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Preface

During the last four years there have been significant advances in China, a country with intense seismic activity and earthquake disasters, in the study of seismology and physics of the Earth's interior. These results are of significant help to the social endeavor for the reduction of earthquake hazard and risk, and potentially have an important impact on the development of seismology and solid-Earth geophysics even in a global perspective. Besides the continuous advancements in the on-going researches on seismic source, seismic waves, earthquake prediction, seismo-tectonics, Earth structure and geodynamics, and interdisciplinary studies related to the phenomenology and physics of earthquakes, among others, in the turn of the centuries, the development of seismology in China is specially highlighted by its comprehensive upgrading of observation/research facilities as marked by the digital broadband seismograph networks and data centers at national, regional and local levels, and the geodynamical modeling using high-performance computation.

The present National Report, organized by the Chinese National Committee for the International Association of Seismology and Physics of the Earth's Interior (IASPEI), reviews the developments in seismology in the Chinese mainland from 2003 to 2007. In China, at present, most of the publications are in Chinese (with English or Russian abstract), although quite a few Chinese seismologists also publish their researches in international journals. Accordingly, the National Report is of special importance for letting international colleagues understand what is going on in the seismological studies in China. It is worth acknowledging that contributions to seismological researches from the Chinese seismologists in Taiwan and Hong Kong, as well as from the overseas Chinese seismologists all over the world, are also significant, which are not reflected in the present national reports due to limitation of space and time. Cooperation between seismologists in the Chinese mainland and other places got fruitful results in many aspects. Seismology as a tool of prospecting the lithosphere and crust structure also contributed much to the study of fundamental geology and the development of oil industry. What is reflected in the present report is only the study of seismo-tectonics in the perspective of the geology and geodynamics of earthquakes.

During the last four years, seismological researches in China got significant supports from the National Natural Science Foundation of China (NSFC), the Ministry of Science and Technology (MOST), the China Earthquake Administration (CEA), and the Chinese Academy of Sciences (CAS), as well as other governmental and non-governmental organizations, especially from the central government. The cooperation with IUGG, IASPEI, Asian Seismological Commission (ASC), and other international organizations, plays an active role in promoting the international exchange and collaboration between seismologists in China and other countries.

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Studies of the Physics of Seismic Source in China

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Abstract: On a basis of the papers published in the Chinese geoscience journals,this paper summarizes the research activities in the physics of seismic source that happened in the years 2003 to 2006 in China. The research works are presented in 6 fields, which are source complexity of the strong earthquakes, source parameters of moderate-to-small earthquakes, application of source parameters, earthquake location, theory and experiment on seismic source, as well as nuclear explosion seismology.

Introduction

Physics of seismic source is one of the important components of seismology, also it is one of the most active frontier fields of geophysical research. In the period of 2003 to 2006 years, more than 40 papers regarding the physics of seismic source were published on Chinese geoscience journals. In this article, we make a summary as the followings, which are divided into 6 parts: source complexity of the strong earthquakes, source parameters of the moderate-to-small earthquakes, application of the source parameters, earthquake location, theory and experiment on seismic source, as well as nuclear explosion seismology.

1. Source complexity of the strong earthquakes

Rupture process or source complexity of stronger earthquakes have been paid much attention to by the world-wide seismologists due to its importance to understanding physics of seismic source. Chinese seismologists have been become active in this direction. Although several years have passed since the 1999 Chi-Chi earthquake, and some studies had been done, some studies have still been done, for example, Zhou and Chen (2006) inverted the near-field seismic recordings for the dynamic rupture process of this earthquake. On the 14th of November, 2001, there occurred a strong earthquake in the western pass of Kunlun Mountain in China. In order to understand the source physics of this earthquake, varieties of research works have been done by Chinese researchers. Xu and Chen (2004) inverted the long-period waveform data recorded by global seismic stations and obtained the rupture process. Also, Ma and Shan (2006) analyzed the InSAR data, and Wang *et al*. (2005) inverted both the GPS and far-field P waveform data. On the 27th of September, 2003, there occurred another strong earthquake of M_S7.9 on the border area of China, Russia and Mongolia, and on the 1st of October in the same year, one stronger earthquake with magnitude M_S7.3 occurred almost at the same location. Zhao *et al.* (2005) inverted the broadband recordings from global seismic stations for their dynamic rupture process. On the 11th of July, 2004, an M_W 6.2 earthquake occurred in Tibet. Li *et al*. (2005) obtained its rupture process by the inversion technique similar to the above.

2. Source parameters of the moderate-to-small earthquakes

Determination of parameters for moderate-to-small earthquakes is a difficult but important work. In China, there are a quite number of researchers working on this. Yu *et al*. (2003) introduced the amplitude ratios of SV/P, SH/P and SV/SH into the method for determination of focal mechanism in order to obtain the results of higher precision. Cheng *et al*. (2003) studied the M_S5.0 foreshock, M_S6.0 mainshock and the whole earthquake sequence which occurred in Yajiang county of Sichuan province in February of 2001 for their focal mechanisms, parameters of source spectrum, variation of stress drop and seismicity of the epicentral area. Qin *et al*. (2003) analyzed the M_S6.4 earthquake sequence for its physical process which occurred on the 15th of January, 2000, in Yaoan of Yunnan province using seismic recordings from a near-field small-apature network. Long (2004) choose the recordings of 88 events of the Yajian earthquake sequence clearly recorded by at least 5 stations, which occurred during the period of the 1st of January to the 30th of June, 2001, relocated these events and determined the focal mechanisms of the 13 bigger events. Wu *et al*. (2004) inverted the waveform data of 33 moderate-to-small local earthquakes from the Yunnan Digital Seismograph Network for their focal mechanisms. Kang *et al*. (2005) applied the first-motion-and-amplitude-ratio technique to the recordings of 32 local earthquakes greater than M_L3 recorded by Guangdong Digital Seismograph Network for their focal mechanisms, and analysized the spatial characteristics of the focal mechanisms in Guangdong and its neighboring areas combining the focal mechanisms of 83 events obtained by others. Mao *et al*. (2006) inverted the direct P waveforms of the vertical components generated by the 2000 Yaoan M_S6.5 mainshock and its aftershocks with magnitudes of M_L3.0~5.0 for their moment tensor solutions. Gao *et al*. (2005) presented the spatial distribution of hazard caused by the Inner Mongolia M_S5.9 earthquake which occurred on the 16th of August, 2003, inverted the long period waveform data recorded by China Digital Seismograph Network for its moment tensor solution and focal mechanism, and analysized for the characteristics of the focal mechanism, aftershock distribution and hazard distribution and the relationship between the focal mechanism and the hazard distribution.

Gao and Zheng (2004) obtained the quality factor (Q value) and the anelastic attenuation coefficients for the central and western Inner Mongolia from the seismic recordings generated by 9 earthquakes and recorded by the Hohhot Digital Seismograph Network. Wang *et al*. (2004) obtained the source spectrum at the lower frequencies for 27 earthquakes and the site effects in the central area of the Central China by means of genetic algorithm. There occurred an M_S6.8 earthquake on the 24th of February, 2003, at the southeastern end of the Jiashi region, Xinjiang, where 9 earthquakes of about M_S6.0 occurred in the period of 1997 to 1998. Gao *et al*.(2004) analyzed the characteristics and stress drop using the focal mechanisms of this sequence. Chuo *et al*. (2004) studied the anelastic attenuation coefficients, the site effect and some source parameters using 310 seismic recordings recorded by 14 seismic stations of Shanxi Digital Seismograph Network. Lan *et al*. (2005) calculated the Q values for Beijing area, the mountain area in the west of Beijing and the plain area in the east of Beijing. Liu *et al*.(2005) calculated the anelastic attenuation coefficients for the epicentral area of Shidian earthquake using Atkinson method and the site effects of 6 stations within this epicentral area using the Moya method (Moya *et al*., 2000). Liu *et al*. (2006) estimated the source parameters of the Huize M_S5.3 earthquake, which occurred on the 5th of August, 2005 and of the Wenshan M_S5.3 earthquake, which occurred on the 13th of

August, 2005, using the seismic recordings from Yunnan Digital Seismograph Network.

Wang *et al*. (2004) determined the source parameters of the earthquakes in the Guangzhong and its neiboring areas by analyzing the spectrum of the seismic recordings from Xi'an Digital Seismograph Network. Zhao *et al*. (2005) proved by the empirical Green's function technique that the source spectra in the central and eastern Tianshan area follow the ω^2 -model. Further more, they determined the spectrum of 105 events with magnitudes M_L2.5～5.7, and calculated the seismic moments, stress drops, and source dimensions. Qin *et al*. (2005) estimated the source parameters of 300 events of the Shidian M_S5.9 earthquake and its aftershocks using the seismic recordings from Kunmin Digital Seismograph Network, which occurred on the 12th of April, 2001.

3. Application of the source parameters

Application of the source parameters to other studies have been an active research field for a long time. Similar situation has continued in the past years. Zhang *et al*. (2004) analyzed the scaling law of the source parameters using the results recently obtained by digital imaging of rupture process of earthquakes. Shi and Zhu (2003) analyzed the variation of the focal mechanisms with depths using the moment tensor solutions offered by Harvard CMT Catalog. Diao *et al*. (2005) estimated the regional stress filed of Jiashi, Xinjian, based on the moment tensor solutions of the bigger earthquakes in the period of 1977~2003 from the Harvard CMT catalog. Zheng *et al*. (2006) discussed the relationship between the solutions of focal mechanisms and the probable potential seismogenic structures in the Chinese mainland southern to 34°N and eastern to 105°E using the focal mechanism solutions.

4. Location of the seismic sources

The double difference (DD) method for earthquake relocation has been widely used in studies of seismicity recent years. By the DD method, Yang and Chen (2004) relocated the mainshock and aftershocks with magnitudes $M_L \geq 3.0$ of Zhangbei-Shangyi earthquake sequence, Zhu *et al*.(2005) relocated 2098 earthquake which occurred in the Capital region, Beijing, in the period of 1980~2000, Huang *et al*.(2006) relocated 404 earthquakes with magnitudes $M_L \geq 3.5$ of the Bashi-Jiashi, Xinjiang, M_S6.8 earthquake sequence which occurred in 2003, and Li *et al*.(2006) relocated the Shihezi, Xinjiang, M_S5.4 mainshock, which occurred on the 14th of February, 2003, and its aftershocks. In addition, new techniques for eathquake location were been developed. Xu *et al*. (2006) relocated the earthquakes in the central Tianshan Mountain and its neiboring area in the period of 1997~1998 in cases that both P- and S-arrival times of the broadband seismic recordings are available and the 1-D and 3-D velocity models of the crust are taken into account.

5. Theories and experiments in the physics of seismic source

Theories and experiments is a very important component of the physics of seismic source. Some seismologists have been sticking on this. Jiao *et al*. (2003) studied the influence of mesoscopic heterogeneity on macroscopic behavior of rock failure and seismic sequence types using a newly-developed numerical method called $RFPA^{2D}$, and suggested that different heterogeneity would result in different types of earthquake sequence. Chen *et al*. (2003) applied the method of discontinuous deformation analysis to rupture processes of the 1966 Xingtai earthquake, the 1969 Bohai earthquake, the 1975 Haicheng earthquake, and the 1976 Tangshan earthquake, and proposed that this method is reliable in numerical modeling of earthquake process. Ding *et al*. (2003) calculated the displacement field in the half-space two-phase saturated medium generated by a concentrated force by some special transforms. According to the principle of fracture mechanics, He *et al*. (2005) proposed the cessation criterion of brittle fracture and gave the equation of minimal crack cessation. By using the zero frequency Green function, they analyzed the steadiness and cessation of brittle fracture driven by the concentrated force and simply distributed forces in different positions, and proposed the critica1 loading, unsteady boundary line and location of cessation points under some typical conditions.

6. Nuclear explosion seismology

Studies of sources of underground nuclear explosion have been interesting though activities of underground nuclear explosion are getting less and less. He and Chen (2006) estimated the relative source time function (RSTF) of probable quakes in the objective area using underground nuclear explosion of small yield as the event of empirical Green function (EGF), and analyzed the differences between the RSTFs of tectonic earthquakes and of underground nuclear explosion. Zhao *et al*. (2005) calculated the parameters of equivalent source model by waveform inversion, and estimated the yield of the India nuclear explosion from the strength of statistic mechanics. Wei and Li (2003) proposed the concept of cepstrum, introduced the method for identification of man-made quakes from tectonic earthquakes into the cepstrum domain from time domain and frequency domain, and set up a discrimination criterion. Also, they applied this method to some tectonic earthquakes and underground nuclear explosions.

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From Analogue to Digital:
The digital seismology of digital seismograph networks

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Abstract: Since the last four years seismological observation in China has completed the transition from analogue to digital systems. To reflect this advancement, this report reviews the technique studies and developments related to digital seismograph networks.

The last four years witnessed the rapid development of digital seismology in China. To much extent it can be said that seismology in China has completed the historic transition from analogue to digital times. Liu Ruifeng et al. (2003) reviewed the development of digital observation systems in China in the national report of 2003. As its continuation and extension, this report focuses on the technique studies and developments related to digital seismograph networks in China. These studies and developments acted as the basis for the planning, deployment, maintenance, and management of the new digital seismological observation system. If the analysis of digital seismograms in the studies of seismic source, strong ground motion, and seismotectonics can be regarded as the digital seismology in a general sense, then this report deals with the digital seismology in a specific sense, i.e., its technique aspects.

At present time agencies and academic organizations coordinating the digital seismological observations in China include the Department of Earthquake Monitoring and Prediction of the China Earthquake Administration (director Li Ke), the Coordination Group for Seismological Observation and Interpretation (group leader Wu Zhongliang) and its Executive Group (group leader Liu Ruifeng), and the Commission for Seismological Observation Technology of the Seismological Society of China (commissioner Yin Chaomin). Provincial Earthquake Administrations (Seismological Bureaus) have their agencies managing the observations, namely Division for Earthquake Monitoring for management, and Center for Seismological Monitoring for network maintenance and data analysis. In the last four years one of the structural changes in the China Earthquake Administration is that the new China Earthquake Network Center (CENC, director Yin Chaomin, chief engineer Liu Ruifeng) was established in 2004, being responsible for the routine observational works of the national seismograph network and the quality-control of the regional and local networks. Before 2004 these jobs were taken by the former Center for Analysis and Prediction and the Institute of Geophysics. After the establishment of the Network Center, the Center for Analysis and Prediction changed to the Institute of Earthquake (Prediction) Science, and the Institute of Geophysics keeps conducting the maintenance and management of the China Digital Seismograph Network (CDSN).

To much extent the digital seismology in China was initiated by the Sino-US cooperative China Digital Seismograph Network (CDSN), a partner of the IRIS Global Seismograph Network (GSN), which is still well functioning till today (Zhou Gongwei et al., 2005). Observing the GSN standards, engineers and technicians also made quite a few improvements to the hardware and software of the CDSN stations to facilitate the observation and data processing (Yu Hui, 2003; Li Zongfen et al., 2003; He Yueshi et al., 2005; Deng Cunhua et al., 2006; Ma Baojun et al., 2006). On the other hand, the advancement of digital seismology in China has been being so fast since recent years that technique developments and scientific researches in the field of digital seismology have been far beyond the scope of CDSN.

Replacement of analogue recordings by digital ones is one of the most important developments since the 1990s. Despite that this process is somehow later in China comparing to that in developed countries/regions, Chinese seismologists still carefully arranged a period of parallel observation of analogue and digital systems to ensure the smooth transition of the observation regimes, which provides useful experience for the organization of long-term geophysical observations. Accordingly, one of the topics under discussion among seismologists working on regional and/or local networks is how to guarantee the smooth transition from analogue to digital systems. A systematic study was organized comparing analogue and digital observational data (Liu Aichun et al., 2003; Xie Caimei and Zhao Aiping, 2003; Di Xiuling et al., 2004; Liu Fu'an et al., 2004; Wang Ping and Di Xiuling, 2004; Yang Jingqiong et al., 2004; Wang Zhaoqing, 2005; Lin Shengfa, 2005; Guo Peilan,2005; Zheng Xiufen et al., 2006; Hu Fengying et al., 2006; Wang Lanlan et al., 2006). It turned out that continuity and consistency of observational results (such as earthquake catalogues) can be guaranteed by the comparison and correction process with the replacement of analogue recordings by digital ones. This investigation acted not only as a technique study for the smooth transition between observational systems, but also as an opportunity of training for seismologists, engineers and technicians working on seismological networks to get familiar with the brand-new observation system.

The Coordination Group for Seismological Observation and Interpretation and its Executive Group organize nationwide evaluation of network performance for the quality-control purpose. Training was organized on the conducting and application of digital seismology. *IASPEI New Manual of Seismological Observatory Practice* was translated into Chinese (leader of the group for translation and publication: Li Ke) as the textbook for the training. At least partly motivated by such evaluation and training activities, experiences were gradually accumulated related to the design, field survey, installation, maintenance, health-state monitoring and trouble shooting, data management, and data service of seismograph networks, together with technique improvements (e.g., Zhao Zhonghe et al., 2003; Zheng Guorong et al., 2003; Liu Aichun, 2003; Shan Dehua et al., 2003, 2004; Mai Haoming and Yuan Guolian, 2003; Liu Dongsheng and Guo Yajiang, 2003; Wang Cuifang, 2003; Chen Fei et al., 2003; Li Zhubo and Huang Wenhui, 2004; Wang Xiaofeng et al., 2004; Chen Jianjun et al., 2004; Liao Fajun et al., 2004; Li Jiang and Xue Bing, 2004; Ma Baojun et al., 2004; Gao Jie and Que Yuncai, 2004; Wang Fengji and Ji Aidong, 2004; Ma Baozhu and Liu Pingren, 2004; Liao Shirong et al., 2004a; Xiao Jian et al., 2004; Zhou Dawei et al., 2004; Tang Mingshuai, 2004; He Jiabin, 2004; Zhao Hai, 2004; Lu Jinshui et al., 2004b; Ge Ning and Zhang Xueying, 2004; Zhang Yonggang et al., 2006; Han Jin and Xie Ronghua, 2006; Cui Qinggu et al., 2006; Chen Hongfeng et al., 2006; Jiang Shaozhi and Zhang Zhiyu, 2006; Lu Yongqing et al., 2006; Wang Cuifang and Song Cheng, 2006). These experiences and technique improvements plays an important role in the quality-control process. This set of knowledge has evident diversity and practical applicability, but at the same time, to some extent, is not very much systematic and is by no means well organized. However, it is such chaotic and detailed knowledge and experience that determines the performance of the network. It is somehow encouraging that quite a few experts like to write down such knowledge for the exchanges with colleagues. *Seismological and Geomagnetic Observation and Research* (editor-in-chief: Xiu Jigang), the magazine edited and published by the China Earthquake Network Center and the Commission for Seismological Observation Technology of the Seismological Society of China and oriented directly to the readers working at seismic stations and/or local/regional seismological bureaus, provides a unique stage for such exchange. It is a pity that most if not all of the papers/letters are in Chinese. A compensation for international colleagues is the English abstracts/titles which are sometimes poorly translated. Nevertheless, there are still many works and experiences out of the scope of the published literatures, somehow an interesting culture in the community of seismological observation and interpretation not only in China but also in other parts of the world.

Calibration and testing of seismological instrumentations is the basis for observation and research, which is also one of the important aspects in the digital seismology in China during the last four years (Yan Qizhong et al., 2003; Zeng Ke et al., 2003; Zhang Zhe and Luo Xinheng, 2003; Cui Qinggu and Tong Wanglian, 2003; Zhou Yunyao and Lu Yongqing, 2003; Zhou Yunyao, 2004a, b, 2005; Li Songyang et al., 2005; Wang Xiaomei et al, 2005; Li Zhonghua et al., 2005; Cai Yaxian and Lu Yongqing, 2005; Zhang Yanbin et al., 2006; Zhou Yunyao and Zhang Bo, 2006; Yang Boxiong et al., 2006). Understanding of the role of seismological observation in the perspective of system science leads to significant improvement in the concepts for the design of observational systems. Traditionally, seismological observation and strong motion observation were conducted independently in China. To bridge the gap between these two observation systems, Yao Lanyu et al. (2004) discussed the transform from seismological recordings (usually velocity) to acceleration, and Jin Xing et al. (2005) discussed the real-time transform from strong motion recordings (usually acceleration) to displacements.

Application-oriented studies had been carried out on seismic waveform analysis.

Wavelet transform was used to data compression (Wang Xizhen et al., 2004b), seismic data analysis (Liu Xiqiang et al., 2003b; Xie Zhoumin et al., 2004; Liu Zemin, 2004; Chen Fei et al., 2004; He Xiaobo and Zhou Huilan, 2005; Li Ying et al., 2006), and discrimination between earthquakes and explosions (Liu Xiqiang et al., 2003a; Yang Xuanhui et al., 2005). Waveform analysis also used different techniques from multi-stage/multi-rate filter (Wang Xizhen et al., 2004a) and time-frequency analysis (Liu Xiqiang et al., 2004; Zhang Fan et al., 2006) to Hilbert-Huang transform (Wu Anxu et al., 2005), among others.

Ren Xiao et al. (2004) presented the noise spectrum of the sites of the China national seismograph network. Noise assessment were also conducted to the stations of Yunnan telemetric digital seismograph network (Yang Jingqiong and Yang Zhousheng, 2005) and the new stations of the Guangxi digital seismograph network (Xu Ning, 2006), as well as other stations of which the noise assessments are only technique archives and are not very much interested for technicians for getting published. Zhang Congzhen et al. (2004) analyzed the microseisms at the Zhangjiakou and Xinglong seismic stations. Fang Yeping et al. (2005) reported their 'real-time tracking system of microseism changes before strong earthquakes' (RTTS), trying to apply it to the studies of earthquake forecast and prediction.

Communication is one of the rapidly developing techniques in seismic network technology in recent years (He Shaolin, 2003; Meng Guojie et al., 2003; Guo Deshun et al., 2004; Liu Qiongxian et al., 2005; Wu Shukun et al., 2005; Wang Hongti et al., 2006b; Chen Yang and Wang Hongti, 2006). Based on this development, automatic picking and analysis of seismic phases attracted the attention of seismologists (Wang Haijun et al., 2003; Yang Peixin et al., 2004; Wang Ji et al., 2006; Teng Yuntian et al., 2006); quick earthquake information service was discussed for digital seismic networks (Liao Shirong et al., 2004b； Ling Xueshu et al., 2004; Zhao Jianhe and Qi Hao, 2004; Li Guihua et al., 2005); networking of regional/local networks had been prepared (Wu Tiesheng et al., 2004); and real-time/near-real-time processing of seismic data had become one of the practical technique issues (Lei Qiang, 2003; Lei Qiang and Huang Wenhui, 2004; Lu Jinshui et al., 2004a; Wang Hongti et al., 2004, 2006a). Attention was also paid to the application of Grid technology (Hou Jianmin et al., 2006).

Advancement in seismological instrumentation can be seen from the development of seismometers, from broadband (Chen Zubin et al., 2006) to very-broadband (Cai Yaxian et al., 2004), and from borehole (Wang Jiahang et al., 2006; Hu Luduan et al., 2006) to ocean-bottom (Shao Anmin et al., 2003), indicating the technique capacity of Chinese seismological community. Ma Jiemei et al. (2006) explored the MEMS velocity seismometer. Feng Yijun and Zhao Jialiu (2005) discussed the standardization of seismological observations. Jin Xing et al. (2006) discussed the future application of seismological monitoring system.

The last four years has shown significant development in the capacity building in China in seismological observations. For international seismological community, maybe most of the names mentioned in this report are not familiar. However, it is this team, the team of seismologists, engineers and technicians with many of whom being young people, that plays the crucial role in the seismological observation in China. Their hard working and creativity is one of the dynamos driving the developments of digital seismology in China.

Similar to most of the developing countries, how to make full use of the modernized seismological observation system for scientific researches and application to the reduction of earthquake disasters is still one of the challenging problems for China. Chinese seismologists are striving for its solution.

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IASPEI National Report (2003~2006)

Development of China's Digital Seismological Observation System

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Abstract

The seismological observation system in China has experienced rapid development over the last four years: the analog-to-digital conversion has been completed and China Earthquake Network Center (CENC) has been established. This report presents an overview of the current National Digital Seismograph Network (NDSN), Regional Digital Seismograph Network, Digital Seismograph Network for Volcano Monitoring and Mobile Digital Seismograph Network. It also gives a brief account of the main functions, data output, data management and general services of China Earthquake Network Center.

1. Introduction

The construction of digital seismograph networks in China started in the 1980s. In May, 1983, China Earthquake Administration (CEA) and the United States Geological Survey (USGS) began an overall design of China Digital Seismograph Network (CDSN), and by 1986, 10 digital seismic stations (Beijing, Sheshan, Mudanjiang, Hailaer, Urumchi, Lasa, Qiongzhong, Enshi, Lanzhou and Kunming) have been set up, giving shape to the first national-level digital seismograph network in China. In 1995, Xi'an digital seismic station was set up and came into the seismograph network. Between 1993 and 2001, CEA and USGS jointly carried out remodeling (the 2nd phase) of CDSN, making its hardware and software systems in conformity with the technical regulations of Global Seismograph Network (GSN) established by the Incorporated Research Institutions for Seismology (IRIS). Now CDSN has become one of the major partners of GSN (Zhou *et al*, 1995).

Supported by the central and local governments, China Earthquake Administration began to establish "China Digital Seismological Observation System" in 1996. According to the principle of uniform distribution of seismic stations and at the same time ensuring intensive observation in some key areas, the observation system was designed to consist of national, regional and mobile seismograph networks (Zhuang *et al*, 2003). The system was completed and began operation at the end of 2000. The National Digital Seismograph Network has 48 seismic stations equipped with very-broadband (VBB) seismographs, among which 37 are newly built by China alone and 11 are updated from the original Sino-US cooperative stations. All of the seismic stations perform 24-bit data acquisition and the waveform data are synchronously transmitted to the Center of National Digital Seismograph Network via a satellite network. There are altogether 20 regional digital seismograph networks in China, which have 267 digital seismic stations performing 16-bit data acquisition. The waveform data are synchronously transmitted to the centers of local seismograph networks. The Mobile Digital Seismograph Network has 100 portable digital seismographs, which are exactly of the same type as those in the regional digital seismograph networks. Between 1999 and 2001, the Capital-Circle Digital Seismograph Network (covering Beijing Municipality, Tianjin Municipality and Hebei Province) for real-time data transmission was established, which has 107 seismic stations performing 24-bit data acquisition. The national, regional and Capital-circle digital seismograph networks went into full operation between 2001 and 2003 and have outputted a great deal of observational data.

The seismological observation system in China has experienced rapid development since 2003: CEA has accomplished analog-to-digital conversion of all seismological networks, thus, full digitization of seismological observation in China has been realized.

2. Seismological Observation System

The updated China Seismological Observation System consists of National Digital Seismograph Network, Regional Digital Seismograph Network, Digital Seismograph Network for Volcano Monitoring and Mobile Digital Seismograph Network.

2.1. National Digital Seismograph Network

The National Digital Seismograph Network now has 152 seismic stations, including the 48 primary national digital seismic stations and 104 newly built seismic stations equipped with VBB digital seismographs. The average distance between seismic stations is about 250 km, except in Qinghai-Tibet Plateau. Among the 152 seismic stations, 16 are equipped with ultra-broadband (UBB) seismometers which have a flat acceleration response from 3 000 s to 360 s and a flat velocity response from 360 s to 20 Hz, the others are all equipped with VBB seismometers from 120 s to 20 Hz.

In order to improve earthquake monitoring in the western parts of China, 2 small-aperture seismic arrays have been established, one in Naqu, Tibet, and the other in Hetian, Xinjiang. Each array, with a diameter of 3 km, has 9 seismic stations. The central stations are equipped with 120s~20Hz VBB seismometers and the others use 2s~50Hz short period seismometers.

Besides, 2 ocean bottom seismic observatories have been built, one in Bohai Sea and the other in East China Sea, to accumulate experiences for future ocean bottom seismic observation.

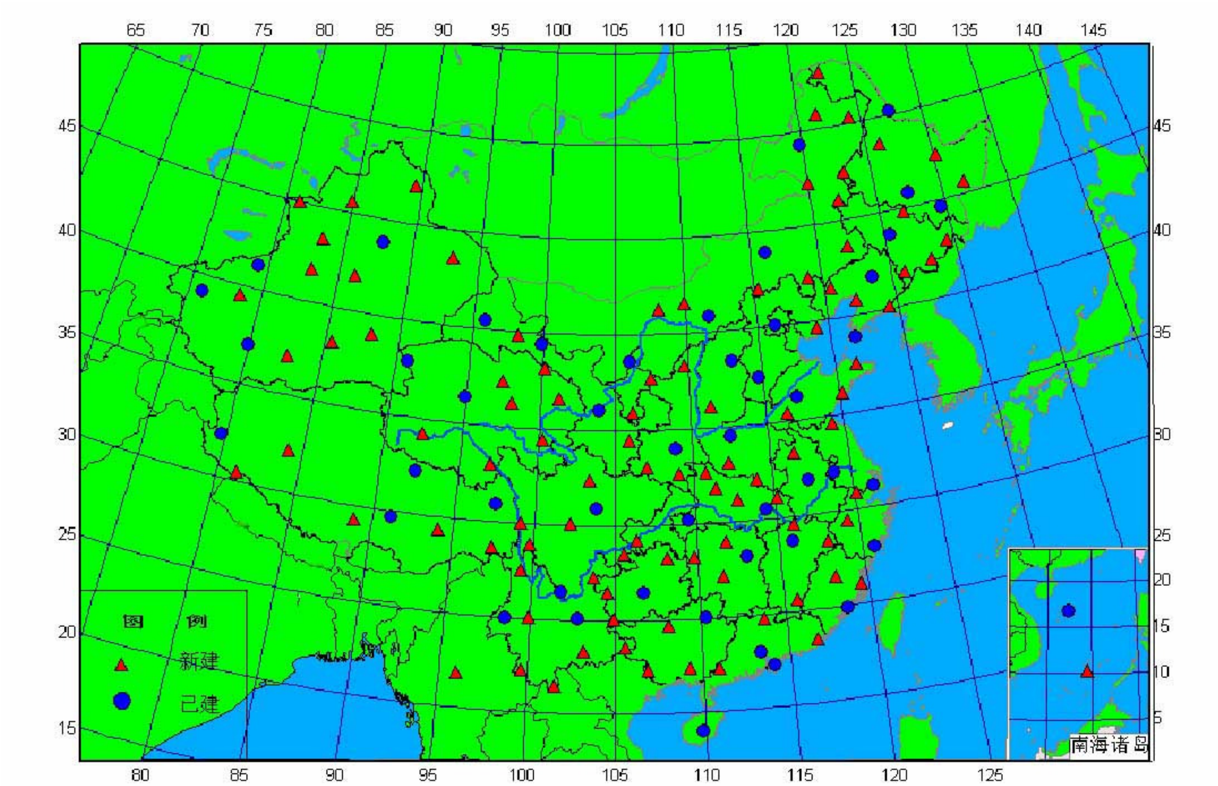

Figure 1 Distribution of stations in National Digital Seismograph Network in China

2.2 Regional Digital Seismograph Network

There are 678 seismic stations working for regional digital seismograph networks (excluding those in the Capital-circle network), among them 267 are updated from the primary stations which performed 16-bit data acquisition and 411 are newly built. Now each of the 31 provinces, autonomous regions and municipalities in China's mainland has a digital seismograph network. The total number of regional digital seismic stations in China's mainland has now reached 785, including the 107 seismic stations recently built in the Capital zone. The average distance between regional digital seismic stations is as short as 30~60 km in key areas for earthquake surveillance and protection, densely populated cities and the east coast area, and around 100~200 km in Xinjiang and Qinghai-Tibet Plateau.

Some of the 678 seismic stations are equipped with 60s~40Hz broadband seismometers, while the others use 2s~50Hz short period seismometers.

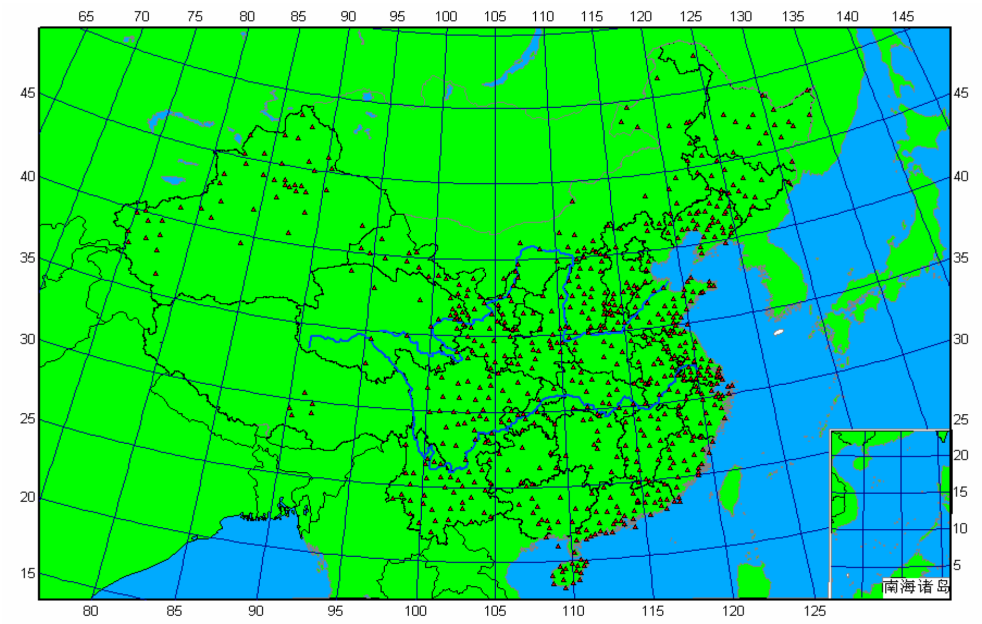

Figure 2　Distribution of stations in regional digital seismograph networks in China

2.3 Digital Seismograph Network for Volcano Monitoring

There are altogether 35 seismic stations in 6 digital seismograph networks for volcano monitoring across China, among which 11 are in the seismograph network for Changbaishan Volcano, Jilin Province, 4 for Longgang Volcano, Jilin Province, 9 for Tengchong Volcano, Yunnan Province, 3 for Wudalianchi Volcano, Heilongjiang Province, 4 for Jingpohu Volcano, Heilongjiang Province and 4 for Qiongbei Volcano, Hainan Province. These stations are equipped with either 60s~40Hz broadband seismometers or 2s~50Hz short period seismometers.

2.4 Mobile Digital Seismograph Network

The Mobile Digital Seismograph Network, equipped with 800 seismometers, consists of two parts: mobile network for earthquake emergency response and mobile array for seismic detection.

(1) Mobile seismograph networks for earthquake emergency response

These are mainly used for foreshock observation before large earthquakes and aftershock monitoring. They contribute to the study of regional seismic activity and earthquake prediction by intensive observation before large earthquakes, high-precision hypocenter location of foreshocks and continuous monitoring of seismic activities in critical earthquake risk areas. After large earthquakes, the networks are used for aftershock monitoring and recording, providing reference for the judgment of earthquake tendency and accumulating essential data for further study of source characteristics and initiation process of earthquakes.

There are altogether 19 mobile seismograph networks for earthquake emergency response. The networks have 200 portable digital seismographs, which are either 60s~40Hz broadband seismometers or 2s~50Hz short period seismometers.

(2) Mobile array for seismic detection

The mobile array for seismic detection can carry out earthquake observation in a study area by various means and on various scales according to different scientific purposes. In an array with densely distributed seismic stations, the distance between stations can be no more than several kilometers. High-resolution seismic records from a mobile array can yield corresponding high-resolution results. When applied to investigations concerning hypocenter location, focal mechanism solution, rupture process of earthquakes and seismic imaging, these high resolution seismic records can help greatly improve precision of the research findings. As an important means for high resolution exploration of Earth's interior, the mobile seismic array can not only be used in seismological research, but has a wide application in geoscience.

The 600 seismographs for the mobile array, including 10 VBB (120s~40Hz), 500 broadband (60s~40Hz) and 90 short period (2s~50Hz), are all under the care of the Institute of Geophysics, China Earthquake Administration (IGPCEA). The mobile array operates in the same way as USArray, probing deep Earth structure of a specific region.

3. China Earthquake Network Center

For "resource integration and information sharing", the State Council of the People's Republic of China approved the establishment of China Earthquake Network Center (CENC) on Feb. 4, 2004. After several months' preparation, CENC came into existence on Oct. 18, 2004. Directly under China Earthquake Administration, CENC is a special institution for earthquake monitoring and prediction, data analysis and processing, and scientific information services. It is a kernel technology platform of the three systems: earthquake monitoring and prediction, earthquake disaster prevention and emergency relief. The office building of CENC was completed at the beginning of 2007, which is located at No. 3 Block of Sanlihe, Xicheng District, Beijing (Figure 3).

Among the various undertakings, major responsibilities of CENC regarding operation and management of the seismological observation system in China include: (1) dada analysis, processing and normal operation of the national and Capital-circle digital seismograph networks; (2) management and coordination, data gathering and quality supervision of the 31 regional seismograph networks; (3) conversion of earthquake waveform data collected by the national and 31 regional seismograph networks to SEED format, compilation of "Observation Report of China National Digital Seismograph Network" based on phase data; (4) rapid earthquake information release of Ms ≥ 4.5 events within China, Ms ≥ 5.5 events around China and Ms ≥ 6.0 events around the globe; (5) establishment of the seismic data management and database system, which provides seismic data service for government organizations, scientific research institutions and the general public. The system is also engaged in international data exchange.

Figure 3 Newly completed Building of China Earthquake Network Center

CENC has extended active cooperation with the Commission on Seismological Observation and Interpretation (CoSOI) of International Association of Seismology and Physics of the Earth's Interior (IASPEI). It has conducted comparison between earthquake magnitudes determined by China seismograph network and US seismograph network (Liu, Chen *et al*, 2005; 2006), methodology study of magnitude determination with broadband digital seismic records (Bormann, P., Liu R. F., 2007) and comparison between IASPEI-released magnitudes determined by new formulae and traditional formulae based on observational data of 2006 from China National Digital Seismograph Network (Bormann, P., Liu, R. F., Ren, X. and Wendt S., 2007). Thus, CENC has facilitated the application of IASPEI-released magnitudes (determined by new formulae) to seismograph networks worldwide.

4. World Data Center (WDC) for Seismology, Beijing

World Data Center for Seismology, Beijing, established in Sept. 1988 as a member of WDC, is supported and managed by CEA and guided by WDC National Committee and Scientific Committee of China. Its primary mission is to carry out international exchange of seismic and geomagnetic data. Since March, 1993, the WDC for Seismology, Beijing, has committed itself to the establishment of national seismic information network, acquiring international earthquake data and offering services to internal customers. Vigorously backed by the various kinds of earthquake monitoring systems and network information systems, WDC for Seismology, Beijing, has made itself a national-level center for seismology by promoting seismological database construction, strengthening the capability of domestic-oriented seismic data services, while carrying out international data exchange. In accordance with the general plan of CEA, WDC for Seismology, Beijing, was put under jurisdiction of China Earthquake Network Center in Oct. 2004 and began to have its own English language website in May, 2005: http://www-wdcds.seis.ac.cn

According to the arrangement of WDC, a group of specialists (David Clark, Jean Bonnin, Tohru Araki and Wenhua Li) made an inspection tour of WDC for Seismology, Beijing, on July 6, 2005. The specialists unanimously concluded that WDC for Seismology, Beijing, has seismic data of national and industry standard, strong capability of data storage, good data sharing facilities and advanced network platform; the seismic data are of great significance to geophysical research and the institution has met performance requirements of WDC in every aspect. The specialists also spoke highly of the management and operation of WDC for Seismology, Beijing.

Figure 4 WDC specialist group at an appraisal meeting

5. Seismological data sharing

Seismological data sharing is one of the pilot projects concerning scientific data sharing initiated by the Ministry of Science and Technology of the People's Republic of China (MSTPRC) in 2003. In accordance with the unitary plan and management of China National Facilities and Information Infrastructure for Science and Technology Program, the project was headed by CENC and participated by the institutions directly under CEA and 31 provincial earthquake administrations. Initiated as a society-oriented, networking and intelligent system for management and service of seismological data sharing, the project has facilitated standardization of seismic data acquisition, processing and storage.

After 4 years of work, a series of measures for administration, grading and classification standards and quality testing criteria concerning seismic data service have been formulated and a persistent, stable and dependable operation mechanism for seismic data service has been established. The seismic data accumulated over a long period of time in China have been standardized by integration and transformation and a standardized database cluster has been set up. For example, standardization of the seismic waveform data and phase data collected since 2001 by the national, Capital-circle and 31 regional digital seismograph networks has been accomplished and a database system has been established, with on-line data exceeding 1000 GB.

Figure 5 Launch ceremony of China Earthquake Data Center website

For data management and service, a seismological data sharing system has been set up, which boasts advanced technology, complete function and need gratification for various users. Users have access to the earthquake data service via China Earthquake Data Center website: http://data.earthquake.cn, which was launched on Sept. 28, 2006. Chen Jian-min, Director General of CEA and Cheng Jin-pei, Vice Minister of MSTPRC attended the ceremony. The data sharing service will greatly improve availability of the seismic data. After an annual acceptance inspection of the project, a MSTPRC specialist group reached the conclusion that the seismological data sharing project is a great success and is expected to have a wide application; they also deemed that the project has demonstration effect for promoting national scientific data sharing service.

6. Formulation of seismic observation standard

To standardize the construction of seismic stations, China Earthquake Administration formulated 2 national standards and 8 industrial standards.

6.1 National standard

(1) General ruler for earthquake magnitude (GB 17740-1999)

(2) Technical requirement for the observational environment of seismic stations—Part 1: Seismometry (GB/T 19531.1-2004)

6.2 Industrial standard

(1) Categories and codes for earthquake-related data, Part 1: Basic categories (DB/T 11.1-2000)

(2) Interface of seismometer (DB/T 13-2000)

(3) Digital strong motion accelerograph (DB/T 10-2001)

(4) Formats for the exchange of earthquake waveform data (DB/T 2-2003)

(5) Classification and code of seismic observation item and observation item for earthquake precursor (DB/T 3-2003)

(6) Code of seismic station(DB/T 4-2003)

(7) Specification for the construction of seismic station: Seismograph station (DB/T 16-2006)

(8) Specification for the construction of seismic station: Strong motion station (DB/T 17-2006)

7. Conclusions

Over the last four years, the seismological observation system in China has undergone analog-to-digital conversion, thus, a digital seismological observation system has come into existence, which consists of the national digital seismograph network, 31 regional digital seismograph networks, 6 digital seismograph networks for volcano monitoring and mobile digital seismograph networks. Meanwhile, China Earthquake Network Center has been established, which is a special institution responsible for the normal operation of the seismological observation system, data gathering, analysis, processing, management and services. All this symbolizes full digitization of China's seismological observation. In the next 5 years, layout of the existing seismograph networks will be optimized and ocean bottom and borehole seismic stations will be built. Therefore, we have every reason to believe that a more rationally arranged seismological observation system, covering both land and sea areas around China, will come into being, which is sure to provide a wider variety of data services for earthquake prediction, geoscience research, national economic development and the general public.

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REVIEW ON STUDIES OF SEISMIC WAVE

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Theoretical study of seismic wave excitation and propagation is a fundamental field of seismology. It has been widely applied to the study of seismic source process, inversion of velocity structure of the earth, strong ground motion and exploration seismology. During 2003 to 2006, with the increasing of installed seismic stations and local arrays and the acquisition of more and more high-quality digital recordings, seismic wave study has progressed significantly in China. In this paper, we briefly review the major developments of study of seismic wave theory and its applications in China.

I. SEISMIC WAVE PROPAGATION IN LATERALLY HOMOGENEOUS MEDIA

Although laterally homogeneous media is a simplified approximation to the realistic earth, study of seismic wave propagation in laterally homogeneous media remains a very important subject in theoretical seismology and applications for specific problems if the lateral variation of structure can be neglected.

Based on the generalized R/T coefficient method, He et al. (2006) developed a new approach to calculate dispersion curves and normal mode solutions of multilayered solid earth model with low velocity layers. They proposed using the secular function set, instead of the single secular function, to calculate different modes respectively through corresponding secular functions. It is difficult to compute synthetic seismograms for a layered half-space with sources and receivers at close to or the same depths using the generalized R/T coefficient method, because the wavenumber integration converges very slowly. Based on the principle of the Repeated Averaging Method, Zhang et al. (2003) proposed an alternative, efficient, numerical method, the peak-trough averaging method (PTAM), to overcome this difficulty. Compared with the semi-analytic method, PTAM is not only much simpler mathematically and easier to implement in practice, but also more efficient. Tian and Chen (2005) proposed a rapid and accurate method for two-point ray-tracing for horizontally layered model. Numerical experiments show that this method provides stable and rapid convergence with high-accuracy, regardless of various 1D velocity structures, take-off angles and epicentral distances. Based on layered velocity model, He et al. (2005a, 2005b, 2005c) carried out systematical studies of generation and characteristics of Lg and Rg waves from underground nuclear explosion. They analyzed the mechanism of the excitation of Lg wave by explosions in layered earth structures of the East Kazakh test site using synthetic seismograms calculated by the global generalized R/T matrices method, analyzed in detail the mechanism of the excitation of the spectral null of Rg generated by the CLVD source with the normal mode method.

Based on the Lagrangian density and covariant Legendre transform, Chen (2004a) obtained the multisymplectic Hamiltonian formulation for a one-way seismic wave equation of high-order approximation. This formulation provides a new perspective for studying the one-way seismic wave equation. Chen (2004b) presented the multisymplectic geometry for the seismic wave equation, derived the local energy conservation law, the local momentum evolution equations, and the multisymplectic form directly from the variational principle and developed the multisymplectic Hamiltonian formulation. These results provide multisymplectic framework for studying the seismic wave equation. Chen and Liu (2004) presented an optimization approximation with separable variables for the one-way wave operator. This approximation enables us to use FFT algorithm which is independent of space variables while suffering no problem of branch points present in the generalized-screen method. Lu and Hanyga (2004) developed a numerical modeling method for wave propagation in a linear viscoelastic medium with singular memory. Using the new method, the velocity-stress equations and the fractional relaxation equations are reduced to a system of first-order ordinary differential equations. Yuan et al. (2006) studied, under a small disturbance, the responses of seismic transient wave in the homogeneous viscolastic media and the analytic solution of the corresponding third-order partial differential equation.

II. SEISMIC WAVE PROPAGATION IN LATERALLY HETEROGENEOUS MEDIA

The lateral variation of the real earth structure can not be neglected in many cases. Hence, we have to study seismic wave propagation in laterally heterogeneous media. This has been a very active research field in the past four years and many progresses have been made in method, algorithm and realistic applications. Researches have been focused on improvements of the efficiency and accuracy of various methods and development of new methods.

In a series of **Advances in Geophysics** published by the Academic Press recently, Chen (2006) was invited to write the Chapter 4 in *Advances in Wave Propagation in Heterogeneous Earth*. This chapter reviewed and summarized the global generalized reflection/ transmission (R/T) matrices method, its successful applications to seismic SH waves' generation and propagation and Love wave in multilayered media with irregular interfaces. Scattering of seismic wave from topography is important in many applications. Through studies on the scattering from various topographies due to an incident SH wave, Cao et al. (2004) evaluated the accuracy, numerical stability and efficiency of three methods for seismogram synthesis (Aki-Larner method, Bouchon-Campillo method, and global generalized R/T matrices method). They found that the global generalized R/T matrices method not only is very accurate, stable and with a modest computational efficiency, but also can treat the very steep topography well. Therefore, the global generalized R/T matrices method is the best method among the three, and provides a very effective tool to synthesize seismograms for complex media. Fu (2005) compared several approximation solutions to rough surface scattering for 2D SH waves for an analytical description of the close relation of topographic statistics and regional phase attenuation. These approximations include Kirchhoff approximation theory, Taylor expansion-based perturbation theory, two-scale model, Rytov phase approximation, and Born series method, with each valid for a range of roughness scales. Based on the Bouchon-Campillo method, Zhou and Chen (2006a) developed a new approach to study seismic waves scattering problem by an irregular topography, in which only those sampling points over the irregular part of surface topography are directly solved; thus the number of unknowns is greatly reduced. The computational efficiency of this local discrete wave-number method is much superior to the original Bouchon-Campillo method, and is expected to be a powerful tool in simulating the seismic wave scattering problem by an arbitrary topography. Zhou and Chen (2006b) applied this method to simulate frequency responses of topography with multiple spatial scales due to incident SH wave, and obtained a resonance-like relationship between the scales of topography and the frequency of incident wave. Ge et al. (2005) developed a boundary element (BE) method to calculate the two-dimensional P-SV elastic response for crustal wave guides with irregular topographic features. To simulate long-range propagation of regional waves, a connection technique is proposed to avoid large matrix inversions that become formidable for long-range, high-frequency problems. The connection technique expands this method to deal with large earth models with irregular topography. Fu (2006) compared different one-way propagators for wave forward propagation in heterogeneous crustal wave guides. It is challenging to implement the traction-free boundary conditions in finite difference (FD) simulation in the presence of surface topography. Zhang and Chen (2006) proposed a new numerical method, named as Traction Image method, to accurately and efficiently solve this problem. Numerical tests show the validity of this method for modeling seismic waves in the heterogeneous media with arbitrary shape topography and its high efficiency.

Some new methods or developments based on traditional methods have been proposed to improve accuracy and efficiency of calculation. Fu and Bouchon (2004) presented a semi-analytical, semi-numerical method of seismogram synthesis for piecewise heterogeneous media resulting from an arbitrary source for 2D SH wave. The method incorporates the discrete wavenumber Green's function representation into the boundary-volume integral equation numerical techniques. Sun and Yang (2004a) presented a FD method with spatially non-rectangular irregular grids to simulate elastic wave propagation. Complicated geometries like curved thin layers, cased borehole and nonplanar interfaces may be treated with non-rectangular irregular grids in a more flexible way. Sun and Yang (2004b) presented a new 3D FD method of spatially asymmetric staggered grids to simulate elastic wave propagation in topographic structures. Zhang (2004a) presented a new numerical technique for modeling wave propagation in media with both fluid (acoustic) and solid (elastic) regions. The scheme can correctly satisfy the fluid-solid interface conditions and accurately models the arbitrary interface topography. Zhang (2004b) proposed a new numerical technique for modeling elastic wave propagation in heterogeneous media with high velocity contrasts, as for instance in the presence of weathered layers or soft marine sediments. The scheme allows a sharp jump in grid spacing across the interface with high velocity contrasts. In order to overcome the numerical dispersion of routine finite-difference operators, Yin et al. (2006) applied 25-point optimized finite-difference operators, and got the optimized coefficient on the basis of the optimization theory and establish a finite-difference format of elastic wave equations in the frequency-space domain. Jia and Hu (2006) presented the theory of the element-free precise integration method (EFPIM) as well as its applications in seismic modeling and imaging. The EFPIM improves the implicit element-free method (EFM) by cutting the computational cost significantly. At the same time, the accuracy of this method keeps as good as that of the implicit EFM. Yang et al. (2004) presented the so-called optimal, nearly analytic, discrete method (ONADM), which is an improved version of the NADM proposed by Yang et al. (2003). Promising numerical results suggest that the ONADM is suitable for large-scale numerical modeling, as it can suppress effectively numerical dispersion caused by discretizing the wave equations when too coarse grids are used. Yang et al. (2006) explored the theoretical properties of the ONADM including the stability criteria of the ONADM for solving 1D and 2D scalar wave equations, numerical dispersion, theoretical error, and computational efficiency when using the ONADM to model the acoustic wave fields. Zhao et al. (2003) proposed a new fast differentiation operator, staggered grid real value FFT differentiation operator, to simulate seismic wave propagation in inhomogeneous medium, and showed that the staggered grid real value FFF differentiation operator for the pseudospectral method is valid for the seismic wave simulation in the heterogeneous medium. Cao and Yang (2003) developed a system of quasi-particle on a discrete lattice, presented the Hamiltonian description of this system that can simulate acoustic and elastic waves. Zhou et al. (2005) introduced a varying time-step numerical integration algorithm for the finite element simulation of wave motion. Xia et al. (2004) presented a set of absorbing boundary conditions of 3D elastic wave equations on the base of paraxial approximations, and apply to the 3D elastic wave numerical modeling in isotropic medium. Zheng et al. (2004) studied the 1D nonlinear P-wave propagation in the nonlinear solid media by numerical method using two FD of centered schemes with different accuracy order of space sampling. Based on Fourier-Bessel series expansion and auxiliary functions technique, Liang et al. (2004a) derived a series solution for surface motion amplification due to underground group cavities for incident plane P waves, Liang et al. (2004b) derived an analytical solution of scattering of plane SH waves by a circular-arc hill with a concentric circular tunnel.

Some researchers studied seismic wave propagation in laterally heterogeneous media based on the asymptotic ray theory. Zhou et al. (2004) introduced a new seismic ray-tracing method based on parabolic travel-time interpolation (PTI) method, which is more accurate than the linear travel-time interpolation (LTI) method. The results of numerical model show that PTI method can trace ray-path more accurately and efficiently than LTI method does. Xu et al. (2004) proposed block modeling to suit complex 3D media. Instead of layers, geological media are regarded as an aggregate of geological blocks. They presented some methods for shooting ray tracing in 3D: triangle-subdivision, triangle-division and subtriangle methods. The calculation indicates that the subtriangle method is most efficient. Li et al. (2004) derived the calculation method for first-arrival travel time of finite difference based on any rectangular grid and a local plane wavefront approximation. Xu et al. (2006) proposed using a set of blocks to approximate geologically complex media that cannot be well described by layered models. Numerical tests demonstrate that the combination of block modeling and segmentally iterative ray tracing is effective in implementing kinematic two-point ray tracing in complex 3D media. Unlike the conventional ray tracing theory, wave-equation tomography can account for the band-limited characteristics of seismic waves. Qin et al. (2006) computed travel times and their wavepaths by solving the suppressed monochromatic frequency-domain wave equation. The results showed that the travel time calculated by the wave equation is much smoother than the ray-theoretical travel time, and the wavepath has different sensitivity and width for different velocity structures.

Studies of seismic wave propagation in laterally heterogeneous media have been applied to the study of earthquake ground motion. Ding et al. (2004) applied the algorithms for the calculation of synthetic seismograms in laterally heterogeneous anelastic media to model the ground motion in Beijing City. The synthetic result is well correlated with the abnormally high macroseismic intensity zone in the Xiji area associated with the 1976 Tangshan earthquake as well as with the ground motion recorded in Beijing city in the wake of the 1998 Zhangbei earthquake. Using numerical simulation technique of wave equation proposed by Zhao et al. (2003), Zhao et al. (2004a, 2004b) and Zhao and Xu (2004, 2005, 2006) investigated the distribution characteristics of collapse ratios of buildings in Kobe city due to the 1995 M7.2 Hyogo-ken Nanbu, Japan (Kobe) earthquake and the interferences due to SH or P-SV and the second surface waves propagating in heterogeneous medium, studied the influences on the ground motion simulations by soil amplification effects and multiple seismic wave interferences in the heterogeneous medium, and clarified the cause for the complicated distribution characteristics of strong ground motion in regions with basin structure and alluvial fan. Wang et al. (2005) compared the strong ground motion simulation for an earthquake by 3D staggered grid FD method and the stochastic method.

Another important application of seismic wave propagation study in laterally heterogeneous media is wavefield modeling and imaging used in exploration seismology. Yang et al. (2003) used a higher order symplectic scheme approximation to the complex exponential function in the one-way wave equation in the seismic migration algorithm. Based on the acoustic wave field theory, Huang et al. (2005) discussed the forward model of seismic data excluding the surface. In the presence of a reflecting free surface, they formulated in detail the forward as well as inversion models for surface-related multiple prediction and attenuation. Xie et al. (2005) presented a scheme of the separable expression of the R/T operator, which can be used to model primary reflected waves in the one-way wave equation seismic modeling. This scheme is adaptable to laterally heterogeneous media and fluctuating reflectors, and can mimic AVA of reflections when the incident angle is less than 45 degrees. Yuan et al. (2006) extended the previous analytic solutions for the conversion point for converted waves in a horizontally layered media to the more general case of converted waves from a dipping reflector with a homogeneous, isotropic overburden. Based on Rayleigh's hypothesis of rough interface, Sun and Du (2006) studied the reflection features of planar acoustic waves from a rough interface with rapid-jumped cosine style. Their result offers a basis for seismic data processing of rough interfaces. Liu et al. (2004) demonstrated that the one-way wave equation modeling scheme exhibits sufficient accuracy in terms of primary reflected waves in comparison with the two-way wave equation scheme in complex 3D structure. Liu and Zhang (2006) proposed a one-way propagator for more accurately modeling wide-angle wavefields in the presence of severe lateral variations of the velocity. The method adds a higher-order correction to improve the split-step Fourier method. Zhao and Zhang (2004) developed an improved minimum travel time tree algorithm for fast calculation of travel times of converted waves in 3D complex media based on Huygens' principle and Fermat's principle. Wang and Singh (2003) presented a new scheme to separate P- and S-wavefields from wide-angle multicomponent ocean-bottom cable data in the τ-p domain. The results showed that both near-offset and wide-angle reflections and conversions from within and below basalt layers are enhanced and clearly identified on the separated wavefields. Assuming that the changes of amplitude and phase for the seismic wavefields in the adjacent traces are small, Hu et al. (2004) presented an effective decomposition method for multicomponent seismic wavefields, in which the vertical and the horizontal components for both longitudinal and shear waves are determined by their different polarization and slowness during propagation. The longitudinal and the shear waves can be reconstructed and then separated.

The complexity of lateral heterogeneity in several regions in China has been investigated from coda wave attenuation study. Zhao et al. (2003) carried out inversion for the Q value of the upper crust along the profile from Baicheng to Da Qaidam using seismic reflection/refraction data. Mak et al. (2004) estimated the coda Q in the Hong Kong region. The results fill an important gap in knowledge about the Q factor and associated crustal attenuation conditions in the Pearl River Delta region including Hong Kong, and provide useful insight into the influence of epicentral distance range in coda-Q measurements, allowing better understanding of the degree of complexity in the crustal structure of the region. Liu et al. (2004a, 2004b) reconstructed the Q(0) image in the crust beneath the North China region with a stochastic modeling and the singular value decomposition. Li et al. (2004) derived an energy attenuation formula of seismic waves in the wavelet-scale domain from the wavelet theory and seismic wave propagation equation in anelastic medium. The energy attenuation formula can be used to estimate the quality factor Q from surface seismic data and to extract energy attenuation section of varied scales as an attribute parameter for discriminating fluid contents and lithology. Based on the laws of inelastic media, Yao et al. (2003) gave a forward Q method for compensating attenuation and frequency dispersion used in the seismic profile of depth domain. Lou et al. (2006) analyzed and processed artificial seismic experiment data to investigate the fine structure of the fault zone generated by the Kunlun M(s)8.1 earthquake on Nov. 4, 2001 with the guided wave trapped in fault zone. They estimated the Q with an amplitude-ratio method. Liu et al. (2005) investigated the variation of Q value before and after the 1999 Xiuyan, Liaoning province, M5.4 earthquake from P wave dispersion analysis. Wu et al. (2006) estimated the S coda attenuation in the Changbaishan Tianchi volcanic area in Northeast China. They interpreted the strong attenuation of coda waves near the Changbaishan Tianchi volcano as being possibly related to high temperature medium caused by shallow magma chambers. Pei et al. (2006) used tomographic imaging to estimate the lateral variations of the quality factor Q(0) (Q at 1 Hz) within the crust of Northern China.

III. SEISMIC WAVE IN ANISOTROPIC AND POROUS MEDIA

The structure of real earth can often be considered as anisotropic and porous media. Study of seismic wave propagation in anisotropic and porous media reveals the complexity of structure and has been applied to the study of earthquake preparedness and occurrence, oil reservoir and velocity structure at various depth and scale.

Numerical method is efficient and powerful in understanding seismic wave propagation in anisotropic media. Yang et al. (2003a) developed a new nearly analytic discrete method (NADM) based on a system of first-order partial differential equations with respect to time t transformed from the seismic wave equations in 2D inhomogeneous anisotropic media. Yang et al. (2003b) presented decoupling n-times absorbing boundary conditions designed to model acoustic and elastic wave propagation in a 2D transversely isotropic (TI) medium. Sun and Yang (2004) presented a new 3D FD method using spatially irregular grids to simulate elastic wave propagation in heterogeneous anisotropic media with topographic structures. Du (2004) derived the pseudospectral recursive formulae of viscoelastic and azimuthally anisotropic media, and carried out wavefield forward modeling with the pseudospectral method in viscoelastic and azimuthally anisotropic media. Wang et al. (2005) modeled seismic wave propagation in monoclinic media using high-order staggered-grid FD method. The numerical modeling results can provide theoretical basis for the inversion of anisotropic parameters and also the fracture parameters with the surface multi-azimuth seismic attributes. Pei and Wang (2005) presented a staggered grid high-order FD scheme for elastic wave modeling in arbitrary tilt anisotropic media. Zheng and Zhang (2005) and Zheng et al. (2006) reported a second order central FD scheme based on a modified flux-corrected transport technique, the MFCTFD, and the modeling of nonlinear seismic wave propagation in 2D transversely isotropic (with vertical symmetry axis) solid media. Zheng et al. (2006) got numerical seismic records corresponding to isotropic, VTI and nonlinear VTI media, respectively, using the FD method with a transformed FCT technique, and adopted wavelet transform to calculate and analyze seismic wave frequency and bandwidth changes induced by the nonlinearity in VTI media. Sun et al. (2005) developed a 3D FD method with spatially irregular grids to simulate the seismic propagation in anisotropic media, and implemented the parallel 3D simulation on a PC cluster. Lu and Yang (2005) investigated the efficient implementation of NADM and present a refinement of the original NADM, and reported three-component synthetic VSP seismograms in 3-layered transversely isotropic media generated by the modified NADM. Liu and Zhang (2006b) propose one-way operators for modeling wide-angle wave propagation in 3D heterogeneous, transversely isotropic media with a vertically symmetric axis. Gao and Zhang (2006) presented a parallel numerical technique for modeling wave propagation in 3D heterogeneous anisotropic media by following a so-called 3D grid method of the elastic-isotropic case. Ruan et al. (2004) studied the crust effect on the analysis of the upper mantle anisotropy using the pseudospectral simulation. Du and Yang (2004) studied the fractured media with arbitrary azimuthal angles, solved incrementally the convolution integral and presented the corresponding time-domain wave equations. The wave equations may be solved to model the wave propagation in the azimuthally anisotropic and viscoelastic media and to reveal the mechanisms of seismic multi-wave propagation in fractured media. Zhang (2005) presented a numerical technique for modeling elastic wave propagation in media with discrete distributions of fractures. The scheme is developed following the explicit treatments of fractures based on a linear-slip displacement-discontinuity model instead of using an effective-medium theory. Liu et al. (2006) presented an effective technique to model seismic wave propagation in media with discrete distributions of fractures based on the combination of the finite difference and equivalent medium theories.

Shear wave splitting has been observed from earthquakes and studied for the complexity of seismic source region in earthquake preparation zone and interior structure of the earth. Gao and Crampin (2003) studied the temporal variation of shear wave splitting observed in field and laboratory studies, and reported the relationship between the temporal variation of shear wave splitting with build up of stress before earthquakes and the stress release as earthquakes occur. Gao and Crampin (2004) further observed stress relaxation before earthquake from shear wave splitting with new data and reappraisal of existing data sets. Gao et al. (2004) studied the temporal variation of shear wave splitting observed in the 2001 Shidian earthquakes in Yunnan province. Hua et al. (2006) studied the shear wave splitting in Dayao earthquake sequence in 2003 in Yunnan province. Wang et al. (2006) studied the shear wave splitting in the aftershock region of the 2000 Yao'an earthquake in Yunnan. Luo et al. (2004) studied the SKS wave splitting beneath the China mainland and adjacent regions. Chen et al. (2005) studied the shear wave splitting in the Chinese Tianshan Orogenic Belt using a linear array of broadband digital stations. Zhao and Zheng (2005) investigated the upper mantle anisotropy beneath the North China Craton using shear wave splitting measurement, and found distinct variation from east to west. Chang et al. (2006) studied the SKS splitting beneath Yunnan region. Lai et al. (2006) investigated the S-wave splitting at the stations of the Capital Circle area and its relationship to the crustal stress field. Xu et al. (2006) studied the crustal anisotropy using P to S converted phase of the receiver function and its application to Ailaoshan-Red River fault zone.

Seismic wave propagation in porous media has been studied mainly through analytic approach and numerical method. Xi et al. (2003) introduced the complex modulus into the Biot equation and studied S-wave propagation through 1D S-wave equation. Using the Fourier-Bessel series expansion technique, Li and Zhao (2003, 2004) derived analytic solution of 2D scattering and diffraction of plane P-waves by circular cylindrical canyons in a fluid-saturated porous media half space and 2D scattering and diffraction of plane SV-waves by circular-arc alluvial valleys with saturated soil deposits. Li and Zhao (2006) further obtained the analytic solution for 2D scattering and diffraction of plane P- and SV-waves by circular-arc alluvial valleys with saturated soil deposits and water. Dong and Zhao (2005a, 2005b) obtained analytic solutions for 3D scattering and diffraction by hemisphere canyons in fluid-saturated porous media half space to plane P- and SV-waves incidence, respectively. Shen and Yang (2004) studied the elastic wave speed in two-phase porous isotropic media and its relation with Biot-flow and squirt-flow, obtained the Green's function for a point load in the two-phase porous isotropic media using the decomposition of the filed potential and the properties of the Delta function. Hu (2005) obtained the elastic pragmatic wave equations and their potential equations in a saturated porous micropolar medium from the results of the micropolar theory and those of the Biot's pragmatic wave theory. Wang et al. (2003) proposed an improved explicit eighth-order staggered FD algorithm in space and second order in time for seismic wave propagation simulation in poroelastic media. Based on Biot theory of two-phase anisotropic media and Hamilton theory about dynamic problem, Liu and Wei (2003) derived the finite element equations of elastic wave propagation of two-phase anisotropic media and performed numerical simulation. Wang et al. (2006) used a high-order staggered FD algorithm to carry out numerical experiments on wave propagation in rock partially saturated by multi-phase fluid with random fluid distribution. Based on the modified Biot's theory of two-phase porous media, Zhou et al. (2006) studied seismic reflection and transmission coefficients at an air-water interface of saturated porous soil media. Xu et al. (2006) studied the scattering of elastic wave by a cylindrical shell embedded in saturated soils.

IV. SURFACE WAVE AND SEISMIC WAVE INVERSION

Many progresses have been made in the study of surface wave theory and their applications to investigate the interior structure of the earth in the past four years. Fan (2004) studied surface seismic Rayleigh wave with nonlinear damping by deducing two nonlinear PDEs as the governing equations into two systems of linearized asymptotic governing equations for each order and analytically solving the first two linearized governing equations. Based on the generalized R/T coefficient method, He et al. (2006) developed a new approach to calculate dispersion curves and normal mode solutions of multilayered solid earth model with low velocity layers. Chen and Sun (2006) proposed a new method, improved equivalent homogenous half-space method, to compute the theoretical dispersion curve of a layered medium based on the equivalent homogenous half-space theory. This new method does not need to deal with the multiple value problem of the phase problem, and the phase velocity resulting from this method can reflect the synthetic effect of all ranks of Rayleigh waves. Liang et al. (2006) derived a high-frequency analytical solution for scattering of Rayleigh waves by a shallow circular alluvial valley using wave function expansion method and analyzed the effects of incident frequency, width of the valley and depth of the valley on wave scattering. Huang et al. (2003) studied S wave velocity structure of China and adjacent regions using Rayleigh wave tomography. Hong et al. (2003) studied the 3D S-wave quality factor of the crust and upper mantle in China using surface wave attenuation characters. He et al. (2004a, 2004b) inverted the S-wave velocity structure of the middle and upper crust in Yunnan region using Rayleigh wave tomography. Huang et al. (2004) presented a surface wave study aimed to resolve the azimuth-dependent propagation velocities of Rayleigh waves (10-184s) in East Asia. Zheng et al. (2006) calculated and evaluated the polarizations of intermediate period Love waves traveling through the Qinghai-Xizang Plateau using a frequency domain singular value decomposition method. The accuracy and resolution of surface wave dispersion results depend on the parameters used for acquiring data in the field. Zhang et al. (2004) determined the optimal acquisition parameters from a preliminary seismic survey prior to a multichannel analysis of surface wave survey in a case study on a fill slope in Hong Kong. Cui (2004) proposed an improved global optimization method based on Simulated

Annealing and Genetic Algorithm and applied it to the inversion of surface wave dispersion curve. Lou et al. (2006) applied surface wave method to invert the S-wave velocity structure of the Kunlun fault zone.

Study of detailed crust and upper mantle structure using teleseismic receiver function has been an active field in the past four years. Zou and Chen (2003) analyzed the character of SV-component receiver function of teleseismic body waves and its advantage in mapping the S-wave velocity structure of crust in detail. Zhou and Yang (2003) developed an inversion method of peeling genetic algorithm to study the depth of seismic discontinuities in the upper mantle using observed receiver function. Wu et al. (2003a, 2003b) estimated receiver function using the Wiener filtering and maximum entropy deconvolution, respectively. Wu et al. (2003c) presented a method of receiver function inversion based on wavelet transformation. Liu and Kind (2004) proposed a method for isolating the three-component receiver function from multi-channel seismic data based on multi-channel maximum likelihood deconvolution principle. Hu et al. (2005) performed a joint inversion using surface wave dispersion and receiver function to investigate the crust-mantle velocity structure beneath western Yunnan province. Wang et al. (2005) applied the wave-equation FD algorithm as a solution for forward modeling and migration of receiver function. Chen et al. (2005a, 2005b) proposed a wave equation-based poststack depth migration method to image the Earth's internal structure using teleseismic receiver functions and applied it to study the subsurface structures of the Japan subduction zone. Teleseismic receiver function study has been applied to invert the seismic wave velocity structures in various region (Ai and Zheng 2003; Ai et al. 2005; An et al. 2006; He et al. 2003, 2004a, 2004b, 2005; Chen et al. 2005; Duan et al. 2005; Liu et al. 2005; Mi et al. 2005; Wang et al. 2006), study the Poisson's ratios (Li et al. 2006a, 2006b; Xu and Zheng 2005) and anisotropy (Xu et al. 2006) of some areas.

Tomographic inversion of velocity structure using travel time of seismic phases such as P, S and regional phases Pn and Sn have been carried out for many regions (Bai and Wang 2004; He et al. 2006; Huang and Zhao 2004, 2006; Li et al. 2006; Liang et al. 2004; Liu et al. 2005; Pei et al. 2004; Qi et al. 2006; Wang et al. 2003a, 2003b, 2005; Xu et al. 2006a, 2006b). Liu et al. (2006) discussed the LSQR algorithms used in seismic travel time tomography and presented a parallel LSQR algorithm implemented on a multi-processor super-computer. Tian and Chen (2006) proposed a hybrid algorithm, which combines the quasi-Newton method and the trust-region method in a least square form, to simultaneously determine hypocenters and velocity structure.

Seismic waveform contains more information than the travel times about the velocity structure. Therefore, seismic waveform inversion could reveal finer structure than the travel time tomography. Luo et al. (2003) discussed the LU decomposition with spectral factorization in seismic imaging. Zhao et al. (2004), Zhao and Zheng (2005) studied seismic velocity structure of the south edge of the Jiyang depression, in the Bohai Bay Basin, northern China, using a method combining an shear horizontal (SH) forward synthetic calculation and waveform inversion. Zhang et al. (2004) proposed a homotopy method for determining the parameters of the earth based on the inversion of one-dimensional seismic wave equation. Fu and Han (2005) proposed a new strategy-regularization-homotopy method for the inversion of 2D wave equation by combining the Tikhonov regularization method for ill-posed problems with the widely convergent homotopy method applied to the inversion process of operator identification. Tian et al. (2005) presented a joint imaging by teleseismic converted and multiple phases to image the crustal structure beneath the INDEPTH-III passive seismic profile in the central Tibet. Ni et al. (2005) studied the 3D structure of the African superplume from waveform modeling using seismic waveforms recorded by the South Africa Array generated by earthquakes in the western Pacific Ocean. He et al. (2006) determined the geographical boundary and shear-velocity structure of a very-low velocity province at the base of the Earth's mantle beneath western Pacific based on the waveform modeling and travel time analysis of ScSH-SH phases. Wu et al. (2006) studied the crustal and upper mantle velocity structure below Chuandian region using regional waveform inversion. Wang and Zhang (2006) presented a genetic algorithm of body waveform inversion for better understanding of crustal and upper mantle structures with deep seismic sounding waveform data. Yang et al. (2005) provided a theory and method of how to introduce the fixed-point theory into the nonlinear seismic scattering inversion and how to obtain the solution, and gave the actually method to create a series of contractive mappings of velocity parameters in the mapping space of wave.

Inversion of elastic parameters is important in study of anisotropic media in practice. Zheng (2004) presented linearized inversion equations of quasi P waves (qP) and quasi S waves (qS) in arbitrary weakly anisotropic media for elastic parameters. Lu et al. (2005) proposed a method to analyze the P-wave travel time using ray tracing and estimate the Thomsen anisotropic parameters using the Niche Genetic Algorithms in orthorhombic media. Chen et al. (2006) presented a joint inversion scheme for travel time and polarization information of wide-angle seismic data to determine three of the five anisotropic parameters (vertical P-wave velocity V-po and Thomsen's parameters epsilon and delta) in transversely isotropic media with a vertical symmetry axis.

V. SEISMIC WAVE STUDY IN PROSPECTING AND LOGGING PROBLEMS AND OTHER

Many progresses have been made in theoretical study of seismic wave and the closely related applications in seismic prospecting and well logging in the past four years. Chen et al. (2003) proposed a wave-equation depth migration method for prestack seismic data based on plane wave decomposition. Liu et al. (2004) studied wave-equation 3D prestack depth migration for the SEG/EAGE salt and overthrust model and discussed in detail the imaging ability to a complex geologic structure using their symplectic 3D prestack depth migration software system. Hu et al. (2004) proposed a method of wide-angle seismic wave field analysis and imaging to explore in high velocity basalt shield area. Cui et al. (2004) derived a one-way wave equation with true amplitude by the decomposition of the wavefield operator for the wave equation in a 3D heterogeneous medium. Lu et al. (2004) presented a new adaptive multiple subtraction algorithm based on independent component analysis. Chen et al. (2004) used beamlet prestack depth migration based on Gabor-Daubechies frame decomposition for angle-domain imaging. Hong et al. (2004) presented an optimal beamforming method and its application to attenuating multiple for low signal-to-noise ratio seismic data, which is better than some popular techniques like f-k and Radon transformation. Zhao and Wang (2004) expressed the spherical divergence corrections on the P-P and P-SV wave sections in unified formulae in which the formula for the P-SV wave section differs from that for the P-P wave section. Fu (2004a) optimized practical implementation of the Fourier wavefield extrapolation and designed three interpolation algorithms: Fourier transform, Kirchhoff, and Born-Kirchhoff for mild, moderate, and large to strong lateral heterogeneities, respectively. Zhang et al. (2005) applied an optimal separable approximation to the characteristic function of one-way wave operator in the seismic migration algorithm. Li and Eaton (2005) studied the delineating of the Tuwu porphyry copper deposit at Xinjiang, China, with seismic reflection profiling. Zhang et al. (2005) described a recently developed true-amplitude implementation of modified one-way operators and presented some numerical examples. Zhao et al. (2006) presented an improved wave equation 3D parallel prestack depth migration method. The method is flexible and selectable by designing different synthetic operators for different input data sets. Zhang et al. (2006) implemented pre-stack full wavefield inversion for the elastic parameters of transversely isotropical media. Chen et al. (2006) developed beamlet propagation and imaging using Gabor-Daubechies frame decomposition based oil local perturbation theory and applied it to target-oriented prestack depth migration. Chen and Ma (2006) presented a general approach to the linear stacking of seismic common shot gathers and their sources based on the linear stacking principle of seismic wavefield. Liu and Zhang (2006c) proposed a one-way propagator for more accurately modeling wide-angle wavefields in the presence of severe lateral variations of the velocity. Fu (2004b) proposed a joint inversion scheme to integrate seismic data, well data, and geological knowledge for acoustic impedance estimation. Jiang et al. (2005) proposed a P-wave velocity and Poisson's ratio nonlinear inversion method by partial stack P-wave velocity and Poisson's ratio inversion simultaneously.

Some researchers developed new data processing techniques to extract more information than using conventional methods from the digital seismic waveform data. Cao et al. (2005) proposed a new method of utilizing combined wavelet with fractal to detect seismic singularities aiming at improving the detecting precision. Chen et al. (2005) presented a method for complex polarization analysis based on windowed Hilbert transform and its application to actual three-component earthquake data. Most methods of studying two-component or/and three-component seismograms assume that body-wave polarizations are mutually orthogonal. This is not correct, however, in cases of anisotropic or inhomogeneous medium; nor can it be used to measure converted phases or phases reflected along different paths. To solve such problems, Lei (2005) presented a new technique called Seismic Polarization-Vector Separation (SPVS). Using an affine coordinate transform, SPVS achieves a more accurate and reliable measurement of almost all kinematic and dynamic parameters on three-component seismograms, including polarization, arrival time, amplitude and extended waveform.

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Study on the structure and physical properties of the mantle

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Abstract The studies on the structure and physical properties of the mantle done by Chinese geophysicists from 2003 to 2007 are reviewed in this report. It mainly contains the seismic velocity structure of the mantle, anisotropy of the mantle, mantle discontinuities, mantle convection and the physical properties of mantle. The review concerns mainly the contents, the methods used and the results of the studies. It can be found that new progress in the study on the structure and physical properties of mantle has been made in the last 4 years in China: In some preexistent areas much progress has been made, advanced methods have been adopted, extensive international co-operation has been conducted in many ways, and the scope of the co-operation has gradually expanded. Moreover, some new fields appear as well.

Keywords mantle structure; physical property of the mantle; seismic tomography; anisotropy; subduction zone; mantle discontinuity

1. Introduction

Progress in the study on the structure and physical properties of the mantle has been made in the last 4 years. Zang et al (2003) has reviewed the studies on the structure and the physical properties of the Earth's interior in China during 1999~2003. Following that way this review will summarize the work done by Chinese geophysicists on the structure and physical properties of the mantle from 2003 to 2007. The contents are mainly on the structure and physics of the mantle beneath the lithosphere and therefore may be limited. Related results can be found in other reviews.

2. Seismic velocity structure of the mantle

In the past four years, the seismic velocity structure of the mantle is still the important research field in China. The areas of study are mainly Chinese mainland and its adjacent region. The main methods are seismic tomography and receiver functions.

2.1 Seismic tomography of the mantle structure

Huang and Zhao (2006) determined a high-resolution P wave tomographic model of the crust and mantle down to 1100 km depth under China and surrounding regions using about one million arrival times of P, pP, PP, and PcP waves. Their model shows the subduction state of the subduction of the Pacific, Mariana, Indian and Philippine Sea, and the relationship between the volcanoes and subductions. Moreover, it can be seen from their model that high-velocity anomalies are revealed in the upper mantle under the Tarim basin, Ordos, and Sichuan basin. He et al. (2006) studied the seismic velocity structure of the lithospheric mantle beneath the western Kunlun orogenic belt (WKOB) and its foreland by a tomographic method using P wave arrival times recorded by 14 broad-band stations. Their results show that the lithospheric mantle beneath WKOB is perhaps the frontier of the subducted lithospheric mantle of the Indian Plate; the lithospheric mantle beneath WKOB with high-velocity anomalies collided with that of the Tarim blocks in the front of Eurasia Plate with low velocity anomalies at the depths from 150 to 300 km. By using four seismic tomographic profiles of nearly 8000 km long across the Qinghai-Tibet Plateau，Xu et al. (2004) obtained the crustal and mantle velocity images and seismic wave anisotropy over the depth down to 400 km, which revealed significant characteristics of the crust and mantle structure in the study region. The depth that extend downward of the strike-slip faults and the subduction northward of the Indian plate are discussed in their paper. Based on the new tomographic data a new collisional model for the uplift of the Tibet plateau is presented. Zhao et al. (2004) used 24241 rays from 926 distant events recorded at 164 portable stations along the cross section of Yadong- Golmud to perform the teleseismic P wave tomography. With their result the dynamic process in which the thick lithospheric mantle of the India plate underthrusting below the Tibet plateau is discussed.

Combining the data recorded by the portable broadband seismic array and the travel time data of the regional seismic network，Guo et al. (2004, 2006) investigate the P wave velocity structure of the crust and upper mantle to the depth of 400 km below Northeastern part of the Tibet, Ordos and Tienshan. Their results show that the structure of the crust and upper mantle below Northeastern part of the Tibet and Ordos has obviously laterally inhomogeneity，which occur not only between different blocks，but also within each block; the crust below Tienshan has an obvious block structure and strong lateral crustal distortion which manifest that the Tianshan crust is compressed strongly by the Tarim block. Moreover, the dynamic evolution of these two areas are also discussed in their paper.

Li et al. (2006) reconstructed the 3-D P wave velocity images of the crust and upper mantle beneath Bohai Sea and its adjacent regions through a tomagraphic inversion by using P wave arrival times from local and distant earthquakes, with a grid spacing of 0.5^{o} (in latitude) x 0.6^{o} (in longitude). The velocity images reveal an evident lateral heterogeneity of the curst and upper mantle of the Bohal Sea regions. Velocity anomalies in the upper-mid crust reflect the character of surface geology.

Hearn et al. (2004) imagined tomographically the seismic P wave velocity variations in the uppermost mantle beneath China using Pn wave travel time data. Different inversions performed for shorter ray path and longer ray path data sets separated the shallow and deep structure within the mantle lid. Based on their results, the relationship between the seismic velocity variations and the tectonics were discussed..

2.2 Mantle structure studied by receiver function and other methods

In the recent years, the receiver function method in studying the deep structure of the Earth has been developed further.

Xu et al. (2005) studied the deep structure below the western Tibet Plateau by a method of receiver function, using seismic data recorded by 49 broad-band stations which were deployed along Yecheng-Shiquanhe cross section by Chinese Academy of Geological Science and French scientific research center from June to November of 2006. From their result it can be seen that there is a low velocity abnormality of S wave located at the depth of 200 km beneath Tianshuihai Terrain where the lithosphere of Tarim Basin and Tibet Plateau converges.

Wu et al. (2005) obtained the upper mantle structures of Himalayas-Tibet from the migration of receiver functions of the teleseismic events recorded by INDEPTH-III. The result of migration imaging shows a dipping interface subducting northward from the depth of 100 km to the 410-km discontinuity underneath southern Tibet. Zhao et al. (2004) analyzed the relationships between ultrahigh—pressure metamorphosed belt and 3-D S wave velocity structure of the upper mantle of the eastern Chinese continent, and pointed out that the geometries of the velocity structure images beneath the region crossing the Dabie orogeny belt may imply that the zones thrusting downward and upward might be related to the ”traces” for the subduction and exhumation process of the formation and evolution of the ultrahigh-pressure metamorphosed belt beneath the Dabie mountain.

Zheng et al. (2006) collected and analyzed the data of three component digital surface wave from 50 portable seismograph stations located in west Yunnan，China． By a method of frequency domain singular value decomposition, the polarizations of intermediate period Love waves traveling through the Qinghai-Xizang Plateau were calculated and valuated．The result shows that there are obvious polarization anomalies，which could be due to the lateral heterogeneity of the lower crust and uppermost mantle velocity structure in the wave propagation path．Besides，theoretical arrival azimuths were computed by using the velocity model from a previous tomography study．There is general consistency between the theoretical result and the majority of the observations, although the theoretical anomalies are often smaller than the observations．

Zhao et al. (2006) used high-accuracy data of arrival times to investigate the range of variations in the travel time residuals which indicate the degree of mantle heterogeneity．It can be seen from their results that variations of the residuals amount to 9 S for P phase，11 S for PP phase，and 15 S for Pdiff phase. A large range of travel time residuals(-6 to + 9 s) for epicentral distances shorter than 40 degrees and a smaller range of residuals(一3 to + 5 s) for longer epicentral distances can also be seen, which indicate that the inference that the upper mantle and transition zone have much stronger heterogeneities than the bulk of the lower mantle.

Ai et al. (2005) used three receiver function stacking methods to study the detailed crust and upper mantle structure beneath south-central Alaska. H-kappa stacking method results show that the crustal thickness under Alaska ranges from 26.0 to 42.6 km, and the V_P/V_S ratio varies from 1.66 to 1.94. Common converted point (CCP) stacking results along three lines show clear Moho and slab images under this subduction zone. The depths of the slab from CCP stacking images are consistent with those estimated from the Wadati-Benioff Zone (WBZ).Common depth point (CDP) stacking results shows not only the 410, 520- and 660-km discontinuities, but also significant variations (-30 to 15 km) in the transition zone thickness under the southwest and southeast parts of the study region.

3. Seismic anisotropy in the mantle

Seismic anisotropy is still a research area which draws big attention from Chinese geophysicists, and new progress has been made in the last four years.

With the three-component broadband digital seismic data obtained from China Digital Broadband Seismograph Network (CB Network) and the United States IRIS data center, Luo et al. (2004) determined SKS wave splitting parameters below more than 80 seismic stations in China and its neighboring regions. The results show that the delay times range from 0. 4s to 2. 4s with an average about 1. 2s in the study region; fast wave polarization directions beneath most stations share a common preferred orientation in a same tectonic block; and the fast axes show good correlation with the past or present-day tectonic movement .

Using SKS shear waves recorded at 47 stations in Yunnan, Chang et al. (2006) calculated and analyzed the seismic anisotropy. It is shown that the fast wave polarization directions are nearly N-S in northern Yunnan and gradually change to W-E in southern Yunnan; Delay times vary from 0.58 to 1.88s; The anisotropy layers are mainly in the upper mantle in the depth range between 67km and 216km.

Based on the tele-seismic events which were recorded in Shanghai seismic array (SSA) and Using seismic array process technology, Wang et al. (2005) calculated the splitting parameters of PpSms，P660S and SKS. The fast wave polarization directions in the crust below SSA is 67.7^{o} and the delay time is 0.26s; 66.6^{o} and 0.25s in the upper mantle; 65.5^{o} and 0.58s in the lower mantle.

Ruan et al. (2004) used the pseudo-spectrum method to simulate the crust effect on the analysis of the upper mantle anisotropy. It is found that when the angle between the anisotropy orientations of the crust and the upper mantle is neither parallel nor perpendicular，the inversed results may be in large error or misjudged. Corresponding suggestions are also made in their paper.

4. Mantle discontinuities

Mantle discontinuity is the main research direction in the past four years, and the research field is gradually enlarged.

Duan et al. (2005) studied the mantle discontinuities below Changbaishan volcanic areas (CBSVA) and Jingpohu volcanic region (JPHVR) by the method of receiver function, using the tele-seismic waveform data recorded by 19 PASSCAL broadband mobile seismic stations which operated nearly one year in CBSVA and other 14 stations with portable broadband digital seismographs deployed about three months in JPHVR. Results show that the 410km, 520km and 660km discontinuities exist beneath the studied area; Both the 410km and 660km discontinuities are continuous and show positive correlation; The 410km discontinuity is a local uplift beneath the CBSVA, and 660km discontinuity is of the complex multi-interface; The 660km discontinuity descends beneath the Huichun deep earthquake area and above the 660kin discontinuity there are some phases，which are not continuous on the two sides of the Huichun deep earthquake area.

Xu et al. (2005) studied the deep structure below the western Tibet Plateau with a method of receiver function, using seismic data recorded by 49 broad-band stations which were deployed along Yecheng-Shiquanhe cross section by Chinese Academy of Geological Science and French scientific research center from June to November of 2006. It can be seen from the result that the conversion interface between spinel (*woltitanium*) phase and periclasite (*magnesiowustite*) phase may appear at the depth from 670 to 700 km.

Ai and Zheng (2003) applied a common conversion point stacking technique of receiver functions in the North China Interior Structure Project (NCISP) to image the upper mantle discontinuity structure beneath eastern China. The appearance of the 410-km discontinuity is sharp and consistent with little influence by Western Pacific subduction slabs. The 520-km discontinuity is relatively weak and consists of splitting phases at depths ranging from 500 km to 550 km. Moreover, a double 660km discontinuities and a narrow depression zone are detected near a depth of 660-km.

Ai et al. (2003) presented a detailed seismic study of the 660 km discontinuity beneath northeast China using the receiver function technique. The 660 km discontinuity is locally depressed in the region from longitude 128.0^{o}E to 130.5^{o}E and latitude 40.0^{o}N to 44.0^{o}N. and then it splits into multiple discontinuities in the surrounding regions.

Zang et al (2006) studied the discontinuities beneath Tonga subduction zone using the deep earthquakes recorded by the Pacific Northwest Seismic Network (PNSN). The multiple discontinuities around 660 km beneath Tonga subduction zone are found using converted phase *SdP*. The amplitude ratios of the converted phase with the direct *P* wave (*Ac*/*Ap*) are also determined. The largest number of robust converted phases with large *Ac*/*Ap* comes from the depth range of 660–690 km, its peak is at 680 km; the second one appears in the depth range of 700–745 km, its peak is at 740 km. The two discontinuities are obviously depressed by the subduction slab. According to experimental and numerical studies, a possible explanation of the observation is that the first discontinuity is formed by the transition of γ-spinel to perovskite and magnesiowüstite and the second is formed by the transition of ilmenite to perovskite.

He and Zhou (2005) analyzed the global topography, the depth of the Moho (the crustal model CRUST2.0) and the depths of upper mantle discontinuities using the spherical harmonics. Based on these data, the spatial large scale distribution information has been obtained by stacking the first 4 degree modes, and the main energy distributions have been understood by synthesizing the four items with the maximal squares of amplitudes. The results show that there exists a large scale asymmetry on the scale of semi—sphere in the topographies of the Moho and the "410" discontinuities, and the asymmetry character of the north—south semi—spheres is more obvious than that of the west—east semi —spheres; However, there exists a scale asymmetry on the small side in the topographies of "520"and "660" discontinuities, instead of such a large semi—sphere scale asymmetry.

Zheng et al. (2007) studied the small-scale variation of P waves beneath the Central Pacific using differences of the travel times between the AB and DF branches of PKP waves. They found that the observed PKP residuals consist with the predictions for Grand's tomographic S model, and have a good correlation in the variation of their magnitude; the inferred P velocity variation (which is about 2 % in the bottommost 200 km D″ layer) is about 36 % of the S velocity variation for the Grand model.

5. Mantle convection

The study of the mantle convection will be reviewed briefly in this report, because it related closely to the structure and the material properties of the mantle. More information can be found in the report of study of the Earth's dynamic.

Wang and Ye (2005) applied a kinetic simulation method to perform modeling for the global lithospheric stress field induced by mantle flow. The results show that both the internal density anomalies and surface plate movements drive the mantle circulation, and a stress filed will be caused at the base of the lithosphere; As a surface force, this stress field will cause lithospheric deformation itself and produces the stress distribution within the lithosphere. It can be found that mantle flow plays an important role in generating and distribution of the large-scale stress field within the lithosphere.

Zhu et al. (2006) developed the mantle convection model with a 3-D variable viscosity constrained by seismic wave velocity and provided a method for solving this kind of problem.

Fu et al . (2005) employed a new model with different viscous ratio between the lower and upper mantle to calculated the mantle convection patterns driven by density anomaly, and discussed the relationship between convection patterns and global tectonics.

Xiong et al. (2005) pointed out that the uplift and formation of the Tibetan Plateau is the dynamic consequence of the collision between the Indian and Eurasian plates. However, the collision model alone and the SW-NE compression between two plates can not explain all the tectonic features of the plateau.

Fu et al. (2005) established a 3-D mathematic-physical mantle convection model driven by density anomalies, and developed the method to inverse the small-scale convention in the mantle using the data of seismic tomography. Numerical results show that this method can be directly used to investigate the upper mantle small-scale convection patterns and its related problems of lithospheric dynamics. Xu et al. (2006) calculated upper mantle convection beneath north-west China and adjacent region using the small-scale mathematic-physical convection model driven by density anomalies in the upper mantle. It is pointed out that one of the reasons for the recent uplift of the Tienshan Mountain is that the upper mantle material in this region is driven southward to the north part of Tibetan Plateau and northward to Tienshan Mountain because of the divergent flow under the Tarim Basin.

Huang and Zhong (2005) investigated the effects of sublithospheric small-scale convection (SSC) and of internal heating on seafloor heat flux and topography and mantle thermal structure, and they examined the dynamic feasibility of the plate model by formulating high-resolution two-dimensional numerical models of mantle convection with strongly temperature-and depth-dependent rheology. It is suggested from their results that the trapped heat and the SSC are responsible for the residual heat flux and topography at old ocean basins relative to the half-space cooling model predictions; For the plate model to be dynamically viable, both the SSC and significant internal heating (> 60%) are necessary.

6. Physical properties of the mantle material

In the past four years, high-temperature and high-pressure experiment studies on the physical properties of mantle material have been developing steadily.

Huang et al. (2005) studied the relationship between the electrical conductivity of synthesized wadsleyite and ringwoodite and the containing water using Kawai-1000 multi-anvil apparatus. By comparing their results with geophysically inferred conductivity, they inferred that the water in the mantle transition zone below Northeast China to be 0.1-0.3 wt%, which is significantly exceed the average water content in the upper mantle, suggesting that partial melting likely occurs at 410km in this region.

Zhang et al. (2004) conducted a shock recovery experiments on ($Mg_{0.92}$, $Fe_{0.98}$)SiO3 enstatite at pressure range from 60 to 110 GPa (corresponding to temperatures of about 2300 -4800 K). Their X-ray diffraction (XRD) and infrared absorption spectra (IR) of the recovered samples indicate that the main phase of recovered samples is single-chain structure enstatite, not the perovskite structure; There is no evidence for the existence of oxides SiO2 and (Mg0.92, Fe0.08) O in the recovered samples; Especially, there is no possibility for the chemical decomposition reaction of (Mg0.92, Fe0.0s) SiO3 to oxides SiO2 and ($Mg_{0.92}$, $Fe_{0.08}$) O occurring under shock compression, so the high-pressure phase of enstatite - perovskite structure remains stable at the experimental conditions.

Liu et al. (2005) measured the elastic P wave velocity and quality factor value of dunite using ultrasonic pulse transmission and spectral amplitude ratio methods in a multi-anvil apparatus up to 4.0GPa at room temperature, and analyzed the effect of the interior structure variation of the dunite on the velocity and attenuation.

Using the observed data to study the physical properties of the mantle material is always an important study area in the geophysics, and much progress has been made. Tang et al. (2005) carried out the Magnetotelluric (MT) measurements at 62 sites in the junction area between the northeastern margin of the Qinghai—-Tibet plateau and the Ordos block along the profile of Maqing-Lanzhou-Jingbian, and analyzed the apparent resistivity，impedence phase curves, skewness and regional strike．In their paper, RRI 2-D inversion has been used for data interpretation and the electrical structure is discussed.

The rheology of the mantle is also a subject for the physical property study of the mantle. Taking into account the variation of the physical property for focal media after earthquake, Zhu and Cai (2006) inverted the viscosities of the crust and the upper mantle in Taiwan with GPS measurements after Chi-Chi earthquake. The preliminary result suggests that the viscosities of lower crust and upper mantle in Taiwan are 1.2 x 10^{18}Pas and 3.6 x 10^{19}Pas, respectively. Lin et al. (2003) collected several tens of mantle xenoliths in Leizhou Peninsula, and estimated their equilibrium temperature and pressure using geothermo-barometers. Then they constructed an upper mantle geotherm for the study area on the basis of the estimation results, which is lower than that of southeast Australia and much higher than the oceanic geotherm. Moreover, the rheological parameters of the upper mantle are estimated. Results show that the equivalent viscosity is within the range of 10^{21}-10^{23}Pas, showing an obvious tendency to decrease with increasing depth.

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IASPEI National Report (2003~2006)

Advances in seismic tomography research in China

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During 2003-2007, with the increasing number of the seismic stations in China, especially the installation of the portable seismic stations, more and more data were collected. This is benefit for seismic tomography research in variety regions in China. The seismic tomography researches were carried out in the whole China region and in the local area imaging. The P wave velocity imaging, Pn and Sn velocity imaging beneath the Moho, Q imaging were studied for whole China region. The local areas for the tomography include the Tibetan Plateau and its surroundings, Tian Shan area, North China, Changbaishan volcano, etc. These research works are important for understanding the crust and upper mantle structures and the continental dynamical processes in China.

1. Seismic tomography research for whole China region

Imaging the three seismic wave velocity structures for whole China has been made many advances since 2003. Huang et al. (2006) obtained a high-resolution P wave tomographic model of the crust and mantle down to 1100km depth under China and surrounding regions by using about one million arrival times of P, pP, PP, and PcP waves recorded by 1012 seismic stations. The subducting Pacific slab is imaged clearly as a high-velocity zone from the oceanic trenches down to about 600km depth. The Pacific slab becomes stagnant in the mantle transition zone under east China. The western edge of the stagnant slab is roughly coincident with a surface topographic boundary in east China. The active Changbei and Wudalianchi intraplate volcanoes in northeast China are underlain by significant slow anomalies in the upper mantle, above the stagnant Pacific slab. These results suggest that the active intraplate volcanoes in NE China are not spots but a kind of back-arc volcano associated with the deep subduction of the Pacific slab and its stagnancy in the transition zone. Under the Mariana arc, however, the Pacific slab penetrates directly down to the lower mantle. The active Tengchong volcano in southwest China is related to the eastward subduction of the Burma microplate. The subduction India and Philippine Sea plates are also imaged clearly. The Indian plate has subducted down to 200-300km depth under the Tibetan Plateau with a horizontal moving distance of about 500km. High-velocity anomalies are revealed in the upper mantle under the Tarim basin, Ordos, and Sichuan basin, the three stable blocks in China.

The 2-D seismic velocity images were obtained by using the data of head wave on Moho discontinuity. Some results were published in China for the Pn and Sn tomography. Wang et al.

(2003) gave the Pn velocity distribution with the horizontal resolution of 3°×3°. The result shows that there is a close relation between Pn velocity lateral variation and delineation of the first order block regions. Roughly demarcated by 105°E , positive velocity anomaly regions dominate in the western part of the China mainland , with the highest positive anomaly in the Xiyu block region and secondary positive anomaly in Qinghai-Xizang Plateau region, while the Yunnan-Burma block region exceptionally shows negative anomaly. Nevertheless, negative velocity anomaly regions are mainly seen in the eastern part, with the lowest negative anomaly in the North China block region and secondary low anomaly in the Northeastern Asia block region. Rather significant correlation between Pn velocity lateral variation and location of strong earthquakes can also be seen. Most $Ms \geq 7.0$ earthquakes took place in the crust above the low Pn velocity anomaly region, with a few occurring in the transition zone between high and low Pn velocity, or in the relative low velocity zone between two high velocity regions.

Pei et al. (2004) inversed the Sn wave velocity images in China and surrounding region. The Sn velocity image in the uppermost mantle beneath the China continent is constructed by the tomography method using 43646 travel times from Annual Bulletin of Chinese Earthquakes. The results show that Sn velocity is low in eastern China and high in western China. The remarkable high Sn velocity mainly exists in the Tarim , Juggar , Turpan-Hami , eastern Qaidam , Sichuan basins and the region south to the Sichuan basin, which is similar to the results of Pn tomography. In the Ordos platform and Taiwan straits , the Sn velocity is high. The low Sn velocity mainly appears in the whole North China basin , east to the Bohai bay , northern Shanxi , and the Tancheng-Lujiang fault zone. In addition , in the middle and lower reaches of the Yangzi river, the northern Tibetan Plateau and the South-North seismic zone , the Sn velocity is slightly low. The velocity anomalies in the tomographic results of Pn and Sn are similar, with the character of low in eastern China and high in western in China.

The new results for quality factor (Q_β) in the region of China mainland are obtained. Hong et al. (2003) inversed the 3-D S wave attenuation coefficient distribution from Rayleigh surface waves in the region of China at the 4°×4°grids. They calculated the layer Q_β in each grid, and got the distribution of Q_β in the different depths (10-350km). The results show that the lateral and vertical variations of Q_β are very clear in the whole research area. The asthenosphere is shown clearly in the images. Q_β structures in some large tectonic structures are remarkable different.

In China marginal sea and adjacent regions, Liu et al. (2005) obtained the velocity images beneath the Chinese marginal seas and adjacent regions (10°～45°N ,105°～145°E , down to 1061km depth) are reconstructed by using 570237 of P wave travel times of 27909 regional earthquakes and 4995 of teleseismic events, supplied by Chinese seismic networks and world seismic networks, and three-dimensional velocity structure features are revealed in the crust and upper mantle in China marginal sea regions.

Cai et al. (2006) discusses the 3-D structure features of the asthenosphere beneath China and adjacent land and sea areas based on a systematic tectonic analysis of the 3-D velocity structure by using seismic surface tomographic imaging. Both high-velocity blocks and low-velocity anomalies were discovered in the asthonosphere of the region, indicating the existence of vertical and lateral heterogeneities in the asthenosphere. Study of the 3-D geometric structure of the low-velocity anomalies in the asthenosphere suggests that the anomaly beneath the South China Sea asthenosphere is composite mushroom-shaped. According to this finding, combined with the mantle body wave tomographic image, it is concluded that a giant composite mushroom-shaped low-velocity mantle plume might occur at over 2000km depth in the region..

2. Seismic tomography in the key tectonic active areas in China

The Tibetan Plateau has been got the attentions from the scientists in geosciences all the world. Since the 1980s, scientists from variety countries carried out many cooperated projects in this region, and obtained a large amount of the seismic recordings. These data supplied the good background to do the seismic tomography work in Tibetan Plateau. Zhao et al. (2004) used 24241 rays from 926 distant events recorded at 164 portable stations (by the Sino-US INDEPTH project and Sino-France 9293 project) along the line Yadong-Golmud to perform teleseismic P wave tomography. The aim of this work was to obtain the velocity structure of the upper mantle beneath the Xizang Plateau with high resolution. Their results shown that the thick lithospheric mantle of the India plate is divided into two layers beneath the High Himalayas during the underthrusting of India below the plateau , representing the first time of its delamination. The lower layer underthrusts beneath the High Himalayas at about 22°angle northward to depth 350km and the upper layer extends northward to Yanshiping , forming the thin lithospheric mantle below the plateau. North to Yanshiping (33.7°N) , the upper layer of the Tibetan mantle fractures and sinks when it meets the lithosphere of the Asia continent. This result also confirmed the existence of a deep low-velocity body beneath Wudaoliang (35. 27°N) and suggested that this low-velocity body in the crust may be associated with upwelling of hot materials at depth.

Xu et al. (2003) collected the Pn arrival time data from the bulletins of both national and regional seismological network in China. These data are tomographically inverted to map the lateral variation and anisotropy of Pn velocity in the northeastern marginal region of Qingzang plateau. The average Pn velocity in this region is 8.09 km/s, being a little higher than the average for whole China. Higher velocity is found in tectonically stable Qaidam basin, while lower velocity is seen in and around tectonically active Shanxi regions. The P velocity at the uppermost mantle of the epicenter of the 1920 Haiyuan Earthquake is low. The velocity in the northeastern margin of the Tibetan plateau (Qilian Mt. area) is high.

Guo et al. (2006) reconstructed the P wave velocity structure of the crust and upper mantle down to 400km along Kuqa-Kuytun profile by using seismic tomography technique from the travel time data of the P arrivals recorded by the passive seismic array across the Tianshan and the regional seismic network. Their results demonstrate that the crust along the profile has an obvious block structure and strong lateral crustal distortion. These manifest that the Tianshan crust is compressed strongly by the Tarim block. Beneath the Tarim and Junggar block , there are high-velocity anomalies with the thickness of 60～90 km at the top of the upper mantle. The high-velocity anomaly below the Tarim and South Tianshan has a clear curved distortion, and that below the Junggar-Northern Tianshan thrusts down to the depth of 300 km at the south side of the central Tianshan. Both of them construct an asymmetric bilateral thrusting system. Beneath the Tarim and Junggar block , in the depth range from 150 km to 400 km, exist low-velocity anomalies. One of them on the Tarim side rises to bellow the south Tianshan. In the upper mantle , at the depth of 200～300 km beneath the Tarim and South Tianshan, exists a high-velocity anomaly, which could be the detached lithosphere of the Tarim melted by the up-welling hot material of the upper mantle. All of our observations manifest that the lithosphere of Tarim block is involved in the northward subduction, but its front is limited to the north border of the south Tianshan. The long-range effect caused by the uplift of the Tibetan plateau could drive not only the subduction of the Tarim lithosphere, but also the upwelling of the upper mantle in the south side of the Tianshan orogenic belt. The low-velocity anomalies widely existed in the Tianshan upper mantle should facilitate the mantle deformation, and the large difference between the high and low velocity anomalies in the upper mantle may promote the small-scale mantle convection. According to the crustal and upper mantle velocity structure beneath the Tianshan orogenic belt, it could be inferred that the main source driving the quick uplift of the Tianshan since Miocene comes from the long-range effect caused by the uplift of the Tibetan plateau, and the relatively soft upper mantle beneath the Tianshan creates the necessary condition for accelerating the uplift and distortion of the crust.

In the North China region, Li et al.(2006) reconstructed 3-D P wave velocity images of the crust and upper mantle beneath Bohai Sea and its adjacent regions through a tomographic inversion by using P wave arrival times from local and remote earthquakes, with a grid spacing of 0.5°×0.6° in latitude and longitude directions. The velocity images reveal an evident lateral heterogeneity of the curst and upper mantle of the Bohai Sea regions. Velocity anomalies in upper-mid crust reflect the character of surface geology: orogenic belt and uplift areas have high velocities, while depressions and sedimentary basins have low velocities; Widely distributed low velocities in the mid-lower crust beneath North China correspond to high conductive layers in this region, which may be caused by partial-melting and magma activity. Velocity anomalies near Moho reflect the variation of crust thickness and the thermal state in crust-mantle boundary, while low velocity anomalies in uppermost mantle may be related with the upwelling of hot materials from asthenosphere.

Wang et al.(2005) inverted the upper crustal 3-D structure of slowness of P, S wave and *V*p/*V*s around Beijing by seismic tomographic method without blocks with the travel-time data from 3-D Moho reflection survey in 2002. The slices of three structures in different depths reveal the NE and NW trends of slowness and *V*p/*V*s distributions. The upper crustal velocity images are resulted of the sedimental heterogeneity by active seismotectonics in the area. Most of regional earthquakes occurred in low *V*p/*V*s zones, it indicates that earthquake activities are not only related to active faults and may be linked to crustal structure and its material property. There is a close relationship among velocity structure, active faults and upper crustal materials around Beijing area.

Zhao et al. (2004) inversed the 3-D seismic velocity structures in Changbaishan area, and found the new evidences of the source for the Changbaishan volcano. They used the teleseismic P arrivals recorded by 19 portable seismic stations and 3 Chinese digital seismic stations. The results show that the low velocity anomalies appear in the crust and upper mantle beneath Changbaishan volcano area. The anomalies are in the size of 200km, with the depth of 400km. The high velocity anomalies are in the mantle transition zone and the part of the lower mantle. These characters were same as that in the global tomography. They inferred that the Changbaishan volcano is not the hot spot volcano. It is the back-arc intra-plate volcano related to the subduction of the Pacific plate slab.

Yang et al.(2005) reconstructed 3-D crustal interfaces and crustal velocity distribution images by the seismic tomography technique using the reflection traveltimes of P wave from the 3-D spatial deep seismic sounding experiment carried out in the Changbai—Tianchi volcanic region. The interface images show that the crustal depth increases from NW to SE in general. The Ma'anshan —Sandaobaihe and Fu'erhe-Hongqihe faults are two main deep structures of this region , especially in both sides of Ma'anshan—Sandaobaihe fault , where the change of crustal thickness is obvious , implying there is a crustal thickness variation belt or deep crustal fault at this position. The velocity images show that an obvious low-velocity anomaly of P-wave exists around the Tianchi at the depth of 10km. It becomes a low-velocity anomalous strip of nearly SN direction at the 15 km depth , which extends about 80～90km in NS direction and 30～40km in EW direction. With the increase of depth , the low-velocity anomalous strip is distributed on the west side of the Tianchi , but with a smaller scale , and it distributes more concentrated and presents higher perturbation. This change image of the P-wave velocity anomaly illustrates the spatial distribution state of the magma system under the Tianchi volcano to certain extent.

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Advances of seismic anisotropy research in China mainland

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Abstract: Seismic anisotropy is a property of Earth's interior media, and it is becoming increasingly important in the field of geophysics and geology. Anisotropic research of media have very important action for application in geodynamics, earthquake monitoring, resource exploration, et al. Important progress of anisotropic research on Chinese mainland is briefly reviewed since 2003, seismic anisotropy in the crust and upper mantle is especially emphasized.

Keywords: Seismic anisotropy, Shear-wave splitting, Geodynamics, China mainland

In 1964, Hess[1] found that there is azimuthal anisotropy beneath mid-Pacific ridge, for the mid-ocean ridges expansion theory provided an important geophysical evidence, firstly revealed the importance of seismic anisotropy in geodynamics. In 1980s, since Crampin[2] discovered shear-wave splitting, seismic anisotropy has become a hotspot in theoretical seismology, exploration seismology, geodynamics, earthquake monitoring, et al. Presently, numerical modeling and physical experiments are used for probing the laws on wave propagation in anisotropic media. Shear-wave splitting, the azimuthal variation of Pn wave and surface-wave imaging are applied in the research of the structure and material exchangement in the earth, the variation of stress field and the formation of earthquake. There is generally anisotropy in the crust and upper mantle. Parallel vertical cracks widely exist in the lithosphere (EDA cracks) and result in shear-wave splitting in the earth’s curst, at least in the upper lithosphere[3].The fast-wave polarization direction reflects the characteristic of stress field on study region, the change of the delay-times between fast wave and slow wave implies the variation of stress state in the crust media, these are propitious to earthquake forecast. Generally speaking, the mantle anisotropy is determined by the lattice-preferred orientation of olivine crystals as a result of the mantle deformation[1,4]. There are various causes resulting in the mantle deformation. Among them, the plate motion is a direct cause. The size and direction of the mantle anisotropy strongly depend on the velocity of the plate motion. In the various subjects of recent studies on geodynamics, the anisotropy in the mantle is one of effective ways to probe the complicated deep structure beneath the continent and its evolution, the crust-mantle coupling deformation, etc.

In recent yaers, the broadband digital technology has made great progress in the research of the Earth sciences. The seismograms recorded by the broadband seismometers deployed in the world are widely used to the study of seismology, deep structure and geodynamics. Likewise, using the broadband digital data, we have made progress with the anisotropic research in China mainland especially the Tibetan Plateau and North China Craton.

1. Crust anisotropy

The crust anisotropy is realized by shear-wave splitting propagating in the crust. In Yunnan region, Wang[5] studied shear-wave splitting in the aftershock region of the Yao'an earthquake in 2000. The shear-wave splitting parameters are determined by the cross-correlation method in this paper. These conclusions are obtained as follow, firstly, the average fast-wave directions of the aftershock region are controlled by the regional stress field and parallel to the maximum horizontal compressive stress direction. Secondly, the average fast directions of disparate stations and regions are different and vary with the structural settings and regional stress fields.

Shi[6] studied seismic anisotropy of the crust in Yunnan by SAM technique, a systematic analysis method on shear-wave splitting, and obtained the dominant polarization directions of fast shear-wave at 10 digital seismic stations. The results show that the dominant directions of plarizations of fast shear-wave at most stations are mainly at nearly NS or NNW direction in Yunnan. Fast shear-wave polarization directions of the stations which locate in active ruptures are consistent with the trend of active ruptures, principal compressive strain of GPS and regional principal compressive stress. Only a few of stations show complicated polarization pattern of fast shear-waves, or are not consistent with the strike of active faults and the directions of principal GPS compressive strains, which are always located at junction of several faults. The result reflects complicated fault distribution and stress field. The dominant polarization direction of fast shear-wave indicates the direction of the in-situ maximum principal compressive stress, which is controlled by multiple tectonic aspects such as the regional stress field and faults.

Xu[7] studied crust anisotropy near the Red River Fault using P to S converted phase of the receiver function derived from four broadband digital seismic stations near the Red River Fault and obtained a fast polarization direction of 132° and delay time of 0.24s. The fast polarization direction in the crust is consistent with tectonic zones of this region but nearly perpendicular to the fast polarization direction of the upper mantle, implying that the crust and upper mantle may be decoupling near the Red River Fault.

Lai[8] investigate the S-wave splitting at the stations of the Capital Circle area from the local event data recorded by the permanent and movable seismic network. The results demonstrates that the crust stress field of the Capital Circle can be separated into the NE trending regional stress field and the NW trending local stress field controlled by the Zhangjiakou-Penglai faults. The direction of the maximal principal compressive stress nearby Tangshan and its eastern side is toward the EW direction. For the local stress field, the direction of the maximal principal stress is roughly parallel to the strike of the Zhangjiakou-Penglai faults.

Gao[9] and Wu[10] also studied seismic anisotropy in the crust in capital area by shear-wave splitting analysis, using the SAM technique. The seismic data was recorded by the Capital Area Seismic Network (It's consists of 107 stations). The results show that the dominant polarization of fast shear-wave appears two dominant directions in northwestern capital area, one is at NWW or nearly EW direction, another is at about NE direction. However, the polarization of fast shear-wave in the southeastern capital area is at NWW or nearly EW direction. The most predominant polarization directions of fast shear-wave suggest the tectonic implication of horizontal principal compressive stress at the direction NWW or nearly EW, which expose the Zhangjiakou-Penglai depression fault zones with strike NWW. According to the polarization of fast shear-wave, this study verifies that the predominant polarizations of fast shear-wave at stations on active faults are consistent with fault strike. Possibly, both the Nankou-Sunhe fault and Xiadian fault are two active faults while the Babaoshan fault is possibly a non-active fault. The polarizations of fast sheer-wave in the North China Basin show the complexity, consistent with the complicated pattern of regional principal stress varying locally, induced by many faults crossing in the depression zone within the basin.

Generally speaking, the fast wave directions of the crust anisotropy are consistent with the strike direction of active faults, and are related to regional horizontal principal compressive stress, it's important to study the crust motion in China mainland and earthquake monitoring. In recent years, we has make progress in the crust anisotropy on capital area and Yunnan area, but still has a lot of work to do, to understand farther the crust anisotropy on China mainland, we should not only fully utilize the existing seismic data, but also add new high-quality data.

2． Upper mantle anisotropy

Seismic anisotropy in the upper mantle has been one of the most useful features in the understanding of the dynamics of the Earth's interior. We can infer kinematic models of the matter in the earth's interior by anisotropy. In the near future, we mainly used shear-wave splitting and azimuthal variation of Pn velocity studied upper anisotropy on China mainland

Tibetan Plateau is a hotspot of the geophysical research in the world. Since 2000, China National Digital Seismograph Network and regional digital networks have been built up successfully. Meanwhile, several portable seismic networks have been deployed in Tibetan Plateau and its adjacent area by the key scientific projects of China. As a result, a denser observational network has been formed in Tibetan Plateau. The broadband digital seismic data recorded by these stations are greatly helpful to the seismological study on the upper mantle anisotropy and the related geodynamics in Tibetan Plateau and its adjacent regions. Many scholars[11-16] studied sesimic anisotropy of the upper mantle in Tibetan Plateau by use of the stacking analysis method and cross-correlation method. Results show, in the inside plateau, the fast-wave directions are NE in the western Kunlong, the fast-wave directions along the road from Lhasa to Golmud are as follows: NE at the southern end (station SANG), northwards gradually turning to NNE, and then nearly EW at the northern end (station GOM), and, to the east, turning to SE. Hence, the fast-wave direction generally trends clockwise from the inside plateau to the eastern margin. The fast-wave directions are approximately parallel to the tectonic trend of this area in the north to the eastern Himalayan syntaxis. There exists a lateral transitional zone of crust-mantle coupling in the eastern edge of the Tibetan Plateau, which is located in the region between 26º and 27ºN in the west of Sichuan and Yunnan. To the south of transitional zone, the fast-wave direction is gradually turned from S60º~70ºE in southwestern Yunnan to near EW in southeastern Yunnan. To the north of transitional zone in northwestern Yunnan and the south of western Sichuan, the fast-wave direction is nearly NS.The fast-wave direction in southern Yunnan differs obviously from that in northern Yunnan. The crust-mantle coupling deformation is analyzed on the basis of combining the GPS observation results and the upper mantle anisotropy distribution in the study area. The Yunnan region out of the plateau has different features of crust-mantle deformation from the inside plateau. Inside the plateau, the crust-mantle deformation is involved in the vertical coherent deformation model -i.e. the strong crust-mantle coupling model, while the pattern of crust-mantle deformation in the Yunnan region out of the Tibetan Plateau is consistent with the crust-mantle decoupling model. The northward movement of Indian plate and the countercheck of Tarim Block plays a key role in forming the shear wave anisotropy within the lithosphere of this region.

The North China Craton is the one of the world's oldest craton. The debate on the destroy of the North China Craton was long lasting and countinues today. Anisotropy research will help to understand Characteristics of the upper mantle deformation beneath the North China Craton. Zhao and Zheng[17] used SKS splitting parameters at 38 broadband digital sesimic stations to study anisotropy beneath the North China Craton. Results show that delay times range from 0.7s to 1.94s, the fast-wave directions are NW at eastern stations of the North China Craton, while the fast-wave directions are NE at central stations of the North China Craton, they are obviously different. The fast polarization directions trend SE beneath the eastern, which implies that northwestward mantle flow has played a significant role during Late Mesozoic to Early Cenozoic. However, a collision event occurred in Early Proterozoic was also a possible cause for the anisotropy beneath the central of the North China Craton, the region has not completely reformed by later tectonic activities. Kelly H. Liu[19] studied shear-wave anisotropy above the deflected Northwest Pacific Slab determined using SKS and S Phases. The fast polarization directions at 5 stations in the North China Craton are basically NWW. The fast polarization directions are consistent with the relative plate motion directions, the delay times between fast wave and slow wave are about 1s, from west to east is gradually increasing. The results between Zhao and Kelly. Liu are different, the different data and methods are possible causes, it's need further study.

Chen[19] obtained shear wave splitting observations results from a linear array of 26 3-component broadband digital stations across the Tianshan Orogenic Belt. The fast-wave directions beneath the southern Tianshan Orogenic Belt are NWW and gradually turn into NEE in the north. Delay times are 0.65□1.48s with average value of 0.97 ± 0.15s and the maximum delay time is observed in the middle mountain and decrease in the south and the north. Fast wave directions are generally parallel to the strike of the orogenic belt, indicating that more than one hundred kilometers of upper mantle is involved in collisional deformation. Change in fast wave direction for stations in the south and north ends of the array is probably resulted from subduction of the Tarim block and the Junggar block into the Tianshan range, respectively.

In addition, Luo[20] used the SC method (Silver and Chan, 1991) to study SKS wave splitting beneath China mainland and adjacent regions. Results show that the fast wave polarization directions beneath most stations share a common preferred orientation in a same tectonic block. The fast axes show good correlation with the past and present day tectonic movement. Wang[21] studied mantle and crust anisotropy beneath Shanghai region inferred from teleseismic waveform splitting of PpSmS, P660S and SKS. The split parameters of PpSms, P660S and SKS are calculated, the mantle and crust medium anisotropies beneath Shanghai seismic array region are analyzed briefly according to the difference among PpSmS, P660S and SKS split parameters.

The azimuthal variation of Pn velocity is induced by inherent anisotropy in the upper mantle crystal, it's the first observed anisotropic phenomenon. As Pn anisotropy may denote the history of mantle deformation, Pn anisotropy has become an important means of lithosphere structure detection. Recently, we has made progress in the upper mantle Pn anisotropy of the whole of

China mainland and some mainland subarea, and revealed the related characteristic between lithospheric mantle and surface geological structure. Wang[22] and Pei[23] studied Pn anisotropy in China mainland. The research shows the mean fast Pn velocity direction in the top mantle of western block regions is generally in NWW, while in eastern block regions it is about in NNW, roughly coinciding with dominant direction of tensional tectonic principal stress there in. Huang[24] studied Pn anisotropy in the top of upper mantle in Sichuan and Yunnan, Pn anisotropy shows a complex pattern of regional deformation. The Pn fast wave direction shows a prominent clockwise rotation pattern from east of the Tibetan block to the Sichuan-Yunnan diamond block to southwest Yunnan, which may be related to southeastward escape of the Tibetan Plateau material due to the collision of the Indian Plate to the Eurasia Plate. Wang[25] studied Pn anisotropy in North China, the fast velocity direction is nearly EW in the central Ordos block, while the fast wave directions around Ordos block and interior block are obviously different. Obvious velocity anisotropy is seen in the Datong Cenozoic volcanic region, with the fast wave direction in NNE. Notable velocity anisotropy is also seen around the Bay of Bohai Sea, and the fast wave directions seem to show a rotation pattern, possibly indicating a flow-like deformation in the uppermost mantle there.

3. Summary

The crust and upper mantle anisotropy research on China mainland is preliminary. In order to better promote the results of anisotropy, we not only should vigorously develop high-definition three-component broadband seismic array, but also combine multiple seismic methods. The use of shear-wave splitting, surface wave, Pn wave, Vertical reflection profile and the inversion method of splitting parameters will be further reveal the multilayer anisotropy structure of the crust and mantle, and more comprehensive understand crust and upper mantle anisotropic characteristic of China mainland and dynamic implications.

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Nuclear Explosion Seismology

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Abstract In the past four years Chinese seismologists conducted researches on CTBT monitoring and related seismological problems. Researches are mainly related to identification and discrimination of seismic source, evaluation of monitoring capability of seismological networks, database and automatic waveform processing system for monitoring purpose, and seismic array technology. This report summarizes the published works during the period 2003~2006, highlighting the new trends in the study of nuclear explosion seismology in China.

Persistently advocating the prohibition and elimination of nuclear weapons, China has been playing an active role in monitoring the *Comprehensive Test Ban Treaty* (CTBT). Previously, the participation of Chinese seismologists in the CTBT monitoring endeavors was mainly technical, for instance, the participation in the GSETT-II and GSETT-III technique experiments and the routine works of the International Monitoring System (IMS). Since recent years Chinese seismologists have also conducted application-oriented researches in nuclear explosion seismology. As a matter of fact, there have been several interesting papers published since the last four years, which are to be summarized in this report.

1 Identification, Discrimination and Characterization of Seismic Source

In nuclear explosion seismology, identification, discrimination, and characterization of seismic source is one of the fundamental problems under discussion. Wei Fusheng and Li Ming (2003) applied cepstrum to the characterization of seismic source. He Yongfeng et al. (2005a, b, c) conducted systematic studies on the properties of regional seismic waveforms generated by underground nuclear explosions in the perspective of Rg wave and Lg wave generation and the effect of spall, respectively. Fisher method was applied by Bian Yinju (2005) to the discrimination of earthquakes and explosions using the m_b/M_S criterion. Yang Xuanhui et al. (2005) proposed the application of wavelet analysis to the discrimination between earthquakes and explosions. Liu Daizhi et al. (2006) discussed the problems in the pattern recognition approach to discriminating explosions from earthquakes. Zhao Lianfeng et al. (2005) used 'relative static source strength' to estimate the yield of the May 11, 1998, Indian nuclear test. Li Xuezheng et al. (2003, 2004) analyzed the aftershocks of underground nuclear explosions in the perspective of magnitude, vibration duration, and frequency of occurrence. Analysis of mining seismicity, collapses, and quarry blasts and their differences from natural earthquakes is also one of the important parts in the characterization of seismic source (Liu Xiqiang et al., 2003; 2005; Wu Ziquan et al., 2004; Zhang Ping et al., 2005; Zheng Xiufen et al., 2006; Zhang Chunhe et al., 2006a; Jiang Fuxing et al., 2006).

2 Evaluation of Monitoring Capability

Evaluation of monitoring capability plays the essential role in the functioning of the International Monitoring System (IMS). Hao Chunyue et al. (2006) evaluated the monitoring and location capability of the China Digital Seismograph Network (CDSN) and the IMS/PS arrays. Wang Cuifang (2004) discussed the method for mapping the monitoring capability of a regional digital seismic network. Magnitude bias of local seismic networks (Jiang Jinjun and Ye Wenyan, 2003; Di Xiuling et al., 2004; Li Liandi et al., 2004; Meng Zhimin et al., 2005; Zhao Mingchun et al., 2005; Wang Qingmin, 2006; Zhang Shuzhen and Yu Guoping, 2006), comparison of earthquake parameters determined by different local/regional seismic networks (Guo Peilan, 2005), analysis of site background noise (Ren Xiao et al., 2004; Xu Ning, 2006), and assessment of monitoring capabilities of local/regional seismic networks (Xu Kangsheng et al., 2003; Pan Yuansheng et al., 2004; Hong Xing and Yang Gui, 2005; Zhang Yonggang et al., 2006; Li Yingbo et al., 2006), while mainly related to the routine works of seismological observation and interpretation, have direct impact on the study and practice of CTBT monitoring. Wang Ping et al. (2006) calibrated the location accuracy of regional digital seismic network using blasts as ground-truth events. Liu Ruifeng et al. (2005, 2006) systematically compared the magnitudes determined by the Chinese national seismograph network and those by the USGS/NEIC.

3 Database and Automatic Waveform Processing System

CTBT Monitoring system uses cutting-edge technology and is more and more characterized by its high-tech property. Development of the monitoring system requires understandings of the new technology and the efficient combination of technological upgrading and practical needs in the monitoring. Zheng Xuefeng et al. (2006) discussed the structure and critical techniques of the seismic information system in CTBT verification. Yan Bo and Song Jiangjie (2003, 2005) reported the design and implementation of a seismic monitoring database. Shan Dehua et al. (2006) developed an explosion waveform database for monitoring purpose. In the filed of automatic processing of seismic waveforms which plays an important role in the monitoring system, Wang Haijun et al. (2003) discussed the automatic detection of spikes in seismic waveforms; Zhang Chunhe et al. (2006b) developed an automatic alarm system for blast monitoring.

4 Seismic Array Technology

One of the important techniques in nuclear test ban monitoring is seismic array (Huang Xianliang and Zhu Yuanqing, 2005; Yan Feng et al., 2006). Since recent years there has been a significant advancement in China in array seismology. In cooperation with CTBTO, the Lanzhou and Hailar seismic arrays have been successfully installed. The preparation and installation process included several interesting seismological problems (e.g., Hao Chunyue et al., 2003; Xu Jiansheng et al., 2005, 2006). In China, another important array, not related to CTBT monitoring, is the newly built Shanghai Array. In the construction and operation of the Shanghai Seismic Array, there have been several seismological researches conducted (Liu Xu et al., 2003a, b; Zhao Zhenling, 2004; Yu Haiying et al., 2005; Yu Haiying and Zhu Yuanqing, 2006; Zhao Shuli et al., 2006), playing an important role in the functioning of this observation system.

5 Concluding Remarks

Since recent years, in parallel to the development of technology, Chinese seismologists have also begun to study the application-oriented problems in nuclear explosion seismology. Study of artificial seismic sources, especially explosive sources, not only plays an important role in CTBT monitoring, but also plays an increasingly critical part in the environment protection, urban planning and land use in the process of social modernization, which is one of the important motives driving the related researches in China. Remarkably, in the field of nuclear explosion seismology, Chinese seismologists have stared to communicate with colleagues by publishing their papers and participating in academic symposia, reflecting the development of science and technology and open policy of China.

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EARTHQUAKE PREDICTION: STUDIES AND EXPERIMENTS（2003-2006）

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In China the earthquake prediction is usually divided into four kinds: long-term (few years to tens years), intermediate-term (few months to few years), short-term (few weeks to few months) and imminent-term (few days to few weeks). The present report will give some research results on intermediate and short term earthquake prediction during the period from 2003 to 2006. The methods of earthquake prediction are based on mainly the precursory observation of seismicity, crust deformation, electromagnetism, underground water, and so on.

I. RESEARCHES ON INTERMEDIATE-TERM EARTHQUAKE PREDICTION

1. Researches of the characteristics of seismic pattern before and after clustering strong earthquake and its post-earthquake influence (Yang Liming etc., 2004)

The temporal structures and its controlling and influence factors of the great earthquakes have been studied in Chinese mainland. The researches include the influence of the wedge “four antenna” activities, the large-scale ordering activity pattern of the moderate-strong earthquake in Chinese mainland, the characteristic of the precursor field periodic transition, the periodic transition of the earth rotation, the b value character of different seismic stage, and so on.

The correlation between earthquake and block activity had been studied, and the preparatory process of seismic high active period. The strong earthquake clustering preparation model is put forward. The evolved process of the great earthquake distribution and its application in prediction are analyzed.

2. Researches of seismological intermediate-term prediction new method and its application

The researches of intermediate-term prediction are developed using the data on crustal structure, active fault and crustal stress state, such as focal mechanism solutions, CMT solutions, radiated energy and active fault slip-rate of Chinese mainland. The characteristics of apparent stresses are analyzed before and after several type earthquakes using digital seismic data (Chen Xuezhong, et al, 2005, Cheng Wanzheng, et al, 2006).

According to the regional characteristics of seismicity, the prediction test for the magnitude-time-predictable model is carried out (Chen Zuo et al, 2004), and the possible approach and method of the accelerating release model is proposed in middle-term prediction (Wang Lifeng, 2004).

The temporal characteristics of small and moderate earthquakes density is studied, and its classification is done. The relation of local crustal state and earthquake is analyzed. The foundation of earthquake prediction is discussed (Wang Jian, et al, 2003).

3. The intermediate-term prediction of potential strong earthquake risk segment in active tectonic zone

Associating the spatially and temporally inhomogeneity of seismic activities with the inhomogeneity of different-time-scale fault activities, we study the division of seismic periods and eposides, and their main active belt.

According to the vertical broken segments and horizontal stress distribution of the rocks, the concept of active tectonic earthquake structure model is proposed. Furthermore, we attempt to quantify the intermediate-term prediction basing on tectonic activities, by applying the stress-triggering model to study earthquake interaction (Hao Ping, 2004).

4. Researches of tectonic deformation changing characteristics in Chinese mainland and the strain accumulation state in the key area.

Using the data of regional GPS and leveling observation, we get the horizontal relative motion velocity fields and horizontal strain rate field images at different stage in Chinese mainland, North China, Southwest China, Northwest China， and also, vertical motion velocity of south-north seismic zone and north China, gradient field image of velocity is obtained (Jiang Zaisen et al, 2003, Yang Guohua, et al, 2004). Some new ideals are obtained by studying the tectonic background, dynamic features and the relation with strong earthquakes in Chinese mainland and several key areas (Jiang Zaisen, et al, 2005, Wang Shuangxu, et al, 2004).

The approach of seismogenic feature deformation field recognition and potential growing strong earthquake source searching with the aid of aseismic dislocation model inversion is proposed (Jiang Zaisen, et al, 2005).

5. Researches of the relation of gravity field dynamic changing and the strong earthquake in Chinese mainland and several key areas.

The study of gravity datum, gravity device parameter determination, robust estimination theory application and bi-cubic spline algorithm based on blocks for discrete data concreting is carried out (Zhu Yiqing, et al, 2005). The new methods such as the gravity dislocation inversion for active fault and the wavelet analysis for gravitational effect of density variation on bedding of different depths are accomplished (Shen Chongyang, et al, 2002).

The result shows that the front direction of gravity variation, the gravity vertical deflection, and the fault movement from dislocation inversion are the key determination basis of the fault movement on active tectonic zones (Li Hui, et al, 2004).

6. The correlation researches between the spatial-temporal evolution of fault deformation and strong earthquake activity.

The cross-fault data in the northeast boundary of Qinghai-Tibert plateau and Sichuan-Yunnan area are systemically processed using many methods. The results indicate that earthquake activities are related with the large-scale grouping synchronous abnormities of faults (Bo Wanju, et al, 2003, 2005).

The same result is obtained in northeast China (Guo Liangqian et al, 2004). The grouping consistent variation of ground tilt direction is helpful for intermediate-term prediction (Peng Wanju, et al, 2005).

7. The Seismic activity, precursor field features and the intermediate-term prediction in the regions with active earthquake

The methods of abnormity determination and the index for intermediate-term strong earthquake prediction are improved. These methods are usually applied in the regions with active earthquake, such as, Xinjiang, Yunnan and Sichuan etc.

The seismicity and precursor anomaly characteristics of clustering or single strong earthquakes at prophase or metaphase are discussed. The base of risk area determination is provided by the means of studying the seismicity in the responsive and sensitive area of strong earthquake and the comprehensive characteristics of fixed crust deformation observation (Qu Yanjun, 2005).

The process of the ground deformation variation is summarized before strong earthquake. Four types of abnormity, i.e. trending transition, deformation tranfer, concave and step-up, are extracted, and the relation with earthquake is studied. The results show that the changing of deformation velocity has some relativity with clustering strong earthquake activities.

Two new prediction models are built. One is on the basis of optimization for prediction and the other is polymorphsim-discrete-spatial-temproal possibility-gain integrative prediction model. The probability of earthquake occurrence within 1-3 years in Chinese mainland is put forward, using the extenics comprehensive prediction model (Wang Xiaoqing).

II. RESERCHES ON SHORT-TERM EARTHQUAKE PREDICTION METHOD

The short-term regular patterns of spatial and temporal precursory field and identified marks of the anomalies for different regions have been brought forward, and the prediction methods in each region depending on combination of single and multiple subjects and statistics and physics have been established. The aftershock sequences in China Mainland are re-collected and studied.

1. Researches on the short-term earthquake prediction methods in North China

(1) The prediction methods by seismicity

From the systematic study on the seismic patterns before 28 earthquakes with M≧5.0 in North China since 1970, the short-term anomalies have been obtained as the following different kinds of abnormal seismicity of M≧2.0 earthquakes:

(a) Seismic quiescence of M≧2.0 earthquakes: none or fewer earthquakes with M≧2.0 occurs in an ellipse-like region with the least long axis length of 300km and short axis length of 100km during 40 days or more. The least long axis length of seismic quiescence region could be 200km in Shanxi seismic zone. If the seismic quiescence region is very large (with that the least long axis length is 600km), the time duration of quiescence could be 30 days. If the seismic quiescence is broken by earthquakes occurred in it, the seismic quiescence anomaly could be taken as finished.

(b) Concentration of M≧2.0 earthquakes: more than 20 earthquakes with M≧2.0 occur successively during more than 40 days in a limited area with none or fewer earthquakes surrounding it. The concentration anomaly could be taken as finished when no more earthquakes occur in the area during at least 20 days later, or there are some earthquakes occurring surrounding the concentration area.

(c) Seismic belt of $M \geqq 2.0$ earthquakes: earthquakes with $M \geqq 2.0$ occur within a belt during at least 30 days and the total number of earthquakes is 12 or more, in the mean time, no other earthquakes occur surrounding the belt. The seismic belt anomaly could be taken as finished when no more earthquakes occur in the belt during at least 20 days later or there are some earthquakes occur surrounding the belt.

(d) Signal earthquake (i.e. imminent earthquake): if an earthquake with $M \geqq 3.6$ occur in the special area with anomalous seismic pattern such as seismic quiescence, seismic belt, seismic gap, etc., this earthquake could be taken as a signal earthquake (or called imminent earthquake) shortly before $M \geqq 5$ earthquake.

If the anomalous seismic patterns have been detected accompanying with seismic parameters such as b value, the turning point of the parameter curve implying that an earthquake with $M \geqq 5$ might occur in a short time (for several months).

(2) Prediction method by multidisciplinary measures

According to the comparing study on the relationship between the spatial and temporal variation of synthetical information by anomalies in different stations and the strong earthquakes with more than 30 year data, the index of short-term criterion for strong earthquake of each subject has been abstracted.

(a) The criterion index of short-term precursor

For underground water: the contour lines of the synthetical underground water anomaly information occur with high gradient, and the intensity of anomaly information increase or decline rapidly and the scale of anomalous region change rapidly, too.

For water radon: the intensity and the scale of the high value of synthetical water radon anomaly information increase or decline.

For electricity resistivity: the intensity and the scale of the synthetical resistivity anomaly information increase or decline, or anomalous region forms rapidly and changes frequently.

For fault short-level: an anomalous region of the synthetical fault short-level anomaly information forms rapidly, or the direction of the boundary line between the positive and negative anomaly regions coincides with that of the fault zone, and the patterns of the anomaly region change rapidly, or the intensity of anomaly strengthens.

(b) The criterion index for the location of potential region

For underground water: strong earthquake might occur in the region with high gradient, or in the region with the intensity of anomaly information increase or decline rapidly accompanied with the scale of anomalous region change rapidly.

For water radon: strong earthquake might occur in the region with the intensity and the scale of the high value of synthetical water radon anomaly information increase or decline.

For electricity resistivity: strong earthquake might occur in the high gradient belt between the positive and negative anomaly regions.

For fault short level: strong earthquakes might occur near the anomaly area forms rapidly, or in the region between the positive and negative anomaly regions coincides with that of the fault zone.

(c) The risk criterion index before M5 or M≧6.0

In the four subjects of underground water, water radon, ground resistivity and fault short-level, it could be taken of a proof to give a short-term earthquake forecast of M5 when one or two of them show the short-term marks, and it could be taken as a proof to give a short-term earthquake forecast of M6 when 3 or four of them show the short-term marks.

(3) Researches on the comprehensive method for short-term earthquake prediction

(a) Characteristics of the grouping anomalies during the active episode and quiescence episode of earthquake.

The parameter of $\overline{M}$ (the mean magnitude of the top five earthquakes during the 90 day time window) is found to be an ideal indicator to describe the short-term signal of seismicity from quiescence episode to active episode. When $\overline{M}$ curve reaches to its peak value which is greater than 4.7, and then decline to the valley value which is less than 3.6 during the next time window, it could be taken as a signal that the active episode of strong earthquake will come in short term. The change of $\overline{M}$ from greater than 4.7 to less than 3.6 imply the physical essence that the seismicity undergoes the process from strengthening to quiescence in the short time (for several months) before the active episode of strong earthquake comes.

The curve of the parameter *b* value (with time window of 90 days and moving step of 10 days) can also be used to describe the active episode and quiescence episode. In the early stage quiescence episode, the average *b* value increases with time, and in the later stage of quiescence episode, the average *b* value decline with time. Contrarily. The average *b* value declines in the early stage of active episode, and increases in the later stage of active episode.

A synthetic parameter called R_t was obtained from multiple seismic parameters which is independent from each other, such as *b* value, frequency, etc. When R_t is very close to the background base value, it implies that the seismicity is in stable state. When R_t deigns to depart far away from the background base value, it implies that the active episode of strong earthquake is coming. For example, when R_t is calculated by M⩾4.0 earthquakes during the period from 1970 to 2005 in north China, the results show that when $R_t \leq 0.8$, the seismicity of north China is in an instable state and strong earthquakes tend to occur in this state. On the contrary, when $R_t > 0.8$, the seismicity of north China is in a stable state and the possibility of strong earthquakes is lower.

Generally, many kinds of seismic anomalies occur in the active episode of strong earthquakes, such as medium-term anomalies of seismic gap, seismic belt, seismic frequency, $\overline{M}$, and short-term anomalies of seismic frequency, seismic swarm, signal earthquake, etc. Fewer seismic kinds of seismic anomalies occur in the quiescence episode. The main seismic anomaly in the quiescence episode is seismic frequency or foreshock.

For the anomalies obtained from multidisciplinary observation, the number of anomalies is more in the active episode than that in the quiescence episode. From the statistical results, the average number of medium-term anomalies is about 6.5 in active episode, and the average number of short-term anomalies is about 15.8. But, in the quiescence episode, the number of medium-term is very low, and the average number of short and imminent anomalies is about 5.5. For anomalies in quiescence episode, their characteristic is that the anomaly appears suddenly and the amplitude of anomaly is bigger.

In active episode, the anomalies distribute widely, and undergo the process that the anomalies appear in the beginning from the potential epicenter then to the surrounding region, and at last distribute in a wide region, while in the quiescence episode, most of the anomalies only appears near the potential epicenter.

(b) Study on the dynamic seismic patterns in North China

Eight of the seismic parameters are chosen to compose the synthetic possibility to describe the dynamic seismic pattern. They are *b* value, intensity factor of M_f value, concentration degree of *C* value, hazardous degree of *D* value, the Benioff strain release of $\Sigma\sqrt{E}$, seismic frequency of *N* value, the modulate ration of R_m value and LURR of *Y* value. These parameters are proved to be meaningful, independent from each other with higher confidence. Taking the region with the confidence of each parameter over 85% as the studied region for prediction, and summing up the possibility of each parameter, we can get the dynamic seismic pattern.

The results show that among the 13 earthquake cases during the period from 1988 to 2003, 9 of them accompany with the anomalous dynamic seismic pattern near the epicenter, say, before 69.2% of strong earthquakes in North China, anomalous seismic pattern appear near around the epicenter. From the temporal process of anomalous pattern evolution, the seismogeneous process could be divided into two stage: the medium to short term stage (a half year to one year) and the short-term stage (within a half year). Among the 13 earthquake cases, short-term anomalies occurred before 7 of them without medium-term anomalies, short-term anomalies occurred before two of them accompanied with medium-term anomalies. Neither medium-term nor short-term anomalies occurred before 4 of the 13 earthquake cases. From the relationship between the spatial distribution of the anomalous seismic patterns and the locations of the epicenters, 9 of the 13 earthquakes occurred in or near ($\Delta < 50\text{km}$) the regions with short-term anomalies.

However, 191 anomalies occurred during the period from 1988 to 2003, which will cause many false alarms. In order to improve the effect of prediction, we can firstly detect if it is in the active episode or quiescence episode by means of $\overline{M}$ parameter mentioned above, and then we just make earthquake forecast in the active episode and ignore the quiescence episode, the effect will be improved highly.

From 53 focal mechanisms of earthquakes with $M_s \geqslant 4.0$ during the period from 1974 to 1983 and $M_s \geqslant 3.5$ during the period from 1984 to 2005 obtained by P wave arrivals, amplitude ratio and synthetic solution of small earthquake, the direction of *P* axis of small earthquakes near the epicenter of the forth coming strong earthquake ($M_s \geqslant 5.0$) will rotate from 42° ～90° shortly before (range from 8 to 1 months) the strong earthquake. These earthquakes are called as “signal earthquakes”. Generally, this kind of anomaly will disappear several months to about one year after the strong earthquake.

(c) Study on the comprehensive characteristics of seismic anomalies

From the data from Jan. 1988 to June 2004, the results show that good relationship exists between the synthetic index and strong earthquakes in North China. Generally, high synthetic index anomaly appears near the epicenter from 9 to 19 months before the forth coming strong earthquake, and the scale and intensity of the synthetic index reaches to the maximum value from 1 to 4 months before the strong earthquake. After that, the anomaly region will scatter and weaken in 2 to 4 months later. Anyway, there is no apparent relationship between the magnitude of the forthcoming earthquake and the duration of the anomaly.

3. Researches on short-term prediction before strong shocks in Southwest China

(1) The short-term prediction method of seismicity

(a) In the medium-term stage, the exceptional activity and enhancement of regional small earthquakes are typical characteristics before strong shock, specially for above M6.5 in Sichuan-Yunnan area (approximately 75%). But in the short-term stage, the exceptional activity and enhancement of small earthquakes, the activity of remarkable earthquakes, and the activity foreshock are main characteristic in the source area (approximately 65%). There are not obvious superiority abnormal phenomenon of small earthquakes in the short-medium term stage, some are the continues and enhancement activity, some are the normal horizontal activity or quiescence. The exceptional activity and enhancement of regional earthquakes is also an active sign of the clustering strong shock (Li, et al, 2005).

(b) The remarkable earthquake is a very important significance for earthquake prediction. When an earthquake occurs, it is very difficult to determine the event whether is a foreshock, but the position and the active background in which the event occurs can determine whether it is the remarkable earthquake.

(2) The short-term prediction method of precursor

The time of short-term precursor is generally several months, and the main performances are the tendency transition, new precursor, increasing number of the abnormity and so on. The abnormity in imminent stage appears several days ago generally, and the main performances are many types of burst characteristics, like kicks, the acceleration, the daily variation and distortion and so on.

The earthquake intensity is predicted based on the duration time length and the distribution range of abnormity. Whether there is the medium-term abnormity and the number of medium-term abnormity are pivotal to predict the magnitude at Sichuan-Yunnan. The prediction study of Sichuan-Yunnan shows that the short-term abnormity of precursor appears generally three months or half year ago before medium-strong shocks, and the short-term abnormities of precursor on various measures are almost synchronous. Namely the size of magnitude is positive dependence with the distributed scope of the short-term precursor. The concentricity and the transference of precursor abnormity may provide a reference for predicting the place of earthquake. Before earthquakes with above M6.0 in Sichuan-Yunnan area, there is a phenomenon on the relative concentricity of the short-term precursor abnormities around the source, which is obviously demonstrated by the ratio between the number abnormities and the total number of station (Zhang L, et al, 2005).

The precursor abnormities have many general characteristics before the strong shock in Sichuan-Yunnan area. The symbol from the medium-term to short-term is that the number of precursor abnormity increased non-linearly. The index from the medium-short term to short-imminent term is that 40% precursor abnormities are over. The unceasing increase of new abnormities number, namely the enhancive fluctuation change of abnormities, also is the main index that strong shock breeding is in short-term stage.

The synthesis scanning results for groundwater level indicated that groundwater has ability to reflect the intermediate-high frequency information of the regional precursor before the strong shocks with different spatial distribution. The intermediate-high frequency information of the precursor around source region has the large-scale fluctuation change 1~ 3 months ago, which is relative centralism before the strong shock 1 month ago.

(3) The comprehensive researches of short-term prediction method

(a) The regional characteristics of seismicity and the comprehensive characteristics of short-term abnormity

Before the first strong shock with above M7 in each strong shock active period in 1960-2004 in Yunnan, the active time of M5 ~ 6 medium-strong shocks is about 5 years, then about 3 year quiescence of M6 earthquakes, and also quiescence time intervals of M5 earthquakes. Finally, there is the first strong earthquake with above M7 and the strong shock active period begins. Statistical analysis about the distribution of half-year greatest magnitude in Yunnan shows that there is a continuously 3-years quiescence time interval that the greatest magnitude is equal to or less than M5.5 before the first earthquake with above M7.

In the medium-term stage, the exceptional activity and the enhancement of regional medium-small earthquakes are typical characteristics before M6 earthquakes in Sichuan-Yunnan area, especially before M6.5 strong shock (approximately 75%). In the short-term stage, the main characteristics of abnormity are the exceptional activity and the enhancement of small earthquake, remarkable seismic activity, foreshock activity at and nearby the source area (approximately 64%). The phenomenon of exceptional activity and enhancement of regional small earthquake is an active sign of clustering strong shocks.

The synthetic studies of the characteristics of seismicity in the source area of 8 earthquakes with M7 and 3 events with M6 since 1970 in the Sichuan-Yunnan area (earthquake sequence region or earthquake sequence region +100km) show that an abnormal phenomenon of low b value in the short-term stage, which indicated the seismicity strengthen (the number increase of medium earthquakes).

The study of 19 cases of M6 earthquakes in Sichuan-Yunnan area using the RTL algorithm (Region-Time-Length algorithm), shows that RTL value can examine the exceptional short-term activity of earthquakes within 1 year, and "the rise" abnormality of enhancement seismicity are accounted for 84%. This further indicated that the exceptional activity and the enhancement are the main characteristic before M6 earthquakes in Sichuan-Yunnan area in the short-term stage (Liu, et al, 2006).

(b) The short-term comprehensive characteristic research of precursor abnormity

The dynamic change curve of monthly abnormity frequency is obtained by selecting 100 precursors measures with relative higher reliability. The result shows that there is a better relativity between the number increase of precursor abnormity and the strong shock, and the obvious increase process begins half of the year ago before M6 earthquakes.

Taking 0.5°×0.5° as an unit, the ratio of the abnormity number of station and the total number of station in an unit is taken as the parameter which describe the density distribution of precursor abnormity. The result indicated that the number of precursor abnormity is relatively fewer in the time interval of non-shock. The density distribution of precursor abnormity appears the enhancement before M6 earthquakes, and achieves the peak value condition 2 months ago, namely there are many higher density places and the broader distribution.

(c) Research on earthquake short-term comprehensive prediction plan

The Sichuan-Yunnan area is divided into 5 secondary blocks: Sichuan-Qinghai-Gansu, western Sichuan, central Yunnan, southwest Yunnan and southeast Sichuan. We studied the earthquake type in each block, the seismogenic structure, the general seismicity characteristic before strong shock and the general short-imminent characteristic of precursor abnormity. We discussed the short-term comprehensiv prediction plan of strong shock in each block of Sichuan –Yunnan area.

The analysis to seismicity precursor of regional small earthquakes before 24 strong shocks at 5 blocks since 1970, shows that the obvious enhancement characteristic is common in the medium-term stage before strong shock, among 24 earthquakes besides Ninglang M6.2 in 1998. In the short-term stage, there is obvious enhancement of swarms in the area before strong shock within secondary block and at the west boundary. The small earthquakes are exceptionally active in the short-term stage before strong shock when the seismicity is not obvious in the medium-term stage. The main characteristic before strong shock is that the activity enhancement of medium earthquake transfers the activity calmness of regional earthquakes, especially the calmness of small earthquakes.

Before the strong shock, the seismicity of regional small earthquakes roughly display three kind of situations: The first is that the frequency of regional seismicity appears to be fluctuant 1 year half ago before the strong shock, but the weaken of the frequency and the obvious enhancement of intensity are the general characteristic 2~3 months ago. The second is that the frequency of regional seismicity slightly reveals increase 1 year half ago, but have not obvious peak, and there are the increased frequency and the obvious enhancement of intensity in 3 months imminent-term stage. The third is that the frequency of regional seismicity obvious increase, the swarm activity is fierce 1 ~ 2 years ago before the strong shock, and the frequency of regional small earthquake obviously tend to be calm.

In five blocks, the foreshock sequence, the precursor swarm as well as the remarkable earthquake has general characteristic, but also has the obvious individuality. The strong shock possibly occurs after the precursor swarms in 1 ~ 2 years in Sichuan-Yunnan and the its neighboring area, and the strong earthquake generally occurs in the nearby regions of precursor swarm or the associated tectonic belt. There is often foreshock sequence before the strong shock in a complex interior structure region in Sichuan-Yunnan area. As a result of the Sichuan Yunnan's connection structure, there are some middle earthquakes before the strong shock in the associated tectonic belt of strong shock in medium-short term stage in Sichuan-Yunnan area, some of which are the isolated middle earthquakes. This kind of middle earthquake mainly distributed in the associated structure with the future strong shock, will have the obvious precursor prediction significance to the future strong shock prediction.

The structure of the most dense precursor abnormity is searched in abnormity distribution. In the prediction districts of Sichuan-Qinghai-Gansu, western Sichuan and southeast Sichuan, the area which has above 5 precursors abnormity in the 100km diameter scope is defined as the dense area. In the prediction districts of central Yunnan and southwest Yunnan, the area which has above 10 precursors abnormity in the 100km diameter scope is defined as the dense area. In the denser area of precursor monitoring network, the number of precursors abnormity should correspondingly increase. The number of the precursor abnormity belong to short-imminent prediction is two times than the general number of abnormity in this area, which may be taken as a criteria of the occurrence of above M6 strong shock. The 70% precursor abnormities distribute on the activity fault zone, which may be taken as a criteria of above M6 strong shock. From the day of the synchronous occurrence of short-imminent abrupt precursors, the future month can be taken as the earthquake occurrence time. The synchronous occurrence means there are above 3 successive abrupt abnormities within 3 days. If the frequency and the intensity in precursor swarms increase unceasingly until there are small swarms with above M4 or the remarkable earthquake, the time interval within 1 month can be taken as the earthquake occurrence time of the short-imminent prediction.

3. Researches on short-term prediction before strong shocks in Northwest China

(1) The Northern area in Qinghai-Xizang Plateau

Seismic Activity (Liu Y F, et al, 2005)

(a) In this area, there are five seismic windows, namely Gulang, Sunan, Zhouqu, Wuhai and Xinghai window. The 80% anomalous seismic windows occurred in 1 to 6 months before strong earthquakes and the strong earthquakes took place during the time of 1 to 3 months after the anomalous windows ended.

(b) The duration time of small earthquake swarms is relatively short, and it is generally 10 to 30 days. But in different time, the frequency of earthquake swarms is different greatly. The results show that the occurrence rate of strong earthquakes is high in 1 to 6 months after the swarms occurred.

(c) The various seismic gaps of about 40 were identified and most of them (87%) related with the following strong earthquakes, while a few (13%) of them had no relationship with the strong earthquakes. The forming and the shapes of seismic gaps are connected with the seismogenic structures, the regional tectonics and the upper earth crust structure. In addition, there are higher ratio in many seismogenic gaps where approaching earthquakes occurred in the verge or inside. The approaching earthquakes can be as a short-term prediction index and we can use it to predict that a strong earthquake would occur in 1 to 6 months after the seimogenic gap formed.

(d) 19 seismic belts have been identified since 1970 and they can be sorted two types. One is called belt with strong earthquake (it means strong earthquakes occurred following the seismic belt), the other is called belt without strong earthquake. Most of the belts (74%) belong to the former type and a few (26%) belong to the latter. The forming and the shapes of the seismic belts are connected with the seismogenic structures and the regional tectonics. The strikes of the belts are mainly in NW or NE direction, and the length of the belts is about 300 to 500km. Some of the belts with strong earthquakes usually disappeared or earthquakes occurred randomly before the expected strong earthquake occurred.

(e) There is usually an obviously intensifying anomaly of seismicity before 87% middle-strong earthquakes. It is noticed that the reducing and even disappearance of the areas with anomalous A(b) value may be a sign of transition from the medium term stage to the short term stage during the strong earthquake preparation.

The Characteristics of Precursor Activity

(a) The ratio of different types of precursors anomalies has important forecasting significance for earthquake magnitude. For earthquakes with M≥7.0, the ratio of geo-stress, geo-strain and geomagnetic anomalies is high (the ratio is larger than 60% in this region). The ratio of apparent resistivity is more than 45%. For earthquakes with M≤5.5, the ratio value of geo-stress, geo-strain and geomagnetic anomalies is rather low (≤33%) except that the average anomaly ratio clearly decrease.

(b) The is no intimate relationship between the anomaly ratio of underground water and the forecasting earthquake intensity, but the anomaly ratio of underground water is related with the types of focal mechanism. For example, the anomaly ratio of underground water and chemistry, especially Radon is high before the thrust earthquakes or the ones with thrust faulting predominantly. While it is low before the strike-slip type earthquakes or the ones with strike slip faulting predominantly (Liu Y W, et al, 2004).

Comprehensive Prediction Researches (Yang LM, et al, 2004)

(a) There are two types of intensifying anomaly of seismic activity in the Qilian seismic zone. One type is continually strengthening, which is that the earthquake frequency increased month by month. The continually strengthening time is usually about 3 to 5 months. Strong earthquakes usually occurred when the intensifying anomaly ended or occurred during the time of 1 to 3 months after the strengthening anomaly ended and the state of seismic activity varied from intensity to weakness. If we take the intensifying anomaly of 3 months as a short-term prediction index, we can predict that earthquakes with M⩾5.0 will take place in the future of 1 to 3 months. The other type of seismic strengthening is paroxysm, which is that the monthly earthquake frequency increased abruptly and the frequency is two times as usual. The curve of monthly earthquake frequency changes abruptly and notably. The strong earthquakes usually occurred in 1 to 2 months after the abrupt change.

(b) Based on the researches on the variety of the amount of precursory anomalies with time in north boundary area of Qinghai-Xizang Plateau, it is showed that there have been 5 anomalous processes since 1985. Moreover there is a intimate relationship between these anomalous processes and the earthquakes with M⩾5.0 occurred in the Qilian seismic zone, especially in the central and eastern section of the zone (The typical precursory anomalies are Wuwei and Linxia geoelectricity, Liujiaxia stress, Qingshui water flow, Menyuan tilt, Lixian water flow and so on. The prediction efficiency of these anomalies is good.). It is obvious that the characteristic of the grouping precursory anomaly activity is synchronous in short-term stage of strong earthquake preparation.

(c) Based on the analysis for mobile observational data of the cross-fault short level at about 50 points in north boundary area of Qinghai-Xizang Plateau, we can see that about the one-third of all the observational data (or more than) are abnormal in one year before strong earthquakes. The one fifth to one third of the spots data (or even more) shows several anomalous forms, which shows that the large regional stress field has been strengthening. These anomalous forms are respectively big turn in the course of the data curve, trend direction variation, clearly trend acceleration or acceleration-turning and the clearly abrupt synchronous or quasi-synchronous change based on long term trend change. The half of the 15 spots (or more than) whose observational data show the typical long term trend variation occurred clearly “trend acceleration or acceleration-turning”, “trend direction change” and “catastrophic jump opposite the trend change” in about half year before strong earthquakes. Among these anomalous spots, correspondingly more spots appeared anomalous change in 3 months before strong earthquakes. The strong earthquake usually occurred in the area where there are more anomalous spots and the appearance of the anomalous change is late. The numbers of the anomalous spots obviously increased in large tectonic region during 3 to 4 months or during half year before strong earthquakes, and there is a characteristic that the anomalous spots moved towards the source area and its vicinity, or concentrate and strengthen around the source area (the distance from epicenter is less than 150km). In several days to 1 month or 1 month to 3 months before strong earthquakes occurred, based on the background of that the anomaly activity turned to weaken in the whole tectonic region (which shows that the tectonic region is correspondingly in blocking state), there are still some anomalous spots in and around the source area and the area with anomalous spots farther reduces (concentrates) or keeps strengthening. Comparing with the anomalous change around the source area which show the anomalous shapes of “trend acceleration or acceleration-turning” and “trend direction change”(big turns often appear in this time), the curves of strain in the whole region begin to drop from the peak value or increase again after dropping.

(2) The Tianshan seismic Zone in Xinjiang

Seismic Activity

It is the short-term prediction index for Ms≥6.5 earthquakes in Xinjiang that the quiescence time of Ms≥5.0 earthquakes is equal to or larger than 6 months. The seismicity enhancement of moderate earthquakes can be served as a prediction index of mid-short term. Based on the spatio-temporal scanning of 33 seismic gaps, we find that 18 gaps have obvious indication earthquakes and warning shocks. The warning earthquake usually occurred in 3 months before strong earthquakes, which is a sign that the seismic activity transited from mid-short term stage to short-term stage in the process of earthquake preparation (Gao, et,al, 2003).

The short-term precursory anomaly characteristics of the observational data

The shape characteristics of short-term precursory anomaly of various types of underground water are bend type (bend up or bend down), step type, spew type, pulse type and so on. The predominant duration time of anomaly lasting time is about 3 months, which shows a short-term feature (Wang X R, et al, 2005).

The characteristic of short-term anomalous change in fixed deformation is that the observational curve with time is different from the normal annual trend change and it presents the shapes of bend up or bend down. The vector curve with time is continually knotting or turning, which means that the observational data is in the process of repeat of stopping change, instability or abrupt change. The probability of anomaly appearance can reach to 80%, which means that the anomaly numbers increased clearly in 3 months prior to strong earthquakes during the short-term stage of earthquake preparation.

Comprehensive study

The characteristic of seismic activity is the enhancement of M⩾4.0 earthquakes in 2 years before Ms⩾7.0 earthquakes in Xijiang and before Ms⩾6.0 earthquakes in the seismic zone of Tianshan seismic zone, which is a symbol that the regional stress field is enhanced at a certain level in intermediate-term stage during the strong earthquake preparation process. Besides, the seismic activity from the whole region to source areas represents a anomalous quiescence followed the enhancement in one year before Ms⩾7.0 earthquakes. While in one year before M⩾6.0 earthquakes, from tectonic zone to structure unit, the seismic activity is obviously anomalous quietness. The common characteristic of the seismic activity in regional and tectonic zone is anomalous strengthening—quiescence in intermediate term stage before different magnitude of earthquakes.

The characteristic of short-term precursor anomaly is the evolvement of grouping precursory anomalies. The grouping anomalies occurred in 7 months prior to strong earthquakes and the strong earthquakes usually occurred during the process of the precursory anomaly increase or occurred within 3 months after the grouping anomalies ended. Some clearly short-term precursory anomalies can be observed before most of earthquakes with M⩾5.0 occurred in North Tianshan seismic zone. There are some short-term precursory anomalies before most of earthquakes with M ⩾6.0 occurred around Keping block (Wang X R, et al, 2007).

The differences in short-term anomalies are great, which are as follows. Firstly, the seismic activity of M⩾3.0 earthquakes gradually weakened from the whole Xinjiang to tectonic zones and to source areas in 3 months before earthquakes with M⩾7.0. The seismicity of the source area is anomalous quiescence in short-term stage, which means that the source areas is being blocked before strong earthquakes. Next, There are seismic gaps formed before some strong earthquakes and warning earthquakes occurred in or around the gaps. The warning earthquakes usually occurred in 3 months prior to strong earthquakes. Then, the anomalous seismic patterns are not clear in short-term stage before earthquakes with M≥6.0. While obvious small earthquakes with M≥3.0 or some small earthquake swarms occurred around the source area in 3 months before M ≥5.0 earthquakes. In addition, in short-term stage before earthquakes with M≥6.0, the precursory anomalies occurred in far field are outstanding and the grouping anomalies are more notably than that of M≥5.0 earthquakes. Finally, the differences of short-term anomalies between M≥6.0 earthquakes and M≥5.0 earthquakes are clear.

In a word, the seismic activity in intermediate-term stage before moderate-strong earthquakes shows a common dynamic evolutional characteristic of strengthening—quiescence in Xinjiang. Moreover, the varied anomalies show a most complex process of anomalous change in short-term stage.

4. Researches on short-term prediction before strong shocks in Southeast China

(1) The short-term characteristics of Seismicity

(a) There is seismic quiet near the epicenter three months before middle-large earthquakes. For part cases, there are the prominent earthquakes near epicenter area of the strong shock or the farther area relating with tectonics, a few days to three months preceding the subsequent strong shock.

(b) There are 80% earthquake cases whose seismic parameters have not variation, except for quiet during short term before strong shocks in South China.

(2) The characteristics of the short-term precursory anomalies

From the anomalous shape, the dominant mid-term precursor is to break annual variation shape, and the short-term precursor is descending-ascending during a few months. The anomalies generally come back to the normal value in short- imminent term, and part cases are during the restoring process when the strong shock occurs.

5. Researches on short-term prediction methods before strong earthquake in China Mainland

(1) Researches on strong earthquake cases in China Mainland

According to the statistics and analysis results of anomalies for 67 strong earthquake cases in China Mainland from 1966 to 1999, the anomalies characteristics of seismic precursors are as following (Zheng Z B, et al, 2006):

(a) The logarithmic distribution of precursor anomalies

The duration of the seismic precursors shows exponential distribution. The duration of the seismic precursors also shows the similar characteristics in different region or different measures. The relation is expressed: $T_e = 6.48 - 1.02 L_n(N)$, where correlation coefficient R=0.99. T_e is duration time of the seismic precursor anomalies (unit: year), N is the accumulative number of anomalies whose durations are more than T_e.

The epicentral distance of anomaly is simply regarded as the distance from an earthquake to its anomaly. The relation between epicentral distance of anomalies within 300km and accumulative numbers is linear distribution, and is expressed: $L = 300 - 0.46N$, where L is the epicentral distance of anomaly (unit: km), N is the accumulative number of anomalies whose the epicentral distances are more than L km.

(b) The relationship between precursor anomalies and magnitude

The larger the magnitude is, the more the number of precursor anomalies is. The number of precursor anomalies of the earthquake with M7 is double one with M6, especially in southwest China. In the same way, the average epicentral distance of anomaly, the duration of precursor anomalies and the time length when the anomalies finish until the strong earthquake occurring increase with the growth of magnitude. The number of precursor anomalies in unit area obviously increases close to the epicenter.

(c) The precursor characteristics of spatial-temporal evolution

The anomalies of seimicity and precursory are mostly mid-term anomaly because the number of the anomalies is 28.7% and 37.4% of the total number within one month and two months. The precursory anomalies including water level, hydrochemistry, electromagnetic wave, gravity and ground deformation have often concentrating trend toward epicenter area of the strong earthquake, while geoelctricity anomalies are reverse. The 80.7% anomalies of the total finish preceding the subsequent strong earthquakes, and the other anomalies finish after the strong earthquakes. The ratio of precursory anomaly of the fixed stations is higher nearby the epicenter.

(d) The anomalous characteristics of different focal mechanisms of strong earthquakes

The anomalous number of the earthquakes with strike-slip fault is more than one of the earthquake with the inverse fault, and the number of earthquake with normal fault is middle. For the earthquake with strike-slip fault and with the normal faults, the anomalous duration time is positive correlation to magnitude, thus, their duration time increase with the growth of magnitude. But for the earthquake with inverse fault, its anomalies are reverse. The number in inverse fault are modulated by earth rotation. The anomalous duration time of earthquakes on the strike-slip faults are often within thirty days.

(e) The characteristics of different measures

In 35 items of seismicity anomalous, earthquake frequency, seismic gap, b value, seismic stripe, seismic window, precursory earthquakes (or swarms), seismicity pattern and strain release appear more frequently than the other items. In 58 items of precursory anomalous, hydrochemistry, hydrophysics, ground deformation, geoelctricity appear more frequently than the other items. Electromagnetic wave, geoelctricity, water level are more effective measures for short-imminent term precursor than others. The electromagnetism, earth resistivity and hydrochemistry are more effective measures for short-term precursor than others.

(f) The characteristics of precursory anomalies in different regions

The decreasing order of the average epicentral distance of anomalies is southwest China, Xinjiang, northwest China and north China. It is suggested that there is more dense observation network than the other regions. The average epicentral distance is longest in southeast China, because of there is more complex seimogenic structure and the distribution range of precursor is large. The increasing order of duration time is north China, northwest China, southwest China and Xinjiang. Weakly tectonic activity leads to longer precursory duration time in north China than other regions. The duration time in Xinjiang is the shortest among them, probably because of fewer samples.

(2) The short-term prediction scheme for earthquake with magnitude over 7 in China Mainland

(a) Prediction for the occurrence time of earthquake with magnitude over 7 in China Mainland

If there are no earthquake with magnitude 5 over 80 days, the probability of earthquakes with magnitude over 7 occurring in half a year is 50%. If there are no earthquakes with magnitude over 5 over 130 days, the probability is 70%. According to the frequency of earthquakes with magnitude over 5, the earthquakes with magnitude over 7 appear almost at the time when the frequency changes from low to high or the turning point from high to low.

(b) The two abnormal stages of the seismic patterns with magnitude over 5 and 4 in Mainland China

The two abnormal stages of the seismicity could be easily figured out for the seismic patterns of 85% earthquakes over M5 and of 88% earthquakes over M4, preceding the subsequent strong shocks over M6.5. The seismicity showed the two significant stages are coherent to the stages of the evolvement of the local tectonic stress field. The 1st stage is defined as the mid-term stage, at which the significant seismic belts and seismic gaps could be marked out due to the enhancement and concentration of tectonic stress. The 2nd stage is defined as the short-term stage, at which less earthquake took place due to the weakening of tectonic stress (Zhang X D, et al, 2004).

(c) The research on the movement of geomagnetic low point

The movement of geomagnetic low point which is correspondence well to the time of earthquake happening reflects the space abnormal characteristic for the minimum of magnetic field’s changes in one day. When there is a significant abnormal point throughout the whole China Mainland, the highest probability of earthquake happening with 90 percent appeared from the time of this point to 27±4 or 41±4 days later.

(d) The number of precursory abnormality in South-north seismic belt

The distribution of precursory abnormality number is correspondence well to the happening of strong earthquake. According to the distribution map of precursory abnormality quantity in south-north seismic belt, strong earthquakes might appear when the frequency of abnormality quantity is larger than a definite constant.

6. Statistic features of aftershock sequences and classification of sequence types

(1) Sequence data and the definition of sequence types (Jiang Haikun, et al, 2006b)

305 aftershock sequences with Ms≥5.0 form 1970 to 2004 in Chinese mainland have been collected. Considering the actual requirement of earlier judgment of sequence types, we take the magnitude difference $\Delta M=M_0-M_1$ as the classification index of sequence types, where M_0 is magnitude of the mainshock and M_1 is magnitude of the maximum aftershock during 12 months since the minshock. The criterions of classification are

(a) Isolated Earthquake Type (IET): $\Delta M \geq 2.5$ and frequency of aftershocks is not much more.

(b) Mainshock-Aftershock Type (MAT): $0.6 \leq \Delta M \leq 2.4$.

(c) Multiple Mainshock Type (MMT): $\Delta M < 0.6$.

Where, the “multiple mainshock type” includes double mainshock type and swarm type suggested by other authors.

The sequence types of 297 sequences could be identified clearly according to the given definition of sequence types. Among of them, 68 sequences are IET, 174 sequences are MAT and 52 sequences are MMT. Viewing from the simple results, the mainshock magnitude of about 80% IET are smaller than 6.0, and there is no IET with mainshock magnitude above 7.0. Comparing MAT with MMT, the ratio of sequence number in a certain magnitude range to the total number of sequence is about the same. With the increment of mainshock magnitude, the ratio of IET decreases and that of MAT and MMT increases.

(2) Some statistic features of aftershock sequences（Jiang Haikun, et al, 2006a）

For fault property of the mainshock, about 48% is strike-slip, 24% is the strike-slip with some dip-slip component, 17% is the dip-slip with some strike-slip component and about 11% is the reverse-slip. The magnitude of the maximum aftershock in 1 year after the mainshock is proportional to the magnitude of the mainshock, but the data is disperse relatively when the mainshock is small. The disperse degree of the data is high for isolated earthquake sequences, and the linear relativity between the magnitude of maximum aftershock and the mainshock is good for mainshock-aftershock and multiple mainshock sequences. The maximum aftershock for most sequences occurred during 200 days after the mainshock, a few sequences with the later large aftershock mainly belongs to the mainshock-aftershock type and generally there is no later large aftershock occurred for isolated or multiple mainshock sequences. About 68% maximum aftershocks occurred during 10 days after the mainshock, these two values are 77% for 30 days and 95% for 120 days respectively. The occurring time of the maximum aftershock and the duration of the aftershock activity with $M \geq 5.0$ or $M \geq 6.0$ are relational to the sequence types and the magnitude of the mainshock. The time interval from the mainshock to the maximum aftershock is shortest for multiple mainshock sequences and is longest for mainshock-aftershock sequences, the time interval of isolated earthquake sequences is shorter than than that of mainshock-aftershock sequences and longer than that of multiple mainshock sequences. If only considering with the mainshock-aftershock sequences, the time interval from the mainshock to the maximum aftershock is shorter when the mainshock is big and it is longer when the mainshock is small.

(3) Aftershock distribution size for moderate or large earthquakes in Chinese mainland （Jiang Haikun, et al, 2007a）

For different sequence types and for different rupture modes of the mainshock, the relationship of the aftershock distribution size R with the magnitude of the mainshock M_0 has been studied statistically. Qualitatively, log$R$ is positively correlative to the M_0, but the data distribution is dispersed. Viewing from different sequence types, the correlation between R and M_0 is very weak for IET sequence, R distributed in range of 5 to 60 km. For MAT, log$R$ is positively correlative to M_0. For MMT, the correlation between log$R$ and M_0 is not very obvious when $M_0 \leq 6.2$ and R distributed in range of 5 to 70 km, and it shows an linear correlation when $M_0 \geq 6.3$. The statistical results also show that the occupational ratios of different sequence types for strike slip and oblique slip are almost the same. But for dip slip (mostly are thrust mechanisms), the ratio of MAT is higher than that of IET and MMT. Comparing with previous results, it indicates that, when M_0 is large enough, R is mainly determined by M_0 and almost there is no relationship with the rupture mode of the mainshock.

(4) Spatial distribution features of sequence types of moderate- and large earthquake（Jiang Haikun, et al, 2006b）

Statistically, the spatial distribution of sequence types reveals the regional characteristics. In southwestern China, generally it takes MAT as the major in Chuandian rhombic block and in Xianshuihe-Anninhe-Xiaojiang seismic belts controlled by Chuandian rhombic block, as well as in Jianshajiang-Honghe seismic belts. There are also some MAT occurred in Simao, Puer and surrounding area in southwest of Yunnan. MMT mainly distribute in Xiaguan, Yaoan and surrounding area in westen Yunnan, as well as in Longlin and Lanchang areas in Tenchong-Bashan block in west of Nujiang-Lanchangjiang faults. Some MMT also occurred in Ludian area in easten Yunnan, Yuanyuan area in boundary of Yunnan and Shichuan, Batang area in westen Shichuan, Mabian area in easten Shichuan, as well as in Songpan-Longmenshan faults in northeasten Shichuan. There are several IET distribute in Shichuan and Yunnan. Among of them, very few IET occurred in Ganzi, Xiaojin and Baiyu in northwesten Shichuan, and there is no one occurred in Yunnan region. In Xiangjiang region, it takes MAT as the major in west segment of south Tianshan mountain and in Wuqia area. In this area, some MMT also occurred in Wushi, Shufu, Jiashi and surrounding areas, intersection of Keping block with the Puchang fault zones. IET mainly distribute in middle Tianshan mountain, but there are very few MMT also occurred in Wusu and Shihezi in this area. In northwestern China, it takes MAT as the major along the Qilian seismic belt, and very few MMT also occurred in this area. In southern and northern Ninxia region, it takes IET and MAT as the major respectively. In Qinghai region, most of sequences are MAT and then are IET and MMT, but the regional features of the spatial distribution of sequence types aren't very clear. In north China, it takes MAT as the major in Yinshan-Yanshan-Bohai seismic belt in north edge of North China. In intersection of north segment of Shanxi seismic belt with the Yinshan-Yanshan-Bohai seismic belt, there are several moderate- or large MMT with M_0 from 5 to 6 occurred. In Hebei plain seismic belt, it also takes MAT as the major, but there are a few MMT with magnitude above 7 occurred in its middle segment. In south part of North China, near by the latitude line of N35°, it takes IET as the major. In this region, large historical earthquakes with magnitude above 7.0 ever occurred.

Spatial distribution of sequence types is relevant to the movement patterns of regional tectonic structures. MAT almost could be produced in all tectonic movement patterns. Especially, ruptures of locked unit or asperity inside of the existing fault, as well as the fracture of neonatal separating segments, usually produce the MAT. MMT is generally relevant to the conjugate structures or intersection of many tectonic settings. Further expanding process of simple fault often produce IET. For example, in neonatal Longling-Lanchang tectonic belt in southwest region of Yunnan, the frequency and intense of seismic activity is very high and the reoccurring time period is very short. Despite there are many MAT occurred, it is the most outstanding feature that there are a lot of MMT (double mainshock type or swarm type) distribute in this area. It has been suggested that the Longling-Lanchang tectonic belt is composed by a serial of sub- and neonatal structures, which spread as the echelon or conjugate faults (Guo Sunfa et al., 2002). Therefore, probably the activity of conjugate structures is a major reason leading frequent occurrence of MMT in this area.

Spatial distribution of sequence types is relative to regional environment of deep medium. MAT mainly distribute in high velocity area in upper crust, or in the transition belt of high and low velocity areas. And MMT mostly occurred in the low velocity area in upper crust. Though the focus depth of large earthquakes in Shichuan and Yunnan region is about from 10 to 20 km in upper crust, but actually, the deep medium features are very difference. In Xianshuihe-Anninhe-Xiaojiang seismic belt and Jianshajiang-Honghe seismic belt, large earthquakes mainly occurred in high velocity area or in the transition belt of high and low velocity areas in upper crust, and low velocity layer is found universally in this area in middle and low crust (Liu Jianhua et al., 1989; Chen Peishan et al., 1990). Lanchang-Genma area in western Yunnan, another high seismic active area, large earthquakes mostly occurred in low velocity area in upper crust (Su Youjin et al., 1999). By contrasting observed results mentioned above, it can be seen that probably MAT mainly distribute in high velocity area or in the transition belt of high and low velocity areas in upper curst, and most of MMT potentially occurred in the low velocity area in upper crust.

For spatial distribution of sequences in Xianjiang region, the mainshock magnitude of total IET and MMT is smaller than 6.5 and all sequences with $M_0 \geq 6.5$ are MAT. Statistic results from Xianjiang and northwestern China show that MMT mostly distribute near by the epicenter areas of historical earthquakes, but several IET since 1970 in North China mainly occurred in the epicenter areas of historical earthquakes. This difference probably concerns the difference of intense level of tectonic activity.

(5) Statistic study on the criterion index for classification of aftershock sequences (Jiang Haikun, et al, 2006c)

9 parameters, such as *h* value, *b* value, energy entropy and so on, of these sequences have been calculated in different periods after the mainshock. Generally, most selected parameters express the capability for classification of aftershock sequences to a certain extent. Among of them, the numerical range of some parameters (such as energy entropy, time entropy, difference of the magnitude and so on) is concerned with the magnitude of mainshock and the classification rule is different when the mainshock distributes in different magnitude range. Some parameters (such as normalized frequency, *h* value and so on) change with the time and there are different classification rule in different period after the mainshock. The time range, in which the parameter is available for classification of aftershock sequences, is different for different parameters, and some parameters seldom have the ability for classification of aftershock sequences, such as *b* value, normalized energy, average magnitude, and so on. For parameters which have a certain capability for classification of aftershock sequences, the suitable condition for daily use and the real judgment index which concerning with the lapse time from the mainshock and magnitude of mainshock have been given. Roughly and averagely, several parameters, such as energy entropy, magnitude difference between mainshock and the largest aftershock and so on, have a high identifiable rate for classification of aftershock sequences.

(6) Synthetical judgment of types of aftershock sequences in Chinese Mainland (Jiang Haikun, et al, 2006b)

Based on calculation results of 11parameters of 294aftershock sequences with mainshock magnitude greater than or equal to 5.0 occurred in Chinese mainland, Fisher discriminant function in different period since the mainshock, taking different sequence parameters as the independent variable, have been established, which could be used for synthetical judgment of sequence types. Besides routine sequence parameters, the rake of the mainshock has also been introduced into the Fisher discriminant functions to make them containing messages of fracture mode of the mainshock. Statistical results show that the accurate ratio of discriminant on types of aftershock sequences increases with the increment of time period since the mainshock and there is something different for different sequence types. The accurate ratio is greater than 0.93 for isolated earthquake type, is from 0.73 to 0.95 for mainshock-aftershock type and is from 0.57 to 0.86 for multiple mainshock type. All of them are highly greater than stochastic corresponding ratio, 0.33, and therefore its forecasting score should be positive.

(7) Sequence decay and generation of aftershocks by parameters of ETAS model

The average features of three major parameters (b, p and α) of ETAS model during earlier stage of the sequence (15 days since the mainshock) have been studied statistically. The problems of aftershock decay and aftershock triggering have been discussed.

b-value increases with the mainshock magnitude but the difference of b-value is not obvious for different tectonic region and for different mainshock fracture mode.

p-value and α-value show some regional features for some extent. Average p-value in southwest and northwest region of China are a little larger than that in Xinjiang and in North China, this means that the decay of aftershock activity is a little slower in southwest region and in northwest region than that of in Xianjiang and in North China. Average α-value is small in northwest region, but is large in North China. It indicates that the earthquake in North China has a high ability to generate high-order aftershocks and this ability is weak in northwest region of China, despite the aftershock activity decay is slow for the former but quick for the latter. This also means that the framework of aftershock sequence is complex in North China and is simplex in northwest region of China.

It is not evidence for the relation between p-value with the fracture mode of the mainshock. In another word, the mainshock fracture mode is not the key factor controlling the aftershock decay rate. α-value is relational to the mainshock fracture mode for some extent. Averagely, α-value is small for strike-slip, middle for oblique slip and large for dip slip. This means that the strike slip has the highest ability to generate aftershocks, and it is weakest for dip slip.

p-value and α-value decrease with the increment of the mainshock magnitude. This shows that the larger the mainshock, the slower the sequence decay and the higher the ability to generate offspring.

There some differences for p-value and α–value with different sequence types. P-value is smallest for mainshock-aftershock type (MAT) and largest for isolated earthquake type (IET), this means that decay rate of aftershock activity is slow for MAT, is quick for IET and is in the middle for multiple mainshock type (MMT). α-value of IET and MAT are about the same, both two is larger than that of MMT. This indicates that MMT has a higher ability to generate high-order aftershocks than that of IET and MAT.

Take the G-R relationship and ETAS model as the restricting conditions of magnitude distribution and frequency evolvement of the aftershock sequence respectively, consulting the Reasenberg's method (Reasenberg et al., 1989), occurring probability of aftershocks, with different magnitude and in different time since the mainshock, has been delineated.

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