Stress value in 2003 Dayao $M_S6.1$ earthquake source region*

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Abstract The $M_S6.2$ Dayao, Yunnan, earthquake occurred on July 21, 2003, followed by a major $M_S6.1$ earthquake about 88 days later in the same region. Hypocenters of the two earthquakes are almost in the same place. Based on the P wave first motion polarities of the two aftershock sequences recorded by temporary stations, we have studied the stress field in the aftershock zone and obtained the two stress field directions in Dayao region using the new version of PKU_Grid_Test Software provided by Chunquan Yu. Assuming that the rotation of the stress field is caused by the second main shock, we estimated the crustal stress value in the focal region by using the stress value calculation method proposed by Yongge Wan. The estimated maximum, intermediate and minimum principal stresses are 166.3 MPa, 158.7 MPa and 151 MPa, respectively, before the second main shock. The normal and shear stresses projected on the fault plane of the second main shock before it occurred are 157.3 MPa, 7.4 MPa, and are 158.8 MPa, 0.2 MPa after it occurred, respectively. The perturbed input parameters experiments attest the stability of the solution. The result shows that the preseismic shear stress is larger than the post-seismic one, and their difference corresponds to the stress drop approximately. The estimated compressive stress level is very high, but the differential stress is low. The result is helpful for friction coefficient estimation, plate motion simulation and related studies.

Key words: composite fault plane solution; stress field; stress magnitude; 2003 Dayao twin earthquake

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1 Introduction

At present, geophysicists have, to a certain degree, understood tectonic stress direction through stress measurement and fault plane solution analysis (Zoback, 1992; Zoback and Healy, 1992), but the stress magnitude is little involved. Therefore they have to adopt some assumptions on stress level in simulating plate motion, mountain uplift, earthquake's preparation and occurrence process, which will bring uncertainty of the results. Giving the stress value will definitely reduce the uncertainty in the above researches. In addition, from the academic point of view, it is imperfect to only know the stress direction of stress field. Therefore to explore stress value is of great significance both in theory and

in practice.

As well known, most studies of stress were limited in shallow crust, and stress values were obtained by using stress measurement (Barton et al., 1988; Zoback and Healy, 1992; Vernik and Zoback, 1992; Tsukahara et al., 1996, 2001; Li et al., 2005; Reynolds et al., 2006; Wu et al., 2007). But as for the earthquakes occurred in tens of kilometers deep in the crust, it is important to detect the stress level in the seismogenic layer of the crust. Some scholars have attempted to estimate quantitatively the crustal stress value using fault plane solution and fault striation data together with geological condition and petrologic data (Zoback and Healy, 1992; Xie and Li, 1995; Plenefisch and Bonjer, 1997; Zhao et al., 2002). Spudich (1992) and Spudich et al. (1998) gave the method for solving the shear stress on the fault plane by using change in fault slip direction and stress drop. Wesson and Boyd (2007) gave a new method for determining the absolute deviatoric stress tensor based

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on the stress direction and stress change estimation. Using the method, they got the average absolute deviatoric stress tensor on the ruptured fault before and after the 2002 Denali earthquake. The average shear stress projected on the preseismic fault is 1–4 MPa. The shear stress on the fault is almost zero (0 ± 1 MPa) after the earthquake. According to the stress axis deflection caused by strike-slip earthquake and stress drop, Wan et al. (2006) gave the expressions about solving deviatoric stress value in two-dimensional stress state, and applied it to the Homestead Valley fault of Landers earthquake, got the tectonic deviatoric stress is 10 MPa. Further, Wan (2006) proposed an algorithm that solves stress value in seismic source of any fault-type according to stress direction deflection before and after an earthquake and corresponding stress drop.

With the development of digital seismic observation technology and the application of broadband digital seismic data, more and more accurately determined hypocenters of small earthquakes are available. Based on P wave first motion polarity data of a large number of small earthquakes before and after a strong earthquake, the stress field direction can be obtained before and after the strong earthquake by grid search method of composite fault plane solution, which laid a foundation for stress field direction study and stress value acquisition. After the Dayao twin earthquake, Earthquake Administration of Yunnan Province deployed a mobile station network around the seismic zone; a wealth of seismic data are recorded, which provides us a good opportunity to estimate the stress level in the source region. In this paper, the stress field directions before and after the Dayao $M_S6.1$ earthquake are estimated by using abundant P wave polarity data. Combined with the seismic stress drop, the stress level is evaluated in the source region of 2003 Dayao earthquake.

2 Data

During 2000 to 2004, there occurred successively four $M_S \geq 6.0$ earthquakes in Dayao region of Yunnan province within a radius of 70 km, i.e., the Yaoan $M_S6.5$ earthquake in 2000 (56 km away from Dayao earthquake), the Yongsheng $M_S6.0$ earthquake in 2001 (65 km away from Dayao earthquake) and the Dayao $M_S6.2$ and $M_S6.1$ twin earthquake in 2003 (8 km away from each other). In these earthquake sequences, the Dayao $M_S6.2$ and $M_S6.1$ twin earthquake was well observed.

The Dayao $M_S6.2$ and $M_S6.1$ twin earthquake occurred at 23:16 on July 21 and at 20:28 on October 16

in 2003, respectively. After the two earthquakes, 2 173 aftershocks were recorded after the first main shock during July 22 to August 21 (Qin, 2005), and 3 793 aftershocks were recorded after the second main shock during October 17 to November 17 by the temporary monitoring network (Qin, 2005).

Hua et al. (2006) relocated the two Dayao aftershock sequences by double difference hypocenter location method, and studied the earthquake sequence characteristics and earthquake triggering phenomenon. The precisely located aftershocks were linearly distributed (Figure 1). The two seismogenic faults are of almost vertical strike-slip. The distributions of the two aftershock sequences are not conjugate or overlapped, suggesting that the two earthquakes are controlled by the same fault. As shown in Figure 1, the first aftershock sequence concentrated in the northwest of the first main shock and the second one concentrated in the southeast of the second main shock, so it is easy to deduce that the two main shocks probably ruptured the different segments of the same fault.

We collected 2 284 P wave first motion polarities from 437 relocated aftershocks (Hua et al., 2006) of the first aftershock sequence and 5 587 P wave polarities of 1 499 relocated aftershocks (Hua et al., 2006) of the second aftershock sequence from the seismological observation reported by Qin (2005) in order to study the stress field in the source region.

3 Method to estimate stress magnitude

Large earthquakes could release parts of tectonic stress in source regions, so the preseismic stress direction will be deflected by the seismic stress drop on the condition that the directions of the seismic stress drops are not in line with those of the preseismic tectonic stress (Wan, 2006). We use this idea to estimate the stress value in the Dayao earthquake source region. For there is no data available for constraining the stress field direction before the Dayao $M_S6.2$ earthquake, we estimate the stress field direction by using the data of its aftershocks, and then take it as the stress field direction before the Dayao $M_S6.1$ earthquake. That is to say, the Dayao $M_S6.1$ earthquake deflected from the stress field direction. The stress direction before and after the Dayao $M_S6.1$ earthquake can be estimated from the P polarities of the two aftershock sequences. The seismic stress drop can be calculated from seismic model. So the relationship between the stress field direction rotation

Figure 1 Epicentral distribution of earthquake sequences of the Dayao $M_S6.2$ and $M_S6.1$ twin earthquake. (a) The aftershock sequence of the Dayao $M_S6.2$ earthquake on July 21, 2003; (b) The aftershock sequence of the Dayao $M_S6.1$ earthquake on October 16, 2003; (c) Superposition of the two aftershock sequences. The station codes MC, ST, DM, TH, LJ, SY, XJ, DY represent the stations Maci, Santai, Damo, Tanhua, Liuju, Shiyang, Xinjie, and Dayao, respectively.

and stress drop tensor can be established. The stress value before the Dayao $M_S6.1$ earthquake can be obtained by solving the equations. The stress value after the Dayao $M_S6.1$ earthquake can also be determined by adding the stress drop tensor of the Dayao $M_S6.1$ earthquake. The normal and shear stresses before and after the $M_S6.1$ Dayao earthquake can be determined through projecting the stress tensor on the seismic fault plane. For details of the method one can refer to Wan (2006).

4 Stress field inversion

Yu et al. (2009) proposed an improved grid search method based on Xu et al. (1983, 1992). This method has the following advantages. Firstly, the weighting factor is employed based on the sparse degree of the data on the focal sphere to partly eliminate the influence of uneven data distribution. Secondly, several possible solutions are selected by weighted inconsistency ratio so as to statistically estimate the fault plane solution. Thirdly, the Jackknife technique is employed to estimate the quality of inversion.

We use the improved grid search algorithm (Yu et al., 2009) to estimate the composite fault plane solutions before and after the Dayao $M_S6.1$ earthquake. The searching step is set to $5^\circ \times 5^\circ \times 5^\circ$. The maximum number of cluster centers is set to 3, but we only get one cluster in our study, suggesting that the solution is stable and reliable.

The estimated composite fault plane solutions are shown in Figures 2, 3 and listed in Table 1. It can be seen that after the Dayao $M_S6.2$ earthquake, the maximum principal stress axis is nearly horizontal in north-northwest direction, the intermediate principal stress axis is almost vertical and the minimum principal stress axis is almost horizontal in east-northeast direction. While after the Dayao $M_S6.1$ earthquake, the maximum principal stress axis in northwest direction deviates from horizontal, and the intermediate principal stress axis deviates from vertical direction. Comparison of the stress directions before and after the Dayao $M_S6.1$ earthquake indicates that the principal stress axes showed rotation, which is probably caused by the Dayao $M_S6.1$ earthquake.

Figure 2 Composite fault plane solutions of the aftershocks occurred during one month after the Dayao $M_S6.2$ earthquake (a) and after the Dayao $M_S6.1$ earthquake (b). Blue dots represent dilatational first motions and green ones represent compressional first motions. Yellow arcs represent the selected fault plane solutions. Red arcs represent the mean composite fault plane solutions.

Figure 3 Directions of P , T , B axes of the composite fault plane solutions after the Dayao $M_S6.2$ earthquake (a) and the Dayao $M_S6.1$ earthquake (b).

Table 1 Composite fault plane solutions after the Dayao $M_S6.2$ and $M_S6.1$ earthquake

Time	Nodal plane 1			Nodal plane 2			P axis		T axis		B axis		Inc.	N
	Strike / $^{\circ}$	Dip / $^{\circ}$	Rake / $^{\circ}$	Strike / $^{\circ}$	Dip / $^{\circ}$	Rake / $^{\circ}$	Az / $^{\circ}$	Dip / $^{\circ}$	Az / $^{\circ}$	Dip / $^{\circ}$	Az / $^{\circ}$	Dip / $^{\circ}$		
July 22–Aug. 21, 2003	295	83	185	205	85	353	160	8	250	1	347	82	0.19	2 284
Oct.17–Nov. 17, 2003	289	51	188	194	84	321	144	31	248	22	6	50	0.30	5 587

Note: Inc. denotes inconsistency ratio; N denotes number of P wave polarity readings.

5 Calculation of stress values

5.1 Stress drop estimation

Seismic stress drop is defined as the stress released by the fault plane:

$$\Delta\sigma = \sigma^0 - \sigma^1, \quad (1)$$

where $\Delta\sigma$ is the static stress drop, σ^0 is the stress on the fault plane before an earthquake (initial stress), and σ^1 is the stress on the fault plane after the earthquake (terminal stress).

Knopoff (1958) simplified the strike-slip fault into anti-shear mode of plane strain, and got analytical expression of the relation between $\Delta\sigma$ and the average fault dislocation $\bar{D}$ as following:

$$\Delta\sigma = \frac{2}{\pi} \cdot \mu \cdot \frac{\bar{D}}{W}, \quad (2)$$

where W is fault width; $\bar{D}$ is the average slip, which is taken as 22.4 cm (Qin, 2005) in this study and μ , shear modulus, as 3.0×10^4 MPa.

In order to get the width of the fault plane of the Dayao $M_S 6.1$ earthquake, we estimate the parameters of the fault plane according to the principle that the after-shocks would occur on the fault and its vicinity (Wan et al., 2008). The result shows that the strike and dip of the fault plane are $108.4^\circ \pm 0.4^\circ$ and $86.1^\circ \pm 0.4^\circ$, respectively (Figure 4), which is consistent with the Harvard CMT result that shows strike 108° and dip 89° . The vertex positions of the fault plane are (25.94°N, 101.18°E, 2.9 km), (25.94°N, 101.18°E, 8.4 km), (25.90°N, 101.32°E, 8.4 km) and (25.90°N, 101.32°E, 2.9 km), respectively, which results in the width of the fault plane is 5.5 km. Putting $\bar{D}=22.4$ cm and $W=5.5$ km into equation (2), we get $\Delta\sigma=7.78$ MPa.

Figure 4 Distribution of precisely located small aftershocks of the Dayao $M_S 6.1$ earthquake and the fault plane determination. (a) The map view. (b) Vertical cross-section along the fault plane. (c) Vertical cross-section perpendicular to the fault plane. (d) Histogram of small earthquakes sorted by their distances to the fault plane. Circles indicate the aftershock locations, thick lines are the fault plane boundaries, AA' is the fault upper boundary. D_D is dip direction, D_F is distance from the fault plane, S_D is strike direction, and f is frequency of the aftershocks.

5.2 Stress magnitude estimation

According to the estimated tectonic stress field in section 3, we can find that the intermediate principal stress is nearly vertical and the maximum and mini-

mum principal stresses are close to horizontal. So the magnitude of intermediate principal stress σ_2 can be approximately taken as the lithostatic pressure:

$$\sigma_2 = \rho gh, \quad (3)$$

where ρ is crustal density, h is depth, g is gravitational constant. If we know the depth of fault, σ_2 value can be estimated by equation (3). The average depth of the Dayao $M_S6.1$ seismic fault plane is 6 km. The crustal density is taken as $2.7 \times 10^3 \text{ kg/m}^3$, so we get $\sigma_2 = 158.7 \text{ MPa}$.

Using the stress drop and the intermediate principal stress value obtained above, together with the CMT result with strike 108° , dip 89° and rake -178° , which are determined from the long-period body-waves and surface waves, we can get the stress value of the σ_1 and σ_3 by the method of Wan (2006). The maximum and minimum principal stresses are estimated to be 166.3 MPa and 151 MPa, respectively. Projecting the stress tensor onto the fault plane, we obtained that the normal stress and shear stress before the Dayao $M_S6.1$ earthquake are 157.3 MPa and 7.4 MPa respectively, and are 158.8 MPa and 0.2 MPa after the Dayao $M_S6.1$ earthquake.

6 Discussion and conclusions

Using the improved grid testing method (Yu et al., 2009), we got the stress field directions before and after

the Dayao $M_S6.1$ earthquake. The results show that the maximum and minimum principal stress axes before the Dayao $M_S6.1$ earthquake are nearly horizontal in the direction of NNW–SSE and ENE–WSW, respectively, and the intermediate principal stress axis is nearly vertical. After the Dayao $M_S6.1$ earthquake, the principal stress axis deviates from the original directions. That is to say, the Dayao $M_S6.1$ main shock induced the rotation of stress direction.

We also estimated the seismic stress drop and intermediate principal stress. According to these estimations, we obtained all the stress values by the method of Wan (2006). The normal and shear stresses on the fault plane are 157.3 MPa and 7.4 MPa, respectively, before the Dayao $M_S6.1$ earthquake, and are 158.8 MPa and 0.2 MPa after the Dayao $M_S6.1$ earthquake. The shear stress before the Dayao $M_S6.1$ earthquake is larger than that after the earthquake, and their difference corresponds basically to the seismic stress drop. It indicates that although the underground compressive stress level is very high, the differential stress is not so high.

In order to estimate the uncertainty of our result, we perturbed separately the parameters of the determined composite fault plane solutions before and after

Table 2 Influence of the deviation of known parameters on the stress value in 2003 Dayao earthquake sequence

Revised range		σ_1/MPa	σ_3/MPa	$N_{\text{pre}}/\text{MPa}$	$S_{\text{pre}}/\text{MPa}$	$N_{\text{post}}/\text{MPa}$	$S_{\text{post}}/\text{MPa}$
Before the Dayao $M_S6.1$ main shock	Strike $-5^\circ - +5^\circ$	164.88–162.57 (2.31)	151.95–154.22 (2.27)	158.13–156.83 (1.3)	6.34–3.75 (2.59)	158.72–158.43 (0.29)	0.72––0.98 (1.7)
	Dip $-5^\circ - +5^\circ$	164.63–163.57 (1.06)	152.60–153.47 (0.87)	157.44–157.35 (0.09)	5.66–4.86 (0.8)	158.79–158.57 (0.22)	0.53––0.45 (0.98)
	Rake $-5^\circ - +5^\circ$	164.82–163.57 (1.25)	153.16–153.08 (0.08)	157.59–157.35 (0.24)	5.60–4.94 (0.66)	158.92–158.55 (0.37)	0.34––0.24 (0.58)
After the Dayao $M_S6.1$ main shock	Strike $-5^\circ - +5^\circ$	163.18–165.08 (1.9)	153.26–152.66 (0.6)	157.16–157.53 (0.37)	4.73–5.94 (1.21)	158.33–158.82 (0.49)	–0.53–0.68 (1.21)
	Dip $-5^\circ - +5^\circ$	164.40–163.52 (0.88)	153.21–152.94 (0.27)	157.60–157.10 (0.5)	5.35–5.05 (0.3)	158.86–158.37 (0.49)	0.12––0.20 (0.32)
	Rake $-5^\circ - +5^\circ$	164.47–163.33 (1.14)	153.08–153.10 (0.02)	157.55–157.12 (0.43)	5.44–4.88 (0.56)	158.79–158.41 (0.38)	0.22––0.38 (0.6)
$M_S6.1$ Dayao main shock	Strike $-5^\circ - +5^\circ$	163.72–164.25 (0.53)	154.09–152.27 (1.82)	157.08–158.00 (0.92)	4.34–5.87 (1.53)	158.85–158.63 (0.22)	–0.30–0.27 (0.57)
	Dip $-5^\circ - 0^\circ$	164.91–164.07 (0.84)	152.83–153.10 (0.27)	157.68–157.41 (0.27)	5.68–5.24 (0.44)	159.01–158.69 (0.32)	0.56–0.01 (0.55)
	Rake $-5^\circ - +5^\circ$	164.79–163.31 (1.48)	153.19–153.06 (0.13)	157.73–157.09 (0.64)	5.59–4.80 (0.79)	158.91–158.47 (0.44)	0.28––0.35 (0.63)
	Stress drop –0.5 MPa–+0.5 MPa	163.60–164.54 (0.94)	153.59–152.61 (0.98)	157.52–157.29 (0.23)	4.78–5.70 (0.92)	158.69–158.69 (0)	0.01–0.01 (0)

Note: σ_1 and σ_3 denote the maximum and minimum principal stresses, respectively; N_{pre} and N_{post} represent the normal stress on the fault plane before and after the earthquake, respectively; S_{pre} and S_{post} represent the shear stress on the fault plane before and after the earthquake, respectively. Numbers in parenthesis are the difference of the two perturbed values.

the Dayao $M_S6.1$ earthquake in a small range, and then substituted them into the formula of Wan (2006), finally got the stress value estimation. Although it is not a rigorous method to estimate the uncertainty of the result, we can estimate the uncertainty of the result qualitatively. The results are shown in Table 2. In Table 2, the absolute values are calculated with perturbed range with their difference in the parenthesis. The result indicates that as each known parameters are perturbed 5° or 0.5 MPa, the estimated maximum and minimum principal stresses and normal stresses only changed by 1.5%, the shear stress before and after the Dayao $M_S6.1$ earthquake changed in the same order of the estimated value. But the conclusion that the shear stress before the earthquake is larger than that after the earthquake would not be changed, which has been verified by the input parameters perturbation.

In this study, we assumed that the intermediate principal stress is equivalent to the lithostatic pressure. This assumption could be off from the reality if the fault was soaked with water, or if regional tectonic stress influenced the intermediate principal stress value. But even considering this sort of influences, the intermediate principal stress would be in the same order as the value we used in this study. The conclusion of low shear stress and high compressive stress in the crust would be unchangeable.

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