Study on seismogenesis of the 1997 Jiashi earthquake swarm, western China*

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Abstract The 1997 Jiashi swarm earthquakes are relocated using the "master event" method improved by the authors. From the relocated hypocenters and focal mechanisms of the earthquakes, it is inferred that a pair of echelon faults, striking in northern north-west direction, right-step allocated and right-laterally moved, may exist in the earthquake swarm region. The composite focal mechanism obtained by analyzing the data of 2177 P-wave first motion polarities indicates that both mean P- and T-axis are horizontal, orienting in N19°E and N110°E respectively, and the mean B-axis is nearly vertical. The co-seismic deformation caused by this earthquake swarm is compressive nearly in North-South and extensional nearly in East-West. Obviously low earthquake stress drops are found via analyzing the source spectra of the swarm earthquakes, which may be one of the main reasons why the Jiashi earthquake swarm has lasted for a long period of time. The interaction between discontinuous segments of the echelon fault has been discussed. The result indicates that the stress drop is usually low for the earthquakes occurring on the right step echelon faults.

Keywords: **strong earthquake swarm, master event method, seismogenic fault.**

The Jiashi strong earthquake swarm started in 1997 and lasted over 4 years. From January 21, 1997 to August 31, 1998 (its main active period), nine Ms $\geqslant$6.0 earthquakes occurred. This earthquake swarm was located in the marginal region of the Tarim basin, which is thought to be a tectonically stable block by most geologists[1,2]. It has been a rare phenomenon since the instrumental records came into being in the 20th century that so many strong earthquakes clustered within a small area in a stable intraplate region. The Jiashi earthquake swarm has attracted wide attention of both geophysicists and geologists, and some researchers have investigated the seismogenesis of the swarm based on the results of researches on crustal and upper mantle structure. For example, it has been found that a low-velocity belt exists in the crust beneath the swarm region[3], which may affect the evolution of the swarm. Liu et al.[4] investigated the 3D S-wave velocity structure of the crust and the upper mantle beneath the swarm region based on the dense broadband digital seismic observations. They found that the Jiashi earthquake swarm occurred in a crustal volume which is just above the zone where the depth of Moho discontinuity varies sharply, and the generation of earthquake swarm may be related to a buried fault[4]. Although these deep structure researches have unveiled the tectonic background for the swarm generation, the seismogenic fault associated with the Jiashi earthquake swarm is still unclear. The question why so many strong earthquakes clustered in a small area within a few months needs to be answered.

The Jiashi earthquake swarm occurred near the western end of the Himalayan plate collision zone and on the northeastern side of the Pamir syntaxis region, where the huge NW-SE stretching Talas-Fergana fault crosses the Tianshan Mountain range and divides it into East Tianshan and West Tianshan range. Burtman[5] found that the northwestern section of the Talas-Fergana fault in Kyrgyzstan was still active in the late Quaternary. However, we do not know where its trace is in western China and whether its section in China is active or not. According to the data of petroleum exploration, a strand of faults striking NW-SE or NNW-SSE may exist beneath the western region of the Tarim basin between Kashi County and Bachu County[6]. Are these faults the southeastern section of the Talas-Fergana fault zone? Are they re-

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lated to the generation of the Jiashi earthquake swarm? These need to be explored.

Precisely locating the hypocenters of an earthquake sequence is one of the most practical approaches to identifying the seismogenic fault. Recently, many researchers have studied the earthquake seismogenic faults with this method[7,8]. Spatial distribution of the Jiashi earthquakes and their focal mechanisms provide us with valuable information about the earthquake fault. Based on the result of relocated earthquake hypocenters, the retrieved source spectra and focal mechanisms of larger earthquakes, the fault associated with the generation of this earthquake swarm and its tectonic implication are explored in this study, and some special phenomena associated with the earthquake swarm will be discussed to enrich our knowledge about its genesis.

1 Relocating hypocenters and inferring seismogenic fault

The master event method proposed by Fitch[9] and Jackson[10] is quite useful in precisely locating the clustered events, like earthquake swarm, when the seismic stations are far from the events. Using this method, a master event whose absolute location can be well determined is chosen and the locations of other events relative to the master event are calculated. Since the distance between the located event and the master event is very small compared with the hypocenter distances between the events and stations, most part of the ray path for the located and the master event will be nearly the same. Therefore, the systematic errors due to an incorrect velocity model will not affect the accuracy of the event location relative to the master event, hence will not affect the locations of the events relative to each other in the cluster. Thus, we choose the master event method to relocate the hypocenters of the Jiashi swarm earthquakes in this study.

The fundamental equations for the master event method can be written as

$$T_{ij} - T_{iM} = T_{oj} - (L_j \cdot \cos S_{ij}/V), \qquad (1)$$

where T_{ij} is the observed travel time of the seismic wave (P or S) from event j to station i, T_{iM} the observed travel time of the wave (P or S) from the master event M to station i, T_{oj} the origin time difference between master event and event j, L_j the distance between master event and event j, S_{ij} the angle between the ray from master event to event j and the ray from event j to station i, V the average seismic wave (P or S) velocity along ray path from the master event to station i. First assume in this method L_j to be much smaller than the distance from the master event to the station, i. e. the size of the earthquake clustered volume is much smaller than the distances from hypocenters to stations, so the Fraunhofer's approximation is satisfied. Second, assume that the origin time and hypocenter location of the master event have been exactly determined.

We can see that in Eq. (1) there are four unknown parameters, i. e. latitude and longitude of the epicenter, focal depth, and the origin time of event j. In the conventional master event method, all the four unknowns are directly found from Eq. (1). However, the coefficient matrix of Eq. (1) may often be ill-conditioned due to the essential correlation between the determinations of the origin time and focal depth. In order to suppress the influence of the uncertainty in the origin time determination on the hypocenter parameters, we introduce a "reference station". As the basic observation, we use the arrival time difference of a given seismic phase between any two stations. One of them is taken as the reference station. In this way, we can eliminate the unknown origin time from Eq. (1).

Taking station R as the reference station, from Eq. (1) we can further infer that

$$T_{iRj} - T_{iRM} = (L_j \cdot \cos S_{Rj}/V) - (L_j \cdot \cos S_{ij}/V), \qquad (2)$$

where $T_{iRj} = T_{ij} - T_{Rj}$ is the seismic wave (P or S) arrival time difference of event j between station i and station R, and $T_{iRM} = T_{iM} - T_{RM}$ is the wave (P or S) arrival time difference of the master event between station i and station R. Obviously the unknown origin time of event j is not included in Eq. (2).

Solving Eq. (2) using singular value decomposition (SVD) algorithm, we found that the eigenvalue corresponding to the unknown focal depth of event j is usually very small, which means a lack of information on focal depth determination in the observed data. In fact, the travel-time of the direct P or S wave is insensitive to the focal depth variation when the epicenter distance is large. Therefore, it is difficult to use direct wave observations to constrain hypocenter depth. Fortunately, the travel-time of head wave is relatively sensitive to focal depth variation. In our improved master event method, the arrival times of

Pn (head wave) and Sn phase are used to constrain the hypocenter depth.

For the crust model of a single homogeneous layer, the travel-time t_n of head wave is expressed as

$$t_n = \Delta/V_2 - (2H - h)\cdot \cos i/V_1), \quad (3)$$

where Δ, H and h are the epicenter distance, the crustal thickness and the focal depth, respectively; i is the critical angle for the refraction wave from crust to mantle; V_1 and V_2 are wave (P or S) velocities in the crust and uppermost mantle, respectively. Eq. (3) holds for both Pn and Sn.

From Eq. (3), the focal depth difference δh between event j and master event M can be found

$$\delta h = [\delta\Delta_R/V_{2S} - \delta\Delta_i/V_{2P} - \delta T_{SR} + \delta T_{Pi}]/[\cos i_s/V_{1S} - \cos i_P/V_{1P}], \quad (4)$$

where V_{1P}, V_{1S}, V_{2P} and V_{2S} are the P or S wave velocities in medium 1 (crust) and medium 2 (uppermost mantle), respectively; i_P is equal to $\sin^{-1}(V_{1P}/V_{2P})$ and i_s equal to $\sin^{-1}(V_{1S}/V_{2S})$. And $\delta\Delta_R = \Delta_{jR} - \Delta_{MR}$, where Δ_{jR} and Δ_{MR} are the epicenter distances from event j to station R (reference station) and from the master event to station R, respectively; $\delta\Delta_i = \delta\Delta_{ji} - \delta\Delta_{Mi}$, where the suffix i means station i; $\delta T_{SR} = \delta\Delta_R/V_{2S} - \delta h \cdot \cos i_S/V_{1S}$; $\delta T_{Pi} = \delta\Delta_i/V_{2P} - \delta h \cdot \cos i_P/V_{1P}$, in which $\delta h = h_j - h_M$ denotes the focal depth difference between event j and master event M.

Eq. (4) shows that the unknown crust thickness does not affect the determination of focal depth.

Finally, 391 Ms≥3.0 earthquakes have been relocated using the improved master event method described above. The result indicates that almost all the relocated earthquakes cluster in a small area of 30 km (N-S) × 15 km (E-W) and their focal depths concentrate in the range of (20 ± 5) km. The epicenters of Ms≥5.0 earthquakes show an echelon-type alignment in NNW-SSE direction (Fig. 1), which implies that a pair of echelon fault segments with NNW-SSE strike and right-step allocation, may exist in the earthquake swarm region. This result is quite consistent with the 3D S-wave velocity structure of the crust and upper mantle in the swarm area obtained by Liu et al.[4]. The epicenters of the Jiashi Ms≧5.0 earthquakes show the same collocation as the NW-SE or NNW-SSE striking faults inferred from the petroleum exploration data[6] beneath the western margin of Tarim basin. This implies that the seismogenic fault of the Jiashi earthquake swarm may be closely related to these NW-SE or NNW-SSE striking faults.

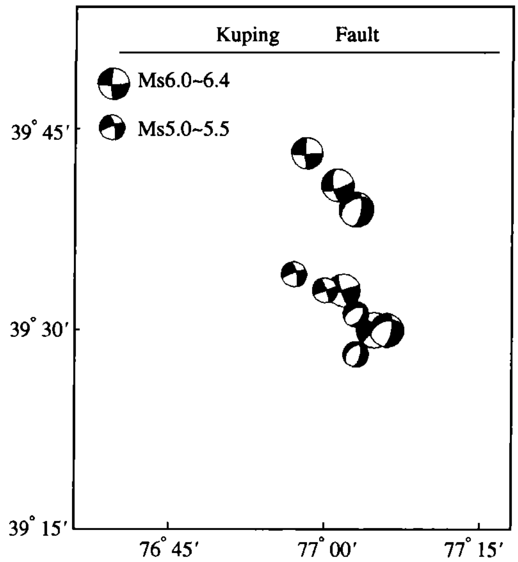

Fig. 1. Epicenters of Ms≥5.0 earthquakes and their mechanisms (Filled quadrant indicates compression, blank dilatation).

2 Focal mechanisms and earthquake rupture characteristics

Based on the central moment tensor (CMT) solutions from Harvard, the focal mechanisms of Ms≥5.0 earthquakes are shown in Fig. 1. We can see that almost all the focal mechanism solutions have a nodal plane striking NNW-SSE, which agrees with the direction of the echelon fault alignment. From Fig. 1 we can further infer that a pair of right-step and right-lateral echelon faults with NNW-SSE strike may exist in the earthquake swarm region.

The focal mechanism of a given earthquake gives the information about the tectonic stress that generates the earthquake. However, it is also influenced by the local heterogeneous structure of the earthquake source region. Examining Fig. 1, we can find that there are certain discrepancies both in nodal plane strikes and in normal faulting components among the focal mechanisms of the earthquakes, which implies that there are certain differences in the local medium structure or in the local stress regime in the earthquake region. In order to infer the general characteristics of the regional tectonic stress field in the earthquake swarm region, we use 2177 P-waves readings of the first motion polarities from 355 earthquakes, which occurred from January 21, 1997 to December 31, 1998, to determine the composite focal mechanism of the swarm earthquakes (Fig. 2).

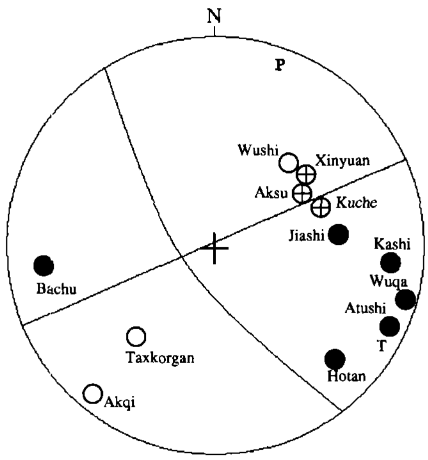

Fig. 2. Composite focal mechanism solution of the Jiashi swarm earthquakes (equal area projection of lower hemisphere).

● P-wave first motions show dominant compression polarity at this station;

⊕ Nearly equal compression polarity readings;

○ P-wave first motions show dominant dilatation polarity at this station.

Fig. 2 shows that the mean P-, T- and B-axis of the composite focal mechanism orient in NNE-SSW, nearly E-W and nearly vertical directions, respectively. The mean P-, T- and B-axis orientations obtained here agree with the orientations of the maximum, minimum and intermediate principal stress axes, respectively, in the western Xinjiang region as given in the stress map compiled by Xu et al.[11]. We have also inverted the first motion polarity data of P-waves from the earthquakes occurring during different time windows to trace the temporal variation of the composite focal mechanisms. We find that the mechanisms vary little in the evolving process of the earthquake swarm and the mean P- and T-axis azimuth vary less than 15°. This means that the tectonic stress field in the source region has almost remained stable during the whole period of the Jiashi earthquake sequence.

We have collected 172 digital broadband seismic records from 16 global digital seismic network (GDSN) stations for 12 Ms≥5.0 earthquakes, and made source spectrum analysis. The data sampling rate was 20 sps. In consideration of possible azimuth variation of the corner frequencies we paid special attention to the selection of recording stations, trying to have them encircle the Jiashi earthquake swarm region. We took the Silver's model[12] to match the low-frequency portion of the observed source spectra and used genetic algorithm to estimate the corner frequencies Fc, source rupture sizes and static stress drops of the earthquakes. The results are listed in Table 1. The results indicate that the static stress drops of the Jiashi swarm earthquakes are all about 0.1 MPa and obviously lower than a normal level of

Table 1. Earthquake parameters, source extents and stress drops inferred from source spectrum corner frequencies using Silver's model

Origin time (UTC)	ϕ_N	λ_E	M_S	$M_0(10^{17}$N.m)	F_c(P)(Hz)	F_c(S)(Hz)	r(km)	$\Delta\sigma$(0.1 Mpa)	Record stations
1997-01-21-01:47:13	39.50°	77.08°	6.0	7.74	0.202	no data	11.6	2.17	11
1997-01-29-08:20:13	39.57°	77.07°	5.2	1.00	0.316	0.205	7.84	0.91	2
1997-02-11-20:20:58	39.45°	77.08	5.0	0.91	0.218	no data	10.8	0.32	3
1997-03-01-06:04:14	39.72°	76.97°	6.0	3.35	0.236	0.100	13.4	0.60	3
1997-04-05-23:46:17	39.55°	77.03°	6.4	7.73	0.209	0.123	12.5	1.73	9
1997-04-06-04:36:32	39.50°	77.10°	6.2	10.5	0.170	0.090	16.3	1.06	10
1997-04-11-05:33:43	39.65°	77.05°	6.4	20.6	0.119	0.085	19.8	1.16	11
1997-04-12-21:09:08	39.52°	77.05°	5.5	1.06	0.283	0.071	16.1	0.11	2
1997-04-15-18:19:09	39.68°	77.02°	6.2	6.56	0.123	0.094	18.5	0.45	12
1997-05-17-03:58:22	39.65°	77.02°	5.4	0.80	0.375	0.235	6.73	1.15	3
1997-06-24-09:24:45	39.50°	77.00°	5.0	0.96	0.317	0.123	10.6	0.35	3
1997-10-17-17:35:11	39.58°	76.98°	5.0	0.81	0.341	0.133	9.8	0.38	2
1996-03-19-15:00:26	39.99°	76.70°	6.9	36.0	0.219	0.088	15.0	4.70	13

Note: (i) M_0 is taken from the Harvard CMT solutions; (ii) origin times, earthquake locations and magnitudes are determined in this study; (iii) corner frequencies are the averages over all three components and all recorded stations; (iv) r and $\Delta\sigma$ are the averages of those inferred from P and S spectra, $f_c = \tilde{\omega}_c/2\pi$; (v) the Artux earthquake occurred on March 3, 1996 is not far from the Jiashi swarm. However, its seismogenic fault is quite different from that of the Jiashi swarm.

several MPa[13], and are also obviously lower than the static stress drop of the Artux earthquake that occurred adjacent to the Jiashi earthquake swarm region on March 19, 1996. The low stress drop implies that deformation restoration in the Jiashi swarm region seems quite slow, which offers an explanation to the question as to why the activity of the Jiashi earthquake swarm has lasted such a long time of over 4 years.

3 Discussion

The seismogenic fault of the Jiashi earthquake swarm may be a pair of right-step and right-lateral echelon faults striking NNW-SSE, as inferred from Fig 2. A lot of field studies have demonstrated that most faults consist of numerous discontinuous segments and commonly aligned as echelon arrays. In some cases, discontinuities between these fault segments influence the distribution of slip and seismicity along faults[14]. Segall[14] et al. derived a two-dimensional solution for any number of nonintersecting cracks arbitrarily located in a homogeneous elastic medium. Their solution included the perturbing stress generated by the cracks, and the research result indicated that the mean compressive stress should decrease and promote the formation of secondary fractures because of the influence of the perturbing stress generated by the echelon faults. Therefore, it is natural that strong earthquake swarm like the Jiashi swarm occurred in such a tectonic background. Since the mean normal compressive stress decreases due to the appearance of right-step and right-lateral echelon faults, the static stress drops of the earthquakes occurring on such faults are generally lower than that of the earthquakes occurring on other faults. This conclusion is consistent with the result obtained from the corner frequency analysis above. Low stress drop implies that the accumulated tectonic deformation energy in the source region releases slowly and the active period of the earthquake sequence will last a long time.

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