Relocation of Earthquakes in the Northeastern Tianshan Mountains Area and Improvement of Local 1-D Crustal Velocity Model

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We apply three methods to relocate 599 earthquake events that occurred from August 2004 to August 2005 in the northeastern Tianshan Mountains area (85°30’ ~ 88°30’E, 43°00’ ~ 44°40’N) by using travel times recorded by regional seismic network and 10 portable seismic stations deployed around the Urumqi city. By comparing the reliability of different results, we determined a suitable location method, and an improved 1-D crustal velocity model of the study area. The uncertainty of earthquake location is significantly reduced with combined data of seismic network and portable stations. The relocated events are clearly associated with regional tectonics of the northeastern Tianshan Mountains area, and are also in agreement with the existence of active faults imaged by deep seismic reflection profile. The relocated seismicity discovers some potential traces of buried active faults, which need to be validated further.

Key words: Earthquake relocation; Velocity model; The northeastern Tianshan Mountains area; Active faults

\textbf{INTRODUCTION}

The Tianshan Mountains with particular geologic tectonic activity background is located at central part of Asian continent, south of Pamir Mountains, sandwiched between the Tarim Basin and Junggar Basin, and stretching for about 2500km from east to west, which is considered to be the consequence of collision between Indian plate and Asiatic plate (Abdrakhmatov et al., 1996). For decades, seismologists have outlined the basic tectonic framework of the orogenic belt in Tianshan Mountains by geophysical survey and deploying portable seismic arrays to study the

\textsuperscript{1) Received on April 8, 2011. This project was supported by the Basic Research Project of Institute of Earthquake Science, CEA (2012IES010103) and the National Natural Science Foundation of China (41204037).}
structure of some regions and analyze seismic activity (Deng Qidong et al., 1999; Deng Qidong et al., 2000; Guo Biao et al., 2006; Lu Deyuan et al., 2000; Mi Ning et al., 2005; Shao Xuezong et al., 1996; Xu Yi et al., 2000, 2005). Earthquakes frequently happened in the northern Tianshan Mountains area. As the east part of northern Tianshan area, the Bogda nappé structure consists of three rows of reverse fault-anticline zones with high potential risk of earthquakes, where the hazard earthquake is the 1965 Bogda earthquake with magnitude 6.6 and the historical earthquake with magnitude 7.0 according to the recorded of paleoearthquake; the west side of the Urumqi city is the northern Tianshan thrust nappé structure, composed of 3 ~ 4 rows of reverse faults-anticline zones, where the biggest earthquake is the 1906 Manas earthquake with magnitude 7.7. Liu Baojin et al. (2007) and Wang Chunyong et al. (2001) revealed the deep crustal structural features by using deep seismic reflection profile.

On condition that seismic stations location are known, the accuracy of earthquake location would be mainly affected by the selection of the initial model and the errors in reading travel time (Chen Qifu et al., 2001). Applying appropriate relocation methods with fit velocity models can improve the reliability of location results. So we can use different accurate location methods to choose velocity models by comparing the quality of relocation results. 1-D reference model is an important foundation for study of regional seismotectonics, and the reliability of 3-D imaging depends on reliability of the 1-D model. On the other hand, with reasonable accuracy, computation based on 1-D velocity model has advantages of low cost and high efficiency with respect to that on 3-D velocity model. Therefore, 1-D velocity structure is still one of the focus of present study on underground structure. At present, the research on 1-D crustal velocity model of the northeastern Tianshan Mountains area is not sufficient. Combined with travel time data recorded by broadband portable seismic arrays and regional seismic network, 3 precise earthquake relocation methods are applied in our research to improve the crustal 1-D seismic P wave velocity model in this area, and help to discover the distribution of nearby active faults and its relations with seismicity. That is, we first obtained an improved velocity model by comparing different relocation results of applying the same location method with different 1-D crustal velocity models then, we compared the location results obtained by applying different location methods with the same velocity model, according to geologic structure information; finally we determined the 1-D crustal velocity model and corresponding location methods which are considered suitable for the research area.

1 EARTHQUAKE LOCATION

1.1 Data

Supported by the exploration of seismic active faults project in the Urumqi city in July, 2006, 10 GüRALP CMG-3ESP broadband seismographs (equipped with REFTEK 130 digitizer) were installed around the active faults zone in the urban of Urumqi, together with regional seismic network, we established a temporary seismic network with a station spacing of 30 ~ 40km (see Fig. 1, note: there are another 4 permanent stations BHT [85.83056° E, 46.9911° N], BTS [90.51417° E, 45.28388° N], LSG [84.275° E, 45.56388° N], and WSU [84.64038° E, 44.12305° N] which sit outside the seismotectonic map).

After continuous observation from August 2004 to August 2005, we intercepted waveform of the events recorded by temporary network, converted its formal and picked up seismic phase. Totally, 2050 P-wave arrival time and 2012 S-wave phases were picked up. combining with 4615 P-wave arrival times and 4359 S-wave arrival times of the 2074 events of monthly phase report, we set up a dataset of phases and earthquake events. In order to ensure the stability of location results, we only select seismic events recorded at least by three stations for the relocation.
1.2 Location Methods

Three earthquake location methods are adopted in this research. One is a procedure HYPOSAT developed by Norway Seismic Array NORSAR (Schweitzer, 2001), which is recommended by the International Association of Seismology and Physics of the Earth’s Interior (IASPEI), which is suitable for location in global and regional scale; another is the HYPOINVERSE method, the single-event location procedure of the US Geological Survey (USGS), which is suitable for near-field precise location (Klein, 2001); the other is the HYPODD method, which was recently widely applied to locate earthquake clustering events (Waldhauser et al., 2000).

1.2.1 The HYPOSAT Location Method

The HYPOSAT location method is based on classical Geiger method (Geiger, 1912). Besides applying traditional seismic phase arrival time, the procedure also considers time difference of arrivals, azimuth from station to epicenter and ray parameter when locating earthquakes. Velocity models adopted by the method to correct travel time include regional and global models (Jeffreys-Bullen, PREM, IASP91, AK135, SP6, CRUST 5.1 etc.). HYPOSAT, as a location procedure of NORSA network, was once used by Walker et al. (2005) to relocate the Iran earthquake which took place in June, 2002. Hicks et al. (2004) adopted the method to evaluate the crustal velocity model in Barents Sea area.

1.2.2 The HYPOINVERSE Location Method

The HYPOINVERSE algorithm is a kind of single-event location method developed from Geiger method. In order to adapt to near-field earthquake location, based on HYPO71 of USGS, the program adds location algorithm which can be applied to gradient layers and multiple crustal
models, so that we could adjust thickness and velocity parameters of each layer of initial models. The principle is first to compute the travel time on model of near field, and then to determine epicenter and depth by travel time inversion. For complicated subsurface structure and distribution of seismic networks, the advantage of this method is that it can effectively improve the accuracy of location by setting up multiple crustal models. The HYPOINVERSE algorithm is one good location application within near field of the USGS which combined with focal mechanism solutions, is used by many seismologists to reveal the rupture process of local faults (Radziminovitch et al., 2005; Li Wenjun et al., 2005), to demonstrate regional seismic activity (Lippitsch et al., 2005) and to explore geologic structures, such as thrust fault (Langin et al., 2003)

1.2.3 The HYPODD Double-difference Location Method

The HYPODD double-difference location method is based on the approximation of the 1st order Taylor expansion of travel time equation. The method takes advantage of the fact that if the hypocentral separation between two earthquakes is small compared to the event–station distance and the scale length of velocity heterogeneity, then the ray paths between the source region and a common station are similar along almost the entire ray path (Waldhauser et al., 2000). By introducing travel time difference between earthquakes, we could well eliminate the location error caused by heterogeneity of velocity models to obtain the relative location and original time of swarm earthquake by means of iteration which is applicable to locate earthquake events at larger scale than main event method. This method is adopted by many seismologists to survey the distribution of fault zone in different regions (Schaff et al., 2002; Shearer, 2002), to explore blind faults (Courboulex et al., 2003; Zhu Ailan et al., 2005a, 2005b), and to reveal the close relation between seismic activity and tectonic activity (Waldhauser et al., 2002; Yang Zhixian et al., 2003).

1.3 Velocity Models Used for Location

The initial 1-D crustal models in this study came from the Geoscience Transects for Xinjiang Tianshan Mountains (Dushanzi)–Tarim–Kunlun Mountains (Quanshuigou), which implemented by Institute of Geology, Chinese Academy of Sciences in 1996 ~ 2000 (Xiao Xuchang et al., 2004, showed by XXC in Fig. 2) and the fine crustal structure obtained from deep seismic reflection profiling through the Manas Mw7.7 earthquake on the north margin of Tianshan Mountains (Wang Chunyong et al., 2001; 2004, showed by WCY in Fig. 2), and the single-

![Fig. 2](image)

Four P-wave velocity structures used for earthquake location
— Amended Xiao Xuchang’s model (XXCR), —— Model used in the Xinjiang Seismic Network (C65), ……… Xiao Xuchang’s model (XXC), —— Wang Chunyong’s model (WCY)
layer velocity structure used for routine earthquake location and cataloging by Urumqi local network was shown for C65 in Fig. 2. In addition, crust structures and tectonics of Urumqi depression revealed by deep seismic reflection profile in the northern margin of Tienshan mountains (Liu Baojin et al., 2007) could help to constrain our results. Since the key point of this research is to relocate earthquakes in this area, we focus on the shallow sedimentary which could significantly affects earthquake location, and define its mean velocity by referring to Urumqi deep seismic reflection profiling, when the depth is less than 40km, we amend our new model from based on Xiao Xuchang’s model, while the depth is more than 40km, we amend our new model based on Wang Chunyong’s model. Finally we obtained our new build velocity model with combined amendment (showed by XXC in Fig. 2).

2 RESULTS AND DISCUSSION

We first apply the HYPOSAT and HYPOINVERSE method mentioned-above to relocate earthquakes occurring in the study area (85°30’ ~ 88°30’ E, 43°00’ ~ 44°40’ N). Then, the HYPODD method is applied for location based on the precise location results of HYPOINVERSE.

2.1 Comparison of Location Results

Firstly, after we apply three method to relocate earthquakes on four initial models, we abandon the data, which travel time residual RMS larger than 1. The result of different model by applying HYPOSAT have similar number to each other with average 47, when applying the HYPOINVERSE method, the number of result different models is also equivalent, with an average of 639; while adopting the HYPODD method, relative to other models, the number of result on model XXCR increases by 50% than those on other models, reaching up to 417.

Secondly, by reference to the deep seismic reflection profile D in Urumqi, three methods are adopted with different initial crustal models (HYPOSAT, HYPOINVERSE, HYPODD) to relocate seismic events that occurred within 10km away profile D (Liu Baojin et al., 2007, see Fig. 6 for profile position) and recorded by our new combined local seismic network, and additionally, we comparative analysis the location results of the Xinjiang routine catalog as well.

![Fig. 3](image)

Projection Image of relocation by HYPOSAT method on profile D

(a) Urumqi deep seismic reflection profile (Liu Baojin et al., 2007) and projection within 10km way profile D of earthquakes occurring from August 2, 2004 to August 10, 2005 recorded by the Xinjiang Seismic Network.

(b) HYPOSAT location results on the WCY model. (c) HYPOSAT location results on XXC model

In Fig. 3 (a), there is obvious inconsistence between the earthquake location from the Xinjiang routine catalog and the result revealed by deep seismic reflection profiling including the fault plane and detachment. This inconsistence may be caused by the use of over simplified single-layer velocity model and uneven distribution of local seismic network, and meanwhile
demonstrates the necessity of more intensive array for observation and precise relocation. Compared with the location results of the Xinjiang Earthquake Catalog, the results of HYPOSAT do not show great improvement. Probably, it is due to that the HYPOSAT method is prior to be applicable for earthquake at large scale, even in global, but not suitable for local earthquake. The other reason might be that the shallow part of the two velocity models can not reflect the complicated structure of the Urumqi area well. So later on, we introduce the 1-D XXCR model for relocation, which amended on the XXC model.

Comparing Fig. 4 with Fig. 3, the result obtained by the HYPOINVERSE method is more consistent with the result of Urumqi deep seismic reflection profiling than that of HYPOSAT, which show that HYPOINVERSE can perform better for near-field earthquake location. For different initial velocity models, the location results of XXCR model which nicely reflects shallow structure display more consistent with high-quality deep reflection results of 120m shot interval with 40m receivers interval. When applying the HYPOINVERSE location method, we first simultaneously use P phase and S phase to locate earthquake, and then only use P phase, we find that simultaneously use P phase and S phase can help us obtain more location result data with smaller root-mean-square value of travel time residual.

Comparing with other velocity models by applying HYPOINVERSE method, the XXCR model produces improved location results in Fig. 4. The decrease of surface velocity of model XXCR effectively increase the number of relocating earthquakes, which depth can be determined,
while velocity variation at the depth of 30 ~ 50km reduces the number of relocating earthquakes occurring in depth of 20 ~ 30km. the depth of relocated earthquake sources indicate that earthquakes mainly occurred at the faults zone revealed by deep reflection profile and near detachment structure at the depth of 10 ~ 18km.

Comparing Fig. 4 with Fig. 5, relocation results of HYPODD by using HYPOINVERSE as initial location seem even more corresponding to the faults zone and detachment than that of HYPOINVERSE. After testing WDCT parameter with different values, we obtain relative optimized relocation result with WDCT 6km, meanwhile the number of earthquake clustering getting down. Although the number of locatable earthquakes of the HYPODD is less than that of the HYPOINVERSE, but the HYPODD method can better reveal the relation between clustering earthquake events and seismotectonics, as pointed out by many seismologists. In Fig. 5, the HYPODD location method shows the advantage of not being much affected by velocity structures, and proves the reliability of HYPOINVERSE location results (see Fig. 4 (d)) on the XXCR model.

Thus, we finally analyze correlation between the local tectonics and relocation earthquakes, which including results obtained by HYPOINVERSE with the amended XXCR model (Fig. 6) and those of HYPODD (Fig. 7).

It can be seen from Fig. 6 that the earthquake monitoring ability in the Urumqi area has been effectively improved with intensive combined local seismic mobile network by deploying 10 more
Fig. 6
Comparison of relocation results obtained by HYPOINVERSE with that reported by the Xinjiang Seismic Network
Earthquake magnitude:
- $3.0 \leq M < 4.0$
- $2.0 \leq M < 3.0$
- $1.0 \leq M < 2.0$
- $0.0 \leq M < 1.0$
- The Xinjiang Seismic Network results.
- The HYPOINVERSE results.
- Newly detected events by temporary seismic network. Green lines show profile $P_1 \sim P_5$, green line D shows deep seismic reflection profile.

Fig. 7
Comparison of the same earthquakes relocated by HYPOINVERSE and HYPODD
- Earthquakes relocated by HYPODD. 
- Earthquakes relocated by HYPOINVERSE.
temporary broadband seismic stations. According to the number of earthquakes recorded by at least three or more seismic stations, the HYPOINVERSE is able to locate 87 more earthquakes than the earthquakes recorded by Urumqi local catalog (see green circles in Fig. 6), about 12% of the total number relocated by HYPOINVERSE (87/727). The mean error of the 727 relocated earthquakes is 1.4~4.5 km in horizontal direction, 3.3 km~10.4 km in depth, and the mean RMS residual is 0.77 s. In Fig. 7, the mean RMS residual of 417 earthquakes relocated by HYPODD decreased to 0.273 s, and mean error of epicenters is 2.9 km in east-west direction, 3.4 km in north-south direction, and mean error of depths is 4.7 km.

The HYPODD method is applied to compare different models by residuals of relocation. For the same 165 events, mean residual by applying WCY model is about 0.447, mean residual by using XKC model is about 0.371, and mean residual by XXR model is about 0.317. With improvement of models, residuals are decreased as well, it reaches the minimum value when we use the amended XXR velocity model.

2.2 Discussion

After relocating by the HYPOINVERSE and HYPODD method, events with depths of 10~18 km account for 58% and 47% of the total, respectively, which further indicates that detachment structure exists at the depth of 10~18 km under extensive tectonic deformation in this area (Liu Baojin et al., 2007). Seismic activity is evidently dominated by thrust nappe structure of the Tianshan piedmont fault and southern Junggar basin fault. Most small earthquakes took place in the Junggar basin and the margin zone between Chaiwobao basin and northern Tianshan Mountains. Influenced by material interchange between Moho and upper-most mantle, the middle-lower crust is characterized by plasto-toughness with rare seismic activity. Our results show that the number of located earthquakes above 30 km depth by HYPOINVERSE method accounts for about 98% of the total; the number located by HYPOD method about 99% of the total, which suggest the dominant distribution of earthquakes is in shallow crust.

Besides the statistics of travel time residuals, we need to consider if the relocation earthquakes could well characterize local known faults zone or not. Since earthquakes distribution close related with active faults (Xu Yi et al., 2005), we can analyze the quality of results referring to known geological faults zone distribution.

![Fig. 8](image)

**Fig. 8**

Distribution of HYPOINVERSE location results in 3-D view

The red circle demonstrates earthquakes recorded by the Urumqi Seismic Network, and the blue circle denotes earthquakes recorded after the temporary seismic stations are deployed.

It can be seen from Fig. 6 that there was significant variation for small earthquake activity around the active faults in Urumqi city, where temporary seismic stations were densely deployed.
in the one-year observation period. It seems that seismicity is relatively weak along the NEE faults and the faults distributed at middle and northern part in target area. Earthquakes mainly distributed in the southern part of target area, concentrated at the Bogeda Mountains, Chaiwobao basin and its western area, which may result from thrust nappe tectonism of the Tianshan piedmont fault and southern Junggar basin fault, and this cause concave distribution of 3D seismicity around the area (43.6°N, 87.5°E). According to analysis and statistics, heaviest seismicity along the border area between Bogda Mountains and Chaiwobao basin may be related to interaction between the northern Chaiwobao blind fault and Hongyanchi fault.

Centering on the target area of Urumqi active fault survey project, we take the profile P1 ~ P5 across the fault as shown in Fig. 7 to analyze seismicity in depth. A seismic zone at depth of 10 ~ 18km is clearly revealed in the P1 ~ P5 profile as shown in Fig 9. It indicates the existence of detachment structure in this area as revealed by deep seismic reflection profile, which may result
Earthquakes profiles

Fig. 9
From top to bottom show earthquakes within 20km away profile P1, 8km away profile P2, 11km away profile P3, 10km away profile P4, and 16km away profile P5. HYPOINVERSE results are shown on the left, and HYPODD result are shown on the right from the effect of structural deformation. While seismicity in shallow part of profile P1 at horizontal axis 60 ~ 120km of HYPOINVERSE probably demonstrates seismicity of the Tianshan piedmont fault and southern Junggar basin fault, which is more evidently showed by P1 profile of HYPODD shown in Fig. 9. Seismicity in southern Junggar basin fault is also revealed at horizontal axis 50 ~ 60km in profiles P2 and P3, most of which distributed at the boundary area between the southern margin of Junggar basin and the northern Tianshan Mountains above the depth of 30km, which may be related to faults zone and fold tectonics, suggesting that this area might be boundary between two blocks with different properties. Shallow earthquakes at horizontal axis 30 ~ 50km of HYPOINVERSE profile P5 may result from Xishan fault activity, which is also shown in the corresponding HYPODD profiles.

It should be pointed out that deep faults possibly exist between thrust nappe structures of the Tianshan piedmont fault and southern Junggar basin faults, which is shown faintly in Fig. 4(d) and Fig. 5(d) and also appear in profiles P1, P2, P3 and P5 as shown in Fig. 9 (see grey segments marked by ? in the map), and this is also revealed in Urumqi-Korla seismic converted wave depth profile (Shao Xuezhong et al., 1996). But the majority earthquakes depth data of results are constrained by observation period and locatable earthquakes. Therefore, further comprehensive research is needed to prove the existence of the deep faults, which including detailed seismic exploration, medium physical property and seismogeologic structure.

3 CONCLUSION

In contrast to other relocation study of this area, we apply mainstream method with travel time data recorded by broadband temporary seismic arrays and regional network to do precise relocation on more detailed 1-D initial crustal velocity models. We significantly improves the seismic monitoring ability of the target area in Urumqi, and provides reliable basic data for seismic risk assessment in the Urumqi city.

Through tests of earthquake relocation with three methods, we optimize the regional velocity structure models for the research area. Spatial distribution of small earthquakes, especially the depth of hypocenters, is of revealing brittle failure of rocks of intercrustal layers (Xu Yi et al., 2005). The relocations of small earthquake activities in this paper clearly reflect the level of tectonic movement around the Urumqi city, and also reveal the existence of detachment structure at the depth of 10 ~ 18km under the effects of structural deformation. Seismic activity is obviously dominated by thrust nappe structure of the Tianshan piedmont fault and southern Junggar basin.
fault. Traces of seismic deep faults may be found between thrust nappe structure of the Tianshan piedmont fault and southern Junggar basin fault, which still need to be further study.

ACKNOWLEDGEMENTS

Location procedure developed by Klein and location procedure developed by Waldhauser and Ellsworth are applied in this research. During this research, full support and cooperation is given by the Earthquake Administration of Xinjiang Uygur Autonomous Region. Many thanks to Mr. Wang Haitao, Mr. Song Heping, Mr. Shen Jun, Mr. Yin Guanghua, Mrs. Wei Ruoping and Mr. Song Lijun who proposed valuable comments and suggestions to solve a lot of difficulties in field work; the authors thanks Mr. Liu Baojin, researcher professor of Geophysical Exploration Center, China Earthquake Administration, who supplied deep seismic reflection CMP stacked time profile and relevant maps.

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