmentation; Coulomb stress changes; seismic hazard assessment

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Introduction

Strong seismicity in China and adjacent regions is distributed over specific zones that configure rigid lithospheric subplates often bounded by active faults. Sichuan and Yunnan provinces correspond to a so-called rhombic shaped subplate that experiences the strongest intraplate seismicity in the territory of China. During the 20th century, 35 devastating earthquakes with magnitude $M_s \geq 6.5$ occurred nearby densely populated areas causing a majority of casualties and deaths.

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Smaller earthquakes are also abundant and are characterized of more dispersing epicentres in the whole southeastern China. This is evidenced in Figure 1 where the seismicity for the period of 1970~2004 is mapped. The study area is treated as an individual microplate that defines the eastern margin of the Tibetan Plateau. During the last 10 Ma post collision extensional stress dominates behind the thrust boundary causing the extrusion of the Plateau main body to the east along east-west rupture zones (Armijo *et al*, 1986; Molnar and Tapponier, 1977), which have been reactivated as strike slip fault zones since Late Cenozoic time (Wang, 1996).

Sichuan and Yunnan region exhibits a complicated tectonic regime that consists of various rupture zones and different faulting types with strike slip prevailing, which is consistent with the regional stress field and geological background. The study area is being extruded to the southeast, driven in response to the Tibetan Plateau. This motion is combined with a clockwise rotation accomplished around a fixed pole at the eastern edge of the Himalayan syntax according to geologic, tectonic, and geodetic data (Holt *et al*, 1991; Peltzer and Saucier, 1996). The east margin of the subplate is constrained by the Garzê, Xianshuihe, Anninghe-Zemuhe and Xiaojiang strike slip fault systems, where left lateral displacement dominates. The west boundary is occupied by Jinshajiang and Zhongdian dextral strike slip faults that extend to the south and meet the Red River fault, which is connected with the extrusion of Indonesia to southeast. In the interior of the subplate, normal faults are found with a north-south strike. The tectonic regime of the area is complicated since faults are segmented and also form rotating conjugate fault systems. Strong earthquakes on these faults have been reported both in historic time and instrumental period. In the present study, adjacent faults to the south and the north of Sichuan-Yunnan block are included such as the Wanding, Nanting, Lancang faults to the south and the north Longmenshan thrust and Minjiang fault at the boundary of Sichuan-Qinghai crustal block to the north.

The fact that Sichuan and Yunnan provinces are densely populated and industrially developed urges the necessity for investigating the occurrence pattern of the region's stronger events through a stress evolutionary model and also identifying the structures that are apt to produce a potential strong seismic event in the future. The characteristic of the tectonic setting is that various long strike slip, normal and some thrust faults exist within the same area, interacting with each other. Such interaction of strong earthquakes has been proved by previous investigation concerning the Xianshuihe fault zone (Papadimitriou *et al*, 2004) and the stress evolution for the northeast Tibetan Plateau from 1920 till present for a viscoelastic model (WAN *et al*, 2007). Stress transfer seems not only to be restricted in a single however segmented fault but also expands over the adjacent faults or conjugate zones, which often bring them toward rupture. The tectonic complexity reveals a real challenge for our investigation, since the interaction is sought among different faulting types. The purpose of this study is to search for the pattern of stress transfer among various faults and reveal the current stress field that resulted from both the coseismic slip of strong earthquakes and the long term tectonic loading on the major faults zones.

1 Methodology

In this study, we apply the stress evolutionary model acquired from Deng and Sykes (1997), who performed a similar investigation for southern California. According to this methodology, the Earth is approximated as an elastic single-layer crust over a homogeneous ductile half space. Stress in the crust is described by a tensor, which varies in time and space and is transmitted elastically due to the accommodated tectonic loading. This long-term process is resulted from relative

plate motion and from coseismic dislocations evolving in the time interval between strong earthquakes. In order to estimate the stress accumulation in interseismic period around a fault zone, the term of the “virtual dislocation” has been introduced. This concept is based on elastic rebound theory, according to which the stress released in an earthquake existed as pre-stress prior to the event. Hence, the accumulated stress can be determined by supposing that the fault could slip backwards powered by the energy that generates earthquakes. This procedure produces an effective approach to the tectonic loading. The suggested model refers to a planar orthogonal fault surface, Σ , with finite dimensions, embedded in an elastic half space (Okada, 1992). Displacement, u , across a surface, Σ , of a fault, according to Steketee (1958), is determined from the following equation:

$$u_k = \frac{U_i}{8\pi\mu} \iint_{\Sigma} w_{ij}^k v_j d\Sigma \quad (1)$$

where μ is the shear modulus, v_j are the direction cosines of the normal to the surface, U_i is the i th component of $\mathbf{U}$ and w_{ij}^k are the six sets of Green's functions. The computation of the elastic stress, s_{ij} , derives from strain, e_{ij} , using Hooke's law, for an isotropic medium

$$s_{ij} = \frac{2\mu\nu}{1-2\nu} \delta_{ij} e_{kk} + 2\mu e_{ij} \quad (2)$$

where μ is the shear modulus, ν is the Poisson's ratio and δ_{ij} is the Kronecker delta.

Earth in this model is treated as an elastic structure, where postseismic deformation is considered negligible. However, since this time dependent effect is hard to estimate, it is suggested (Jaumé, 1994) that the effect reinforces stress change in the future. According to Nur and Mavko (1974) the relaxation on strike slip faults that govern the study area rarely occurs, because they fail to break to sufficient depth in order to allow measurable postseismic deformation.

According to Scholz (2002) the Coulomb fracture criterion examines the conditions under which failure occurs on brittle rocks. According to this criterion, earthquakes occur along a plane when Coulomb stress exceeds the strength of the rock. Changes in Coulomb failure function (ΔCFF) depends on the change in shear stress, $\Delta\tau$, on the failure plane and on normal stress, $\Delta\sigma$, and is given by the following equation:

$$\Delta CFF = \Delta\tau + \mu' \Delta\sigma \quad (3)$$

Here, μ' corresponds to the apparent coefficient of friction, which depends on the coefficient of friction μ and is given by:

$$\mu' = \mu(1 - B) \quad (4)$$

where B is the Skempton's coefficient, and varies between 0 and 1. The parameter μ' includes both the effect of pore fluid and material property of the fault zone. The role of μ' corresponding to the change of pore pressure has been widely investigated and is treated as a material constant or a time dependent parameter varying before and after an event. It has been shown that low values of μ' are related to weak fault zones with well-developed gouge often saturated with fluids (Stein, 1999). According to Parsons *et al* (1999), the apparent coefficient of friction is low for long fault zones ($\mu' < 0.2$) whereas it is high for small ones ($\mu' > 0.8$). Nalbant *et al* (2002) as well as Toda *et al* (1998) chose $\mu' = 0.4$ for their calculations. Reseanberg and Simpson (1992) used $\mu' = 0.2$ for Loma Prieta earthquake and King *et al* (1994) suggested that even if μ' varies essentially it

Figure 1 Seismicity in Sichuan-Yunnan provinces from 1970 to 2004

Strong earthquakes mainly distribute along active fault. It is evident that strike slip faults dominate in the whole area. Horizontal lines indicate the division between the northern (a), central (b) and southern sub-region (c)

doesn't alter the stress distribution in adjacent area of the seismic source.

Earthquakes occur due to slip along active fault surfaces approximated as rectangles dipping within the brittle layer of the Earth's crust. Fault planes are adequately described with the geometrical parameters such as the fault length, width, strike and dip. In the absence of geological data or any aftershock information, the geometrical parameters are computed using scaling laws or in-

ferred by later earthquakes generated by the same fault zone. Papazachos *et al* (2004) collected worldwide data and suggested scaling laws relating the moment magnitude (M) with fault length, L (km), and slip, u (m), for different seismotectonic environments. These laws are used for the model constraints of this study if no other relevant information is available. The equations used for length and coseismic slip for strike slip faults are:

$$\lg L = 0.59M - 2.30 \quad (5)$$

$$\lg u = 0.68M - 2.59 \quad (6)$$

The corresponding equations for dip slip faults are:

$$\lg L = 0.50M - 1.86 \quad (7)$$

$$\lg u = 0.72M - 2.82 \quad (8)$$

In addition to the fault geometrical properties the awareness of the fault plane solution regarding the strike, ξ , the dip, δ , and the rake, λ , are essential because the variation of these parameters affects the pattern of the resulted stress field (King *et al*, 1994). The majority of the fault plane solutions are taken from Yang *et al* (2005), while additional information from CMT catalogue or local studies dealing with seismic sequences is also used. Moment magnitudes for the earthquakes since 1976 are taken from CMT solutions whereas for the earthquakes before 1976 magnitudes are provided from the seismicity catalogue of Engdahl *et al* (1998), and M_s magnitudes from Yang *et al* (2005). The optimal nodal plane for each event is assigned based on available field survey information, such as surface ruptures and in the absence of visible tectonic features, the ones consistent with the regional stress field are chosen. Relocated epicentres from Yang *et al* (2005) are used, with some exceptions that concern the Songpan and Lung Ling seismic sequence (Jones *et al*, 1984; CMT Catalogue). Focal depths of the strong earthquakes mainly vary between 3 km and 15 km within the crust, determining in this way the width of the brittle seismogenic layer. In order to get more detailed results the study area has been divided into three sub-areas, the northern one (northern Sichuan Province), the central sub-area (southern Sichuan and northern Yunnan provinces) and the southern one (southern Yunnan Province and part of its neighbour countries, Myanmar and Vietnam) (Figure 1).

2 Fault segmentation and long-term slip rate constraint

The deformation in China is strongly in response to the kinematic process of the Tibetan Plateau. In central China major fault zones exist, such as Altay fault, trending east-west where large displacements of the order of thousands meters have been identified. Fault offsets mainly observed with the help of geologic markers, such as landforms, alluvial fans and hydrographic features give quantified information on the slip rate for each major fault zone that cuts them across. Using slip rates the mean tectonic motion over a long period of time can be quantified. Slip rates of the major faults in the study area are adopted from various researchers who investigated geologic, geodetic and geomorphologic information or velocity field of crustal motion in China (Chen *et al*, 2000; Holt *et al*, 2002; Qin *et al*, 2002). Slip rates for the most important fault zones in the study area along with their names are illustrated in Figure 2. For a more detailed study the area was divided into three sub areas, and the fault zones were further divided into segments based on the difference of fault properties and slip rates. Information on the fault segmentation for the northern, central and southern region is given in Tables 1, 2 and 3, respectively.

Figure 2 Slip rates on the major faults that are used for determinating tectonic loading

Dark grey colored arrows correspond to left lateral strike slip faults, whereas light dark colored arrows represent right lateral strike slip faults. Rate estimation are based on geodetic seismologic and geologic data

Kirby *et al* (2000). The slip rates for the Garzê fault system ($S_1 \sim S_7$), the Jinshajiang ($S_{10} \sim S_{15}$, $S_{21} \sim S_{24}$) and the Batang (S_{25}) faults are taken equal to 1 mm/a (Zhao *et al*, 1999). In Longqianshan ($S_{46} \sim S_{48}$) and Mabian faults ($S_{49} \sim S_{50}$) the attributed slip rate is equal to 3 mm/a, as referred from Chen *et al* (2000). Segments S_8 and S_9 without particular seismicity exhibit a rate of 1 mm/a. For the Litang fault ($S_{26} \sim S_{29}$) Tang *et al* (1984) have estimated a rate of 5 mm/a. Lijiang-Daofu fault that is associated with the 1996 strong earthquake has an average slip rate of 4 mm/a (Wang and Burchfiel, 2000).

In Figure 3b the fault segments of the central part of our study area are illustrated, for which long-term slip rate values were assigned based on previous investigations of Wen *et al* (2000) and

In Figure 3a the 55 fault segments of the northern sub area, the epicentres (denoted by circles) and the fault plane solutions, as lower-hemisphere equal-area projections, of the strong earthquakes included in the evolutionary model are depicted. The Xianshuihe fault is characterized by a relatively high slip rate according to Allen *et al* (1991), starting with 15 ± 5 mm/a at the northern part and ending up to a reduced value of 5 mm/a at the southern edge. The mean slip rate used for the evolutionary model is taken as 6.5 mm/a (segments: $S_{30} \sim S_{34}$, $S_{37} \sim S_{38}$) in accordance with Wen *et al* (2002). The Longmenshan thrust zone is a structure where major shortening around 100 km occurred due to Tibetan escape tectonics to the east (~ 20 mm/a). The tectonic escarpments formed there are analogous to the Himalayan thrust zone, however recent studies reveal a reduced shortening, probably less than 2–3 mm/a. According to Chen *et al* (2000), the Longmenshan fault zone is characterized by active shortening < 3 mm/a while Royden *et al* (1997) assume that the compression in the whole area is 0–5 mm/a. Based on the above, a slip rate equal to 2 mm/a is taken (segments $S_{40} \sim S_{45}$). In addition to the compression taking place in this part, active strike-slip displacement associated with the Minshan fault ($S_{51} \sim S_{53}$) is observed. The slip rate in the latter fault zone is taken equal to 1 mm/a following

Table 1 Long-term slip rates on the major fault segments in the northern Sichuan Province

Segment No.	Centre		Length/km	Depth/km	Strike/°	Dip/°	Slip rate /mm·a ⁻¹
	$\varphi_N/^\circ$	$\lambda_E/^\circ$					
S ₁	31.945	99.107	131	0~15	298	65	1.0
S ₂	31.493	99.669	52	0~15	300	65	1.0
S ₃	31.625	99.000	50	0~15	300	70	1.0
S ₄	31.034	99.584	41	0~15	343	70	1.0
S ₅	31.066	100.158	20	0~15	190	75	1.0
S ₆	30.974	99.997	34	0~15	190	75	1.0
S ₇	30.760	99.382	50	0~15	313	75	1.0
S ₈	31.832	102.198	30	0~15	137	75	1.0
S ₉	31.486	102.489	22	0~15	137	75	1.0
S ₁₀	31.345	98.261	26	0~15	125	75	1.0
S ₁₁	30.905	98.890	56	0~15	140	75	1.0
S ₁₂	29.864	98.975	79	0~15	200	75	1.0
S ₁₃	30.552	99.074	31	0~15	140	75	1.0
S ₁₄	29.348	98.820	16	0~15	182	75	1.0
S ₁₅	29.915	99.221	29	0~15	175	80	1.0
S ₁₆	29.447	99.276	30	0~15	195	80	1.0
S ₁₇	29.097	99.258	13	0~15	180	75	1.0
S ₁₈	29.964	99.357	41	0~15	170	75	1.0
S ₁₉	29.487	99.463	15	0~15	160	75	1.0
S ₂₀	29.217	99.382	22	0~15	337	75	1.0
S ₂₁	29.987	98.641	12	0~15	165	80	1.0
S ₂₂	29.729	98.684	23	0~15	150	75	1.0
S ₂₃	30.358	98.573	16	0~15	183	75	1.0
S ₂₄	29.311	98.596	34	0~15	190	75	1.0
S ₂₅	30.047	99.533	20	0~15	187	84	1.0
S ₂₆	30.213	99.974	66	0~15	138	80	4.0
S ₂₇	29.880	100.569	25	0~15	135	80	4.0
S ₂₈	29.578	100.522	27	0~15	135	80	1.0
S ₂₉	29.606	100.757	19	0~15	135	80	1.0
S ₃₀	31.295	100.734	118	0~15	315	80	6.5
S ₃₁	30.566	101.610	11	0~15	277	87	6.5
S ₃₂	30.452	101.793	15	0~15	315	80	6.6
S ₃₃	30.305	101.789	30	0~15	315	80	6.5
S ₃₄	30.192	101.830	23	0~15	310	85	6.5
S ₃₅	29.207	101.187	29	0~15	221	85	2.0
S ₃₆	29.509	101.595	69	0~15	221	80	2.0
S ₃₇	29.701	102.066	22	0~15	190	80	6.5
S ₃₈	29.782	101.824	50	0~15	160	80	6.6
S ₃₉	29.201	102.241	22	0~15	170	80	6.7
S ₄₀	30.084	102.411	53	0~15	220	50	2.0
S ₄₁	31.053	103.279	90	0~15	211	50	2.0
S ₄₂	31.770	103.888	22	0~15	240	50	2.0
S ₄₃	31.514	104.043	125	0~15	230	50	2.0
S ₄₄	30.789	103.393	122	0~15	215	50	2.0
S ₄₅	31.754	104.557	47	0~15	230	50	2.0
S ₄₆	30.208	103.614	58	0~15	220	80	3.0
S ₄₇	30.616	104.319	66	0~15	200	80	1.5
S ₄₈	30.518	104.374	70	0~15	200	80	1.5
S ₄₉	29.352	103.279	44	0~15	168	80	3.0
S ₅₀	29.145	103.529	16	0~15	170	80	1.0
S ₅₁	32.791	103.723	25	0~15	190	80	1.0
S ₅₂	32.618	103.878	22	0~15	86	80	1.0
S ₅₃	32.215	104.142	50	0~15	170	80	1.0
S ₅₄	32.335	104.701	36	0~15	240	50	1.0
S ₅₅	31.597	100.181	11	0~15	245	45	6.5
S ₅₆	32.244	103.620	41	0~15	10	60	1.0

Table 2 Long-term slip rates on the major fault segments in the central Sichuan-Yunnan province

Segment No.	Center		Length/km	Depth/km	Strike/ $^{\circ}$	Dip/ $^{\circ}$	Slip rate /mm·a ⁻¹
	$\varphi_N/^{\circ}$	$\lambda_E/^{\circ}$					
S_1	28.599	99.096	13	0~15	3	60	3.0
S_2	28.853	99.189	18	0~15	30	60	3.0
S_3	28.084	99.597	104	0~15	130	70	4.2
S_4	27.663	99.729	86	0~15	150	70	4.2
S_5	27.069	100.125	43	0~15	10	75	4.0
S_6	26.681	99.894	33	0~15	10	75	4.0
S_7	26.238	99.809	168	0~15	330	80	5.0
S_8	26.708	98.954	76	0~15	345	80	5.0
S_9	25.501	99.820	90	0~15	315	80	5.0
S_{10}	25.309	98.612	33	0~15	223	75	3.0
S_{11}	25.510	98.898	58	0~15	190	75	3.0
S_{12}	28.586	101.183	55	0~15	195	75	3.0
S_{13}	28.391	101.725	81	0~15	210	75	3.8
S_{14}	27.119	100.764	91	0~15	220	75	3.8
S_{15}	26.825	100.779	125	0~15	205	80	3.0
S_{16}	26.617	100.962	37	0~15	220	80	3.0
S_{17}	27.131	101.476	50	0~15	210	75	3.0
S_{18}	27.974	101.748	50	0~15	190	75	3.0
S_{19}	26.133	101.917	131	0~15	2	75	2.0
S_{20}	25.517	102.224	54	0~15	5	75	2.0
S_{21}	26.062	102.251	13	0~15	13	80	2.0
S_{22}	28.375	102.195	55	0~15	180	75	6.5
S_{23}	27.289	102.566	63	0~15	330	75	6.5
S_{24}	26.688	102.273	19	0~15	190	75	6.5
S_{25}	26.842	102.743	26	0~15	175	84	6.5
S_{26}	26.215	102.698	19	0~15	180	80	6.5
S_{27}	25.530	102.692	56	0~15	185	80	6.5
S_{28}	26.591	102.812	22	0~15	190	80	6.5
S_{29}	25.974	102.919	58	0~15	175	80	6.5
S_{30}	25.253	103.003	27	0~15	182	80	5.0
S_{31}	28.485	102.680	59	0~15	163	87	3.0
S_{32}	27.510	102.875	54	0~15	182	80	3.0
S_{33}	26.717	103.003	34	0~15	170	80	3.0
S_{34}	27.761	103.477	90	0~15	236	85	3.0
S_{35}	28.231	103.408	45	0~15	182	85	3.0
S_{36}	28.407	104.534	25	0~15	220	89	3.0
S_{37}	28.674	103.620	43	0~15	155	80	3.0
S_{38}	28.798	103.814	27	0~15	140	80	3.0

YI *et al* (2004), who estimated a rate of 6~7 mm/a. Thus, a slip rate of 6.5 mm/a is attributed to Anninghe and Zemuhe faults (S_{22} ~ S_{23}), as well as in the whole left lateral fault zone (S_{30} ~ S_{34} , S_{38} , S_{39}). The Zhongdian (segments S_3 ~ S_5) and Jianchuan fault zones (S_6) have a rate of 4 mm/a, taking into account the results of Wang and Burchfiel (2000). In this area, the northern active segment (S_7) of Red River fault is included with a slip rate equal to 5 mm/a (Leloup *et al*, 1995). For the Huayinshan (S_{34} ~ S_{38}), Liangshan (S_{31} ~ S_{32}) and the Yulongxi (S_{13}) fault zones that are located in the broader area of Sichuan basin an average slip rate of 3 mm/a is assigned, taking into account the GPS measurements of Chen *et al* (2000). The Yongsheng (S_{15}) and Muli-Jiulong (S_{12}) faults are slipping at a rate of 3 mm/a in accordance with Qinhe fault (S_{14}) moving with 3.8 ± 0.7 mm annually estimated from Xu *et al* (2003). The same value with Qinhe has been given to the Puduhe, Yimen and Luzhijiang left lateral faults striking north-south, parallel to Xiaojiang fault.

Fault segmentation of the southern part of the study area is presented in Figure 3c. The longest part of the Red River fault is included in this area. Allen *et al* (1984) estimated a rate varying from 2 to 7 mm/a with a total offset of 5.5 km, considering features of surface faulting, fault

Table 3 Long-term slip rates on the major fault segments in the southern Yunnan Province

Segment No.	Center		Length/km	Depth/km	Strike/°	Dip/°	Slip Rate /mm·a ⁻¹
	$\varphi_N/^\circ$	$\lambda_E/^\circ$					
S_1	24.837	98.206	27	0~15	223	70	3.0
S_2	24.371	98.461	58	0~15	229	69	3.0
S_3	23860	98.372	43	0~15	242	70	3.0
S_4	24.258	99.093	44	0~15	229	70	3.0
S_5	24.636	98.877	33	0~15	188	75	3.0
S_6	23.952	98.998	43	0~15	178	75	3.0
S_7	23.418	99.294	27	0~15	130	75	3.0
S_8	24.694	99.497	26	0~15	170	75	1.0
S_9	24.357	99.456	25	0~15	200	75	1.0
S_{10}	23.967	99.348	23	0~15	180	75	1.0
S_{11}	23.930	99.694	79	0~15	225	75	1.0
S_{12}	22.999	98.940	23	0~15	12	75	3.0
S_{13}	22.599	98.954	20	0~15	345	75	3.0
S_{14}	22.009	99.300	55	0~15	349	75	3.0
S_{15}	21.430	99.513	13	0~15	24	80	3.0
S_{16}	22.529	99.866	118	0~15	340	80	3.0
S_{17}	24.708	100.58	27	0~15	350	75	3.0
S_{18}	23.889	100.33	65	0~15	20	75	3.0
S_{19}	22.996	100.17	41	0~15	350	75	3.0
S_{20}	22.282	100.49	45	0~15	337	75	3.0
S_{21}	21.480	100.42	59	0~15	30	80	3.0
S_{22}	23.316	100.71	26	0~15	2	75	3.0
S_{23}	22.564	100.97	69	0~15	150	75	3.0
S_{24}	21.526	101.41	29	0~15	167	75	3.0
S_{25}	23.772	100.89	54	0~15	160	84	3.0
S_{26}	22.639	101.35	79	0~15	140	80	3.0
S_{27}	22.508	101.30	47	0~15	50	80	1.0
S_{28}	24.496	101.01	65	0~15	150	80	5.0
S_{29}	23.718	101.43	29	0~15	165	80	5.0
S_{30}	23.104	102.20	86	0~15	124	80	5.0
S_{31}	21.904	102.46	111	0~15	150	87	3.0
S_{32}	21.819	103.30	134	0~15	135	80	3.0
S_{33}	23.316	102.68	51	0~15	195	80	3.0
S_{34}	24.133	102.04	38	0~15	325	85	3.0
S_{35}	23.543	102.67	43	0~15	310	85	3.0
S_{36}	24.636	101.74	52	0~15	144	89	3.0
S_{37}	24.040	102.51	55	0~15	290	80	3.0
S_{38}	24.609	102.56	52	0~15	5	80	3.0
S_{39}	24.644	102.21	40	0~15	5	80	3.0
S_{40}	24.241	102.76	90	0~15	10	80	3.0
S_{41}	24.848	101.75	15	0~15	5	80	3.0

scarps, stream channel offsets, and younger formations cut by the fault. According to Replumaz *et al* (2001), slip rate of the Red River fault ranges from 1 to 10 mm/a based on the geomorphic disturbances of the drainage network. The hardness in assessing the age of geomorphologic marker offset causes the scattering of the estimated slip rates. Leloup *et al* (1995) suggested a rate of about 5 mm/a, taking into account that the left lateral motion ceased around 15 Ma and the fault was reactivated as a dextral one around 15 Ma. The fault segments to the south of the Red River fault zone present a slip rate equal to 3 mm/a. Segment S_7 as well as segments $S_{28}\sim S_{30}$ slip with a rate of 5 mm/a. Nanting and Wanding faults ($S_2\sim S_4$) slip with a rate of 3 mm/a (Socquet and, Pubellier, 2005). Qujiang and Jianshui faults ($S_{36}\sim S_{37}$ and S_{34} ,) located to the north of Red River fault exhibit a slip rate of 3 ± 3 mm/a (Leloup *et al*, 1995). The rest of the zones striking NE-SW and its NW-SE conjugate ones, located to the south of the Red River fault trace (S_1 , $S_{11}\sim S_{15}$, $S_{17}\sim S_{26}$,

$S_{31}\sim S_{32}$), including Lancang-Gengma zone (S_{16}) also slip with an average rate of 3 mm/a, according to Allen *et al* (1984) and Socquet and Pubellier (2005).

3 Stress evolutionary model

The evolution of stress field before the occurrence of each strong event is computed at a depth of 8 km, chosen to be several kilometers above the locked depth of the seismogenic layer and approximately in the middle of the brittle crust and the resulted pattern is presented as snapshots (Figures 4, 5 and 6). The parameters included in equations (1) and (2) such as the shear modulus and Poisson's ratio are fixed as 33 GPa and 0.25, respectively. However, alternative values for the apparent coefficient of friction have been testified in order to detect possible variations in the stress pattern. The calculated stress field includes a combination of both coseismic stress change and the effect of the cumulative seismic displacements on major structures measured from a starting event. The dense fault network results in a complicated distribution of stress change over the region. It is considered that before the first strong shock of 1904, 1913 and 1925 for the southern, central and northern region, respectively, ΔCFF are originally zero. Changes in shear and normal stress of each earthquake are resolved onto the subsequent event's fault plane, as it has been assumed to be in accordance with the orientation of regional stress. Therefore, the stress field before an earthquake is analyzed for the faulting type of the causative fault colored black. The results are exhibited in a schematic manner, with the stress change denoted with a color scale. In the snapshots pure green indicates no significant change in Coulomb stress. Blue regions denote negative change in CFF and infer decreased likelihood of fault rupture, and are called stress shadows (Harris and Simpson, 1993, 1996). Yellow to red regions represent positive ΔCFF and increased likelihood of fault rupture, so they are called stress bright zones. Shadow zones and bright zones are specific to strike, dip, and rake of the fault whose triggering is inspected.

3.1 Northern Sichuan region

The evolutionary stress model for the northern part of the study area is presented in the snapshots of Figure 4. The first strong event occurred in 1904 in Daofu fault segment and its coseismic stress change is shown in Figure 4a. The stress pattern corresponds to a typical strike slip faulting that creates a bright zone at the northern and southern tip of the fault that ruptured, whereas large parts are under a stress shadow. Two increased stress lobes are along the strike of the Xianshuihe fault zone and the other two are perpendicular to them. The Luhuo earthquake in 1923 is favored to be triggered since its epicenter is located in the region with increased Coulomb stress. In Figure 4b the stress accumulation before the 1923 event is displayed. There is strong evidence that the earthquake had been advanced by the 1904 event occurrence since it is obviously located in a bright zone created by the previous event. In Figure 4c the stress field calculated according to the faulting type of the 1933 Diexi earthquake is shown. The epicenter of this event is quite far from the previous ones to be triggered by them, and the positive ΔCFF are due solely to the tectonic loading. The stress field just before the 1948 earthquake is shown in Figure 4d, indicating that the associated fault is located inside a bright zone. The 1955 rupture is located in an enhanced stress area (Figure 4e) and is probably triggered by the previous occurrences on the Xianshuihe and Litang faults. The 1960 event is close to a stress shadow zone created by the 1933 Diexi earthquake (Figure 4f). This mismatch may attribute either to errors in epicentral determination or to blind normal fault associated with this event. The 1967 Zhuwo event occurred inside a stress enhanced area attributed to the coseismic stress change of previous events along the Xianshuihe

Figure 4 Stress evolution in Northern region of Sichuan province. Coulomb stress changes are calculated at a depth of 8 km
 (a) Computed stress just before 1948 Litang event; (b) Stress state just before 1955 Mianming event; (c) Stress field before the strong 1967 event; (d) Stress model before 1973 Luhuo earthquake along Xianshuhe fault; (e) Stress state just before 1973 event; (f) Stress field before the first main shock is displayed; (g) Stress changes until the occurrence of Songpan third strong shock; (h) Stress changes until the second Batang strong event; (i) The stress before the last strong earthquake of this century in the northern region with earthquakes of magnitude $M \geq 6.0$ that followed

Table 4 Rupture models for earthquakes with $M \geq 6.5$ that occurred in the northern part (northern Sichuan Province) of the study area from 1904 to 1989 and are included in the evolutionary model

Date a-mo-d	Location	Epicenter		Magnitude		Fault plane solution			L/km	U/m	SS/m	DS/m	Ref.
		$\phi_N/^\circ$	$\lambda_E/^\circ$	M_S	M_W	Strike/ $^\circ$	Dip/ $^\circ$	Rake/ $^\circ$					
1904-08-30	Xianshuihe	31.00	101.10	6.8	6.8	322	85	13	50	1.08	+1.05	-0.23	1,2, Eq.6
1923-03-23	Xianshuihe	31.30	100.80	7.2	7.2	116	90	10	60	2.36	+2.30	0	1, 2, Eq.6
1933-08-25	Minjiang	32.00	103.70	7.3	7.3	14	60	-167	102	2.36	-2.29	+0.53	3, Eq. 5-6
1948-05-25	Litang	29.50	100.50	7.3	7.3	315	90	0	60	2.36	+2.35	-0.04	4, 2, Eq.6
1955-04-14	Xianshuihe	30.00	101.90	7.5	7.5	337	81	-3	35	3.23	+3.23	-0.10	1,4, Eq. 6
1960-11-09	Minjiang	32.78	103.66	6.5		60	50	-130	34	0.68	-0.44	+0.52	3,5, Eq.7-8
1967-08-30	Xianshuihe	31.61	100.33	6.8	6.1	245	45	42	20	1.48	+0.59	-0.53	6, Eq. 7
1973-02-06	Xianshuihe	31.48	100.53	7.6	7.4	125	87	0	116	2.77	+2.77	0	1, 6, Eq.7-8
1973-08-11	Minjiang	32.93	103.90	6.5	6.1	343	85	15	20	0.36	+0.34	-0.09	3, Eq. 8
1976-08-11	Songpan	32.61	104.13	7.2	6.7	165	63	40	30	1.1	+0.84	-0.7	7
1976-08-21	Songpan	32.60	104.40	6.7	6.3	215	30	90	12	1.2	0	-1.2	7
1976-08-23	Songpan	32.50	104.30	7.2	6.4	165	65	40	22	1.1	+0.84	-0.7	7
1981-01-23	Xianshuihe	30.98	101.10	6.9	6.5	319	73	-4	47	0.56	+0.56	+0.03	2, 8, Eq.6
1989-04-16	Batang	29.92	99.20	6.4	6.5	74	62	-99	22	0.54	-0.08	+0.53	3, 9, 10, Eq.7
1989-04-25	Batang	30.00	99.370	6.7	6.1	245	40	-114	15.5	0.32	-0.13	+0.3	3, 10, Eq. 7

Note: 1: Allen *et al* (1991), 2: Papadimitriou *et al* (2004), 3: Yang *et al* (2005), 4: Molnar and Deng (1984), 5: Chen *et al* (1994), 6: Zhou *et al* (1983a), 7: Jones *et al* (1984), 8: Zhou *et al* (1983b), 9: HAN and JIANG (2004), 10: Gao *et al* (2000). L stands for fault length, and U , SS , DS for displacement, slip along strike and slip along dip, respectively.

fault zone and the tectonic loading (Figure 4g). In this case triggering is noticed in a secondary structure almost perpendicular to the previously ruptured causative faults.

The Luhuo fault segment that failed in 1973 was well inside a bright zone (Figure 4h). The location of the 1973 Minjiang earthquake is not predicted by the evolutionary model, since it is located in a stress shadow (Figure 4i). Nevertheless its coseismic slip contributes to the increase of positive stress change in the Songpan region that suffered few years later from a triplet of strong events in 1976 across the Huya fault. This is a rather seldom and complex phenomenon which is characterized of the subsequent strong earthquakes that occur close in time and space. They are attributed to an en echelon structure with two strands separated by an additional right stepping offset and the strong influence among the three main shocks is proved. In Figure 4j the calculated stress field before the first 1976 Songpan earthquake is shown. It is suggested that the Huya fault is advanced toward failure and triggered by the increased stress change induced by the 1933 Diexi and 1973 Minjiang main events, since the whole area around the fault is located in a bright zone. The stress transfer from the first rupture brought the second en echelon segment closer to failure, since the positive stress change is provoked mainly by the first 1976 event (Figure 4k). Thirty hours after the second mainshock the last one occurred, south of the second aftershock zone (Figure 4l) in an enhanced stress zone reinforced by the previous strong events.

The most recent significant earthquake along Xianshuihe fault zone occurred in 1981 and is associated with the Daofu fault segment that ruptured for a second time (the first was in 1904) in the 20th century. It is noticed that the stress change is not enhanced enough so as to interpret the occurrence of Daofu earthquake (Figure 4m). Both the epicentre of the first Batang earthquake and the associated fault, are located in a stress shadow zone (Figure 4n). A possible explanation is the lack of geologic knowledge and the tectonic complexity of the region as well as the incompatibility between the mapped faults and the fault plane solutions. The remarkable characteristic is that the events are produced in a region where a series of N-S faults dominate, while the fault plane solutions of the earthquakes are attributed to east-west normal faults. HAN and JIANG (2004)

based on the small slip degree suggested that the first Batang earthquake occurred on a blind fault. The fault segment associated with the second Batang earthquake is inside a bright zone (Figure 4o), and is probably triggered by the former shock of the sequence. The calculation in the stress evolutionary model extends up to the present and the current stress field is compared with the smaller magnitude seismicity, which seems to be located in stress enhanced areas (Figure 4p).

3.2 Central Sichuan-Yunnan region

The stress evolution in the central part of our study region since the beginning of 20th century is illustrated in Figure 5. The first event occurred in 1925 and the coseismic stress change is shown in Figure 5a. It creates bright zones along the northeastern continuation of the Red River fault. In Figure 5b the state of stress before the 1952 earthquake in Anninghe fault is displayed. A broad area of positive stress change has been created that is attributed to the 27 years (1925~1952) of tectonic loading. The occurrence of the 1955 main shock is in accordance with the stress evolutionary model (Figure 5c), although its epicentre is located far from the previous event and possible triggering cannot be substantiated. The stress bright zones where the next main events occurred (1966 event (Figure 5d), 1974 Panxi rift (Figure 5e), 1976 event (Figure 5f), 1995 event (Figure 5g), and 1996 event (Figure 5h)) are mainly due to the tectonic loading. The characteristic feature of this area is that strong earthquakes occur in long distances and are randomly distributed in contrast with the other two sub regions where seismicity occurs along the known fault zones

Figure 5 Stress evolution in central region regarding South Sichuan and North Yunnan province. Coulomb stress changes are calculated at a depth of 8 km. (a) Coseismic Coulomb Stress Changes associating to 1925 event; (b) Stress state just before 1952 event along Anninghe fault; (c) Stress field before the strong 1955 event; (d) Computed stress just before 1966 event; (e) Stress changes until the occurrence of 1974 event; (f) Stress field just before 1976 event; (g) Stress field before the strong 1995 event; (h) Stress model before the devastating 1996 Lijiang earthquake; (i) Stress field after 1996 in the central area accompanied with strong events that followed

and close in time on adjacent fault segments. The majority of earthquakes with $M < 6.5$ after 1996 seem to occur in stress enhanced areas (Figure 5i).

3.3 Southern Yunnan region

The first strong earthquake that struck the southern part of our study area occurred in 1913 in an active structure that ruptured twice in the 20th century. The coseismic stress change of this event is shown in Figure 6. The stress evolution just before the occurrence of the 1941 event is shown in Figure 6b. The 1941 event is located quite far to be triggered by the previous occurrence, while it is the positive stress changes along the southern adjacent fault segment where the next main shock occurred in 1950 (Figure 6c). Triggering is also evidenced by the 1913 main shock to the 1970 one, which is associated with a fault segment adjacent to that of the 1913 main shock (Figure 6d), through stress transfer between the adjacent fault segments. The 1971 event occurred in a bright zone when the stress field is calculated according to its faulting type (Figure 6e).

The 1976 Longling sequence started with the first event being inside a stress enhanced area due only to the tectonic loading since it is located far enough from previous strong events being hardly triggered by them (Figure 6f), but they evidently triggered the second event of the sequence that took place in an adjacent fault segment (Figure 6g). Eight years after the 1971 main shock a second one struck the same area (Figure 6h), being located in an area between positive and negative ΔCFF values. The 1983 earthquake associated with the Dien Bien Phu fault in Northern Vietnam is due solely to the tectonic loading since it is quite far from the previous events and therefore triggering cannot be inferred (Figure 6i).

The 1988 Lancang-Gengma sequence started with the activation of a fault segment adjacent to the one associated with the 1941 main shock. The first Lancang 1988 event was probably triggered by stress transfer due to the coseismic slip of the event (Figure 6j). The second 6 November 1988 Gengma main shock of this sequence is evidently triggered by the previous one (Figure 6k), as both are associated with the adjacent fault segment of the same strike. The occurrence of the last 1995 strong event in this part of our study area occurred in a stress enhanced area in accordance with the stress evolutionary model (Figure 6l). Earthquakes with magnitude $M \leq 6.5$ after 1995 have occurred in bright regions as well (Figure 6m).

4 Discussion and conclusions

In order to evaluate future seismic hazard, we applied a stress evolutionary model for the Sichuan and Yunnan region of China. The evolution starts at the beginning of the 20th century and is accomplished in this study by calculating the static stress change due to coseismic slip of the strong events and long term tectonic loading on major regional faults. The stress evolution of the stress field was calculated for the time intervals 1904~2007, 1925~2007, 1913~2007 for the northern, central, and southern region, respectively. Initial stress values just before the 1904, 1925 and 1913 event are assigned to be zero everywhere. The fact that the region has been divided into three sub-regions has no effect on the calculation of stress change since the events are located in large distances. It has been shown that there is no important impact. The time advance of the shocks is less important in distant places such as the central area. The study area includes first order tectonic complexities have been taken into account as the regional fault network, while minor active faults are not included. Thus, for a more detailed survey the results are presented separately for each one of the three sub areas.

Figure 6 Stress evolution in southern region regarding South Yunnan province at its borders with Myanmar and Vietnam

Coulomb stress changes are calculated for the depth of 8 km. (a) Coseismic Coulomb Stress Changes associating to 1913 event; (b) Stress state just before 1941 shock at Lancang-Gengma fault zone; (c) Stress field before the strong 1950 event along the same fault zone; (d) Computed stress just before 1970 Tonghai event; (e) Stress changes until the occurrence of 1971 event; (f) Stress field just before 1976 sequence; (g) Stress field before the second main shock; (h) Stress model before the devastating 1979 earthquake; (i) Stress state just before 1983 event; (j) Stress field before the 1988 Lung-Ling sequence. The epicentre of the first main shock is displayed; (k) Stress field after the first main shock; (l) Stress field after the second main shock of the sequence; (m) Stress variations after the last strong event of 1995. Latter strong events with magnitude $M > 6.0$ are also presented

Stress transfer among adjacent faults or fault segments, or conjugate faults is confirmed to dominate in this area. In most of the cases triggering is evidenced and many events are located in bright zones where static stress changes have relatively high positive values. Although fault

Table 5 Rupture models for earthquakes with $M \geq 6.5$ that occurred in the central part (southern Sichuan-northern Yunnan Province) of the study area from 1925 to 1996 and are included in the evolutionary model

Date a-mo-d	Location	Epicenter		Magni- tude		Fault plane solution			L/km	U/m	SS/m	DS/m	Ref
		$\phi_N/^\circ$	$\lambda_E/^\circ$	M_S	M_W	Strike/ $^\circ$	Dip/ $^\circ$	Rake/ $^\circ$					
1925-03-16	Red River	25.70	100.20	6.8	7.0	150	90	180	68	1.48	-1.48	0	1, Eq. 5-6
1952-09-30	Anninghe	28.40	102.20	6.8	—	354	40	30	52	1.08	+0.93	-0.54	2, Eq. 5-6
1955-04-14	Xiaojiang faults	30.00	101.90	6.8	7.5	210	87	20	59	1.26	+1.18	-0.43	3, Eq. 5-6
1966-02-05	Xiaojiang faults	26.20	103.20	6.5	6.9	159	85	-11	17	0.31	+0.3	+0.06	3, Eq. 5-6
1974-05-11	Huayinshan	28.20	103.90	7.1	6.8	237	81	176	52	1.08	+1.06	-1.19	3, Eq. 5-6
1976-11-07	Qinhe	27.45	101.08	6.7	6.3	19	66	-6	26	0.47	+0.42	-0.21	3, Eq. 5-6
1995-10-24	Xiaojiang faults	25.95	102.30	6.5	6.2	13	75	-9	23	0.23	+0.23	+0.04	3, Eq. 5-6
1996-02-03	Lijiang	27.34	100.25	7.0	6.6	6	44	-78	28	0.35	0.07	0.34	4, 5, Eq. 7

Note: 1: This study, 2: Papadimitriou *et al* (2004), 3: Yang *et al* (2005), 4: HAN and JIANG (2004), 5: Zhao *et al* (1999). L stands for fault length, and U , SS , DS for displacement, slip along strike and slip along dip, respectively.

Table 6 Rupture models for earthquakes with $M \geq 6.5$ that occurred in the southern part (southern Yunnan Province) of the study area from 1913 to 1988 and included in the evolutionary model

Date a-mo-d	Location	Epicenter		Magnitude		Fault plane solution			L/km	U/m	SS/m	DS/m	Ref.
		$\phi_N/^\circ$	$\lambda_E/^\circ$	M_S	M_W	Strike	Dip	Rake					
1913-12-21	Qujiang	24.15	102.45	7.0	7.2	116	87	180	89	2.02	-2.02	0	1, Eq. 5-6
1941-12-26	Lancang	22.10	100.10	7.0	7.0	145	90	180	68	1.48	-1.48	-0.13	1, Eq. 5-6
1950-02-03	Lancang	21.70	100.10	7.0	7.0	149	85	180	68	1.48	-1.48	0	1, Eq. 5-6
1970-01-05	Qujiang	24.00	102.70	7.8	-	291	80	-15 7	102	2.37	-2.18	+0.93	2, Eq. 6
1971-04-28	Lancang	22.90	101.00	6.7	6.3	117	70	170	26	0.49	+0.48	-0.08	1, Eq. 6
1976-05-29	Ruili	24.50	99.00	7.3	6.7	232	82	-10	50	0.92	+0.90	+0.16	1, Eq. 5-6
1976-05-29	Ruili	24.45	98.86	7.4	6.7	242	88	0	50	0.92	+0.92	0	1, Eq. 5-6
1979-03-15	Pu'er	23.20	101.10	6.8	6.0	312	86	163	17.5	0.31	-0.29	-0.09	1, Eq. 5-6
1983-06-24	Dien Bien Phu	21.72	103.38	6.8	6.3	114	80	-17 2	26	0.5	-0.49	+0.44	1, Eq. 5-6
1988-11-06	Lancang	22.92	99.75	7.4	7.0	144	79	179	68	1.48	-1.48	-0.03	3, 4, Eq. 5-6
1988-11-06	Lancang	23.37	99.50	7.2	7.0	158	77	136	68	1.48	-1.06	-1.03	5, Eq. 5-6
1995-07-11	Myanmar	21.89	99.22	—	6.8	330	89	175	52	1.08	-1.07	+0.09	1, Eq. 5-6

Note: 1: Yang *et al* (2005), 2: Zhou *et al* (1983a), 3: Chen and Wu (1989), 4: Mozzafari *et al* (1998), 5: Jiang (1993). L stands for fault length, and U , SS , DS for displacement, slip along strike and slip along dip, respectively.

surfaces are irregular and ruptures are more complicated, meaning that slip is not uniform but varies along its segments, it is believed that the approximate models are sufficient for identifying the areas of stress change when they are computed for distances far from the causative fault. A subsequent event can be triggered on the faults having proper orientation and being close to failure even if the stress change is only a few bars. Stress increment does not declare subsequent epicenter location but correspond to the segment sufficient to fail because it has reached high stress level and is close to failure, in accordance with Coulomb failure criterion. However, there are cases where epicenters are found in stress shadows before reloading. This fact can be attributed to fault interaction that inhibits faults to complete an integral seismic cycle and they rupture before approaching the required maximum stress or different seismic cycles exist in a small area. Misfits in the stress computation are attributed to the complexity and the existence of minor faults in this multi-segmented crust. The accumulative result of possible post seismic effects, such as viscoelastic relaxation beneath the brittle part of the crust and transient postseismic slip below the rupture zone are not incorporated in the evolutionary model. Stress diffusion in each case needs further

study since there is a wide variation in the post seismic behavior of rupture. Thus, it is suggested (Jaumé, 1994) that the postseismic slip when exists, will reinforce both regional stress and stress change caused by coseismic slip. These effects, along with differences in non-elastic changes and rate-state friction are not included, since they need to be addressed in further study.

The results were extrapolated to 2007 so as to determine the areas with current enhanced stress change where an earthquake is likely to occur, assuming that no other strong earthquake has occurred until now. The final patterns are illustrated in Figure 7 and changes are calculated for the strike, dip and rake of the representative faulting type of each subarea. The model results indicate that some faults are encouraged to rupture whereas in many areas there is a fault relaxation and a quiescence seismic period follows. The results derived from the evolutionary model coincide with the ones of Papadimitriou *et al* (2004) who suggested that stress transfer is a driving mechanism in the whole area and seismic activation is expected to be started in segments of bright zones. A

Figure 7 Coulomb stress evolution computed extrapolated for 2007 for the northern the central and the southern region at the depth of 8.0 km

The stress model has been computed for different fault types, coloured black, with a mean fault plane solution, for a different value of the effective coefficient of friction, μ' ; (a) Calculations for the northern Region for a fault with mean fault plane solution $160^\circ/80^\circ/-10^\circ$ for $\mu'=0.2$; (b) Calculations for the northern region for a fault with mean fault plane solution $160^\circ/80^\circ/-10^\circ$ for $\mu'=0.4$; (c) Calculations for the northern region for a fault with mean fault plane solution $60^\circ/80^\circ/-10^\circ$ for $\mu'=0.6$; (d) Calculations for the northern region for a fault with mean fault plane solution $240^\circ/50^\circ/-170^\circ$ for $\mu'=0.2$; (e) Calculations for the northern region for a fault with mean fault plane solution $240^\circ/50^\circ/-170^\circ$ for $\mu'=0.4$; (f) Calculations for the northern region for a fault with mean fault plane solution $240^\circ/50^\circ/-170^\circ$ for $\mu'=0.6$; (g) Coulomb stress evolution computed, extrapolated for 2007 for the central region at the depth of 8.0 km, for a fault with $350^\circ/80^\circ/30^\circ$ for $\mu'=0.4$; (h) Coulomb stress evolution computed, extrapolated for 2007 for the southern region for a fault with $130^\circ/85^\circ/170^\circ$ for $\mu'=0.4$; (i) Calculations for the southern region for a fault with $230^\circ/85^\circ/-5^\circ$ for $\mu'=0.4$

similar study of WAN *et al* (2007), whose evolutionary model includes some common studied earthquakes (the 1973, 1955, 1933, 1976a, 1976b earthquake), proves that strong earthquakes ($M \geq 7.0$) are highly triggered by their previous ones.

Alternative values of the apparent friction coefficient are testified in our calculations. In particular, lower ($\mu' = 0.2$) and higher values ($\mu' = 0.6$) were used. The resulted computation of the stress evolution shows unimportant difference in stress pattern. Low sensitivity has been noticed but not to such a degree resulting to the alteration of the sign of the calculated stress field. Parsons *et al* (2006) conducted a similar test in the adjacent region of Himalaya and reached the same results. Based on the above discussion, the value of the apparent coefficient of friction selected and used in the present study ($\mu' = 0.4$) is suitable for the performed calculations (Figure 7).

A feature characterising long fault zones is that they are found segmented and distinct parts of faults rupture each time until they complete a seismic cycle. It is evidenced in the present study that strong earthquakes in a long fault zone undoubtedly encourage a second event along strike. Characteristic examples are demonstrated in the case of Xianshuihe fault zones in northern Sichuan and Lancang-Gengma fault zone in southern Yunnan, where almost all the segments of the fault have ruptured in the last century. According to YI *et al* (2000) the Xianshuihe-Anninghe-Zemuhe left lateral strike slip fault possesses the ability for mechanical interaction between adjacent fault segments and this is confirmed by stress bright zones revealed in the model. In Figure 7a it is noticed that the southern segment of Xianshuihe remains unruptured, and it lays inside stress enhanced region, therefore, a future rupture is anticipated. These results are in accordance with the calculations made by WEN *et al* (2002) who assessed a high probability for the Minjiang segment to fail. For the case of Lancang-Gengma rupture zone, we notice that seismic excitation begins with the 1950 main shock, which ruptures the southern part of the zone and occurs in a highly enhanced segment. After 38 years the Lancang-Gengma doublet broke the whole stress increased northern part of the zone. In the 2007 calculation no seismic hazard is posed for this area. Qujiang fault also seems to be triggered by stress transfer along strike since the strong Tonghai event has possibly been triggered by the previous event in 1913 on the same fault. Clustering is also confirmed by Songpan triplet in Minjiang fault zone.

Most earthquakes concentrate in the places around fault tips or on the sites where fault changes its strike since there is a high stress increase. Coulomb stress changes certainly influence the location and timing of the following earthquakes and can serve as a fundamental tool in seismic hazard assessment since there is a correspondence between positive changes and earthquake occurrence.

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