Active tectonic blocks and strong earthquakes in the continent of China

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Received September 28, 2002

Abstract The primary pattern of the late Cenozoic to the present tectonic deformation of China is characterized by relative movements and interactions of tectonic blocks. Active tectonic blocks are geological units that have been separated from each other by active tectonic zones. Boundaries between blocks are the highest gradient of differential movement. Most of tectonic activity occurs on boundaries of the blocks. Earthquakes are results of abrupt releases of accumulated strain energy that reaches the threshold of strength of the earth's crust. Boundaries of tectonic blocks are the locations of most discontinuous deformation and highest gradient of stress accumulation, thus are the most likely places for strain energy accumulation and releases, and in turn, devastating earthquakes. Almost all earthquakes of magnitude greater than 8 and 80%—90% of earthquakes of magnitude over 7 occur along boundaries of active tectonic blocks. This fact indicates that differential movements and interactions of active tectonic blocks are the primary mechanism for the occurrences of devastating earthquakes.

Keywords: active tectonic block, interactions of blocks, differential movement, strong earthquake activity.

DOI: 10.1360/03dz0002

China is prone to earthquakes. Statistics of global earthquakes indicate that about 33% of global continental earthquakes occurred in continental China which only takes up 7% of global area[1]. Earthquakes that occurred in China since 1950 cause a loss of 285000 lives that account for 54% of the total caused by all major natural disasters[2]. The most threatening earthquakes are those destructive events immediately underneath major cities. The 1976 Tangshan 7.8 earthquake is a tragic example, which claimed approximately 240000 lives and more than US $2 billion in economic loss[3]. Thus, seismic hazards pose a major threat to the social and economic development of China.

China is tectonically located in the southeastern part of the Eurasian plate bounded by the Indian, the Philippine Sea and the Pacific plates. Interactions of these plates result in varied style of tectonic structures and control the distribution of major earthquakes in China[4−6]. The most remarkable feature is that the crust has been cut by large Quaternary active faults to form active tectonic blocks of different grades[1,6−11]. These tectonic blocks continue to be active from the late Quaternary to the present. Almost all earthquakes of magnitude greater than 8 and 80%—90% of earthquakes of magnitude over 7 occur near boundaries of active tectonic blocks[1]. Thus, motions and interactions of the blocks make the evolutionary history of late Quaternary tectonic deformation and dictate the occurrence of major earthquakes in continental China.

1 Definition and delineation of the active tectonic blocks

Late Quaternary active faults are distributed over a vast region of China with a full spectrum of styles and structural orientations. The primary pattern of tectonic deformation is characterized by relative movements and interactions of tectonic blocks[1,6−11]. Active tectonic blocks are in fact geological units that have been separated from each other by active fault zones. Most of tectonic activity occurs on boundaries of the blocks[1]. The boundaries of tectonic blocks may follow those of old geological units, but may also be newly formed during the latest phase of tectonic deformation in the late Cenozoic. Active tectonic block has geometric grades. High-grade blocks may consist of several blocks of low grade. Relative motions between blocks of different grades show concordant fashion in the frame of continental scale tectonics. Tectonic activity in the interior of blocks shows two distinctive patterns. One is relatively stable with little or no tectonic activities. The other shows some tectonic activities, but nothing is comparable with that along the boundaries in both magnitudes and frequencies. In addition to the driving force exerted from plate boundaries, dynamic processes in the depth (mantle and low crust) also influence the behavior and movements of blocks. The bottoms of the blocks may be controlled by decollement or detachment zones at different levels. As the deep processes are different for different blocks, the style of tectonic and seismic activity also depicts different patterns.

In contrast to the fault-block theory put forward by Zhang[12] and sub-plate and block theory by Ma[7] and Ding[8], the active tectonic block theory described in this paper lays emphasis on the following two characteristics. In the temporal scale, it studies structures with late Quaternary tectonic activity, and pays special attention to recent activity that is closely linked to present-day seismicity. In the tectonic status, it emphasizes block movements and tectonic deformations related to future strong earthquakes.

According to definition and characteristics of active tectonic blocks, we use late Quaternary tectonic activity as a principle to delineate the blocks. There are two main reasons for this. First, the tectonics that has significant impact on geomorphologic framework and environmental evolution was initiated in the late Cenozoic. Boundaries of active tectonic blocks, controlling occurrence of major earthquakes, have been strongly active from the late Quaternary to present[8,13,14]. Second, the purpose of tectonic block delineation is to study mechanism of strong earthquake generation in terms of block interactions. Only late Quaternary and present tectonic activity is intimately linked to future earthquakes.

In light of the above principle, we delineate the Chinese continent into two grades of active tectonic blocks. The first grade is active tectonic block region (block region for short), and the second grade is active tectonic block (block for short). The Chinese continent (and its surrounding areas) can be divided into 6 block regions: the Tibetan Plateau, the Yunnan-Burma, the Xiyu, the South China, the North China, and the Northeastern Asia. We also delineate active tectonic blocks as follows: the Lhasa, Qiangtang, Bayan Har, Qaidam, Qilian, Chuandian, Dianxi, Diannan, Tarim, Tianshan, Junggar, Sayan, Altay, Alxa, Xing'an-East Mongolia, Northeastern China, Ordos, Yanshan, North China Plain, Eastern Shandong-Yellow Sea, Southeast China, South China Sea block etc. (fig. 1). Because boundaries of block regions and blocks consist of active tectonic zones of different width and geometry, we use the actual width of active tectonic zones to delineate geometry of the boundaries (fig. 1).

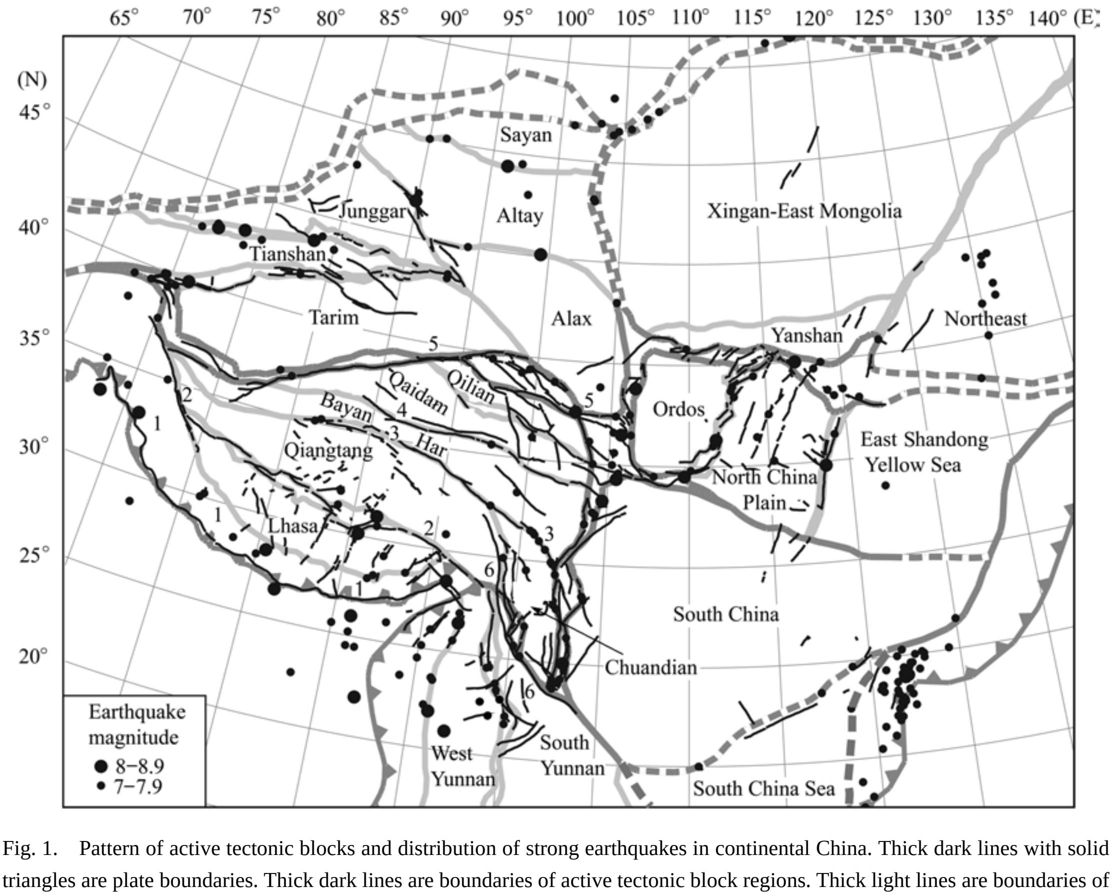

Fig. 1. Pattern of active tectonic blocks and distribution of strong earthquakes in continental China. Thick dark lines with solid triangles are plate boundaries. Thick dark lines are boundaries of active tectonic block regions. Thick light lines are boundaries of active tectonic blocks. Thin black lines are late Quaternary active faults. 1, The Himalayan main thrust fault zone; 2, the Karakorum-Jiali fault zone; 3, the Mani-Xianshuihe fault zone; 4, the Kunlun-Maqin fault zone; 5, the Altun-Haiyuan fault zone; 6, the Jinshajiang-Red River fault zone.

2 Characteristics and kinematics of active tectonic blocks

Motions of tectonic blocks and associated deformation are the main cause of continental earthquakes[1,11]. Kinematic behavior of each active tectonic block provides important background information in assessing future earthquakes. We study kinematic pattern of blocks on the basis of active faults and Global Positioning System (GPS) observations[15—17]. The GPS velocity used in this paper is relative to stable Eurasia that consists of Western Europe and Siberia (fig. 2) [15].

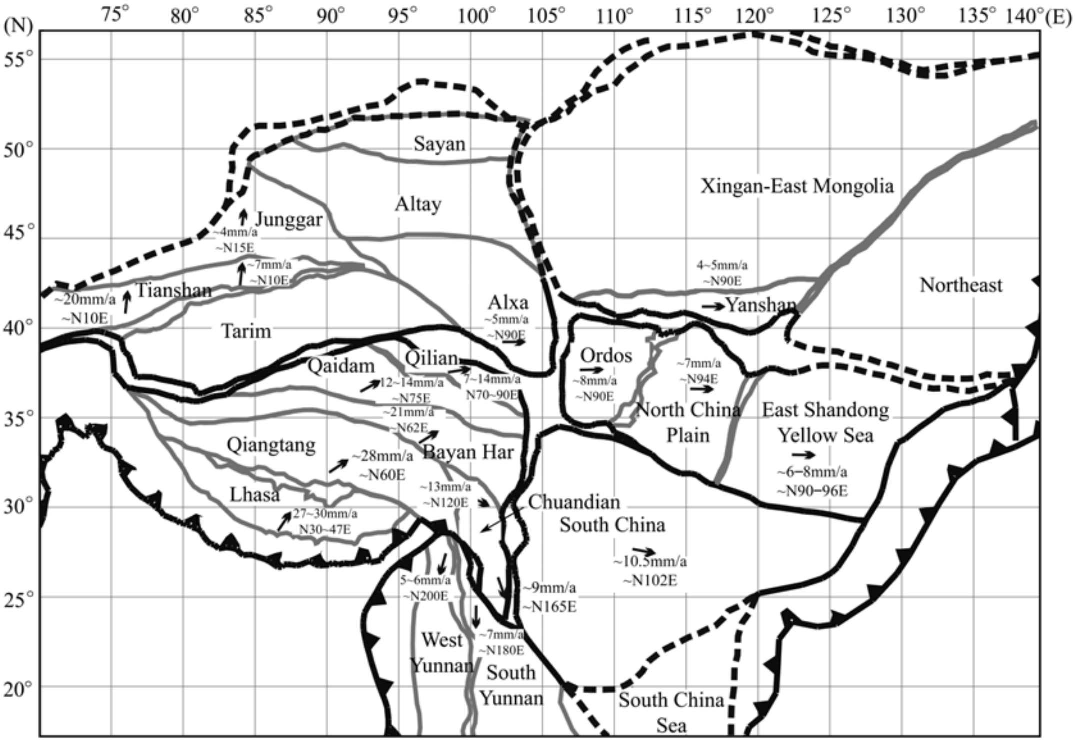

Fig. 2. GPS velocity of active tectonic blocks of China continent.

2.1 The Tibetan Plateau active tectonic block region

In geological history before Cenozoic collision of India with Eurasia, the Tibetan Plateau was built up by crustal accretion through welding of 6 plates successively from north to south as indicated by the 5 suture zones within the plateau[18,19]. The collision and afterward penetration of India into Eurasia since about 50 Ma ago reactivated and modified some of these sutures to form a huge active fault on the scale of several hundred kilometers. From south to north these faults are: The Himalayan Main Thrust fault zone, the Karakorum-Jiali fault zone, the Mani-Xianshuihe fault zone, the Kunlun-Maqin fault zone, the Altun-Haiyuan fault zone, and the Jinshajiang-Red River fault zone. These 6 major fault zones cut the Tibetan Plateau into 6 active tectonic blocks of (The Lhasa, Qiangtang, Bayan Har, Qaidam, Qilian, and Chuandian) different shapes each with different kinematic behavior (figs. 1 and 2).

Late Quaternary tectonic deformation in the Lhasa block is characterized by a series of north-trending normal faults, grabens, and right-lateral strike slip faults, which represent combination of eastward extension and right-lateral shear[20,21]. GPS measurements indicate that the Lhasa block moves to NE30°— 47°, at a rate between 27 and 30 mm/a (fig. 2). There are only five GPS stations in the Qiangtang block, and all of these five stations show relative motion of NE 60° at a rate of 28±5 mm/a. The movement of Bayan Har block is in the direction of NE62° at a rate of about 21 mm/a. Stations in the Qaidam block show similar direction of movement to the Bayan Har block, but the rates decrease to 12—14 mm/a (fig. 2). Northward to the Qilian block, most stations move in NE70°—100° direction, and the rates decrease to 7—14 mm/a. The Chuandian block is located in southwestern corner of the Tibetan Plateau, and is one of the most seismically active areas in China. Similar to results of active faulting studies, GPS measurements indicate a combination of a south-southeastward motion and a clockwise rotation of the block[22—24]. In its northern part, the movement is in the direction of NE120°, and changes to NE165° in the southern part of the block (fig. 2).

The southern boundary of Tibetan Plateau block region is the Himalayan main thrust zone. Active tectonic studies across it obtain about 18 mm/a shortening rate, whereas GPS measurement gives 13—15 mm/a[15—17]. This rate is similar to the rate predicted by improved global plate tectonics model (REVEL)[25]. The northern boundary is the Altun-Haiyuan fault zone. Recent GPS measurements show 7—9 mm/a left-lateral slip rate along the Altun fault[15,26,27], which agrees with geological slip rate of 3—5 mm/a given by Chinese geologists[29] and significantly differs from 30 mm/a slip rate raised by Peltzer et al.[28]. In the Haiyuan fault region, GPS meas- urements give 4.0±1.0 mm/a shortening rate and 7.5±1.5 mm/a left-lateral strike-slip rate[15—17] which also agree with geological rates[32,33]. Crustal shortening across the eastern boundary is not prominent, and left-lateral strike slip is the major on-going tectonic process. For example, the Xiaojiang fault, southern part of the eastern boundary has a left-lateral strike slip rate of 10—15 mm/a[36].

2.2 The Xiyu active tectonic block region

The Xiyu block region consists of the Tarim, Tianshan, Junggar, Alxa, Altay, and the Sayan blocks (fig. 1), among which the Tianshan block is the most highly tectonically and seismically active. Other blocks either have less seismicity or lack available data. In this paper we only concentrate our discussion on the Tianshan block.

The Tianshan block is a rejuvenated intracontinental mountain belt[37—40]. It is flanked from south by the stable Tarim block and from north by the also stable Junggar block. Widespread active faulting and folding, uplifting of mountain range, and high seismicity within the belt attest to continued crust shortening throughout the Tianshan[40]. West of Kashi in western part of Tianshan, GPS stations in Tarim basin show about 20 mm/a component of northward movement. Further northward across Tianshan into Kazakhstan, the northward velocity decays to 0—2 mm/a[41]. The total shortening of Tianshan at this longitude is thus about 18 mm/a. East of Kashi in Kuqa area, the shortening across the Tianshan reduces to about 13 mm/a. Further east to Urumqi area, the shortening is only 2 mm/a. At the eastern end of Tianshan, the northward velocity reduces to 0 and no shortening takes place. This kind of eastward decrease in shortening rates may result from a combination of northward pushing of the Pamir to western Tianshan and clockwise rotation of the Tarim block[27,37,38].

2.3 The North China active tectonic block region

The North China block region consists of three blocks: the Ordos, the North China Plain, and the Eastern Shandong-Yellow Sea block (fig. 1). Except compressions in its southwestern corner by Tibetan Plateau, all other boundaries of the Ordos block are characterized by normal faults and extensional grabens. Its northeastern and eastern boundaries are the Yinchuan-Jarantai normal fault zone and the Shanxi graben system respectively. The Hetao graben and the Weihe graben systems form its northern and southern boundaries with prominent normal faulting component. GPS measurements indicate the Ordos block itself as a relative rigid block with very little internal deformation. Stations within the Ordos block show the block moves eastward at a rate of about 8 ± 1 mm/a (fig. 2). Its boundaries however show a complex kinematic pattern where the northern boundary moves eastward, the eastern and southern boundaries move south-southeastward, and western boundary moves east-northeastward[27].

Western boundary of the North China Plain block is the Shanxi graben system, and the eastern boundary is the Tanlu fault. The northern boundary appears to be the widely distributed, discontinuous, and very complicated Zhangjiakou-Bohai fault zone. The southern boundary is not well defined, and we regard the range-front fault of the Dabie Mountains as the southern boundary (fig. 1). The North China Plain block was subjected to intensive extension during early period of the Cenozoic. A series of normal faults, grabens and horsts were formed, and structural pattern was similar to the present-day Basin and Range province in the western United States. The extension probably stopped or significantly slowed down since the Pliocene time. Right-lateral strike-slip faults started to form on the existing NNE-trending normal faults. The block itself may comprise several blocks of lower grade, such as the Taihang block, and the Hebei block. GPS measurement indicates the entire North China Plain block moves eastward at a rate of about 7 mm/a (fig. 2). The northern boundary depicts a prominent left-lateral motion, along which 2—4 mm/a left-lateral strike-slip rate can be obtained across the Zhangjiakou-Bohai fault zone[15, 27].

The Eastern Shandong-Yellow Sea block also moves toward east-southeast. GPS measurement shows that the average rate of movement is a little faster than that in the North China Plain block. This suggests minor extension between the two adjacent blocks.

2.4 The South China active block region

The Southeast China and the South China Sea blocks make up the South China block region (fig. 1). Most part of the Southeast China block has been tectonically and seismically stable. Except a few late Quaternary active faults and large earthquakes along the southeastern coast, there are no large-scale late Quaternary active faults in most part of the South China block. The seismic activity is also lower in comparison with the North China block. There are 22 GPS stations distributed over the South China block. The observations show no prominent velocity gradient that may represent different movement along a possible fault. Thus, the South China block behaves as a relatively rigid block to move in the direction of NE102° at a rate of about 10.5 mm/a (fig. 2).

Most part of the South China Sea block is occupied by oceanic water. Both the tectonic and the seismic activity in this block appear to be low.

2.5 The Northeast Asia active tectonic block region

The Northeast Asia block region is also tectonically stable. No late Quaternary active fault has been reported in the region. Deep earthquakes (depth between 300—600 km) and volcanoes that occurred near China and Korea border represent tectonic activities in the region. 11 GPS stations show relative velocity of less than 3—4 mm/a with various directions. Because the stations are only surveyed twice, we believe the uncertainty is large. It appears that the relative motion between the stable part of Eurasia (western Europe and Siberia) and the Northeast Asia block region is insignificant, and the relative motion within the block region is also negligible.

2.6 The Yunnan-Burma active tectonic block region

The Yunnan-Burma active block region, located south and east of the Himalayan syntax, includes western Yunnan Province, northern Burma, northern Laos, and northern Vietnam. This is an earthquake-prone region. The western boundary of the region is the Burma Range subduction zone where Indian Ocean plate subducts beneath Indo-China. The subduction forms fold and thrust belts along the Burma range as well as right-lateral strike slip fault, the Sagaing fault. Most strong earthquakes are products of this subduction and associated processes. The eastern boundary of the block region is the Jinshajiang River-Red River fault. Northern part of the fault controls the occurrences of some strong earthquakes. Southern part of the fault shows obvious tectonic activity without historical large earthquakes. The southern boundary of the block region is the Andaman Arc and Sumatra subduction zone.

The block region consists of the West Yunnan and the South Yunnan blocks. The Lancang River-Nu River fault zone, separating the two blocks, shows very strong seismic activity. The fault zone comprises a series of NS-trending faults and NE-trending faults to form a discontinuous and complex earthquake zone. No continuous fault strand along the zone can be found on the surface. This kind of fault zone has been referred to as the newly formed fault zone or earthquake zone[43,44].

3 Relationships between active tectonic blocks and strong earthquakes

The fact that almost all earthquakes of magnitude greater than 8 and 80%—90% of earthquakes with magnitude over 7 occur along or near boundaries of different tectonic blocks[1] indicates causal relationship between interaction of different blocks and occurrences of strong earthquakes. Earthquakes are results of abrupt releases of strain energy accumulated by long-term crustal deformation. Major faults, the most discontinuous features in the earth's crust, are the most likely places for strain energy accumulation and releases. Active faults along boundaries of tectonic blocks are of large scales in both length and depth, and therefore are favorite places for strong earthquakes (figs. 1 and 2). These may explain why most strong earthquakes occur along or near boundaries of the blocks.

A good example is the 8.1 magnitude earthquake of Kunlun Mountains on November 21, 2001. This earthquake occurred along the boundaries between the Bayan Har and Qaidam tectonic blocks. It is the largest earthquake in China in the past 50 years. The earthquake formed more than 300 km long surface rupture zone with the maximum displacement of 6 m[45]. There have been GPS measurements across the earthquake rupture. Fig. 3 shows the motion of the stations in the Bayan Har and Qiangtang blocks with respect to the Qaidam block. The Qaidam block behaves as a rigid block because stations within it depict very little or no relative motions. The velocity gradient occurs across the Kunlun fault. The gradient indicates 10—12 mm/a left-lateral strike-slip rate, which agrees very well with geological rate[31].

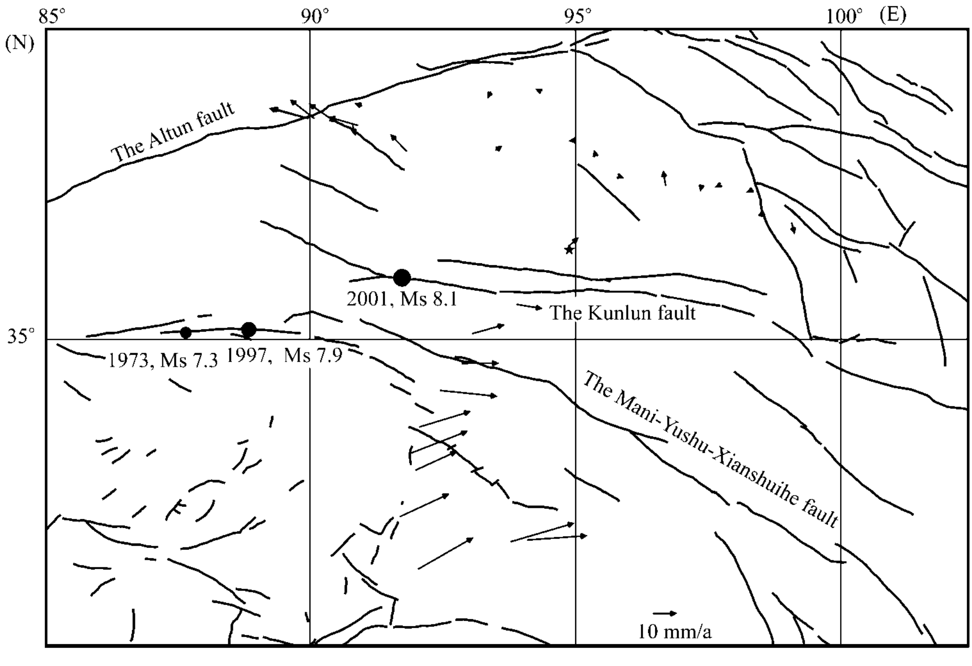

Fig. 3. Velocity of GPS stations in the central Tibetan Plateau relative to the Qaidam block.

Earthquakes in the Tibetan Plateau mostly occur along block boundaries. The southern boundary zone of the block region is the Himalayan main thrust system that controls 5 historical earthquakes with magnitude over 8 including the Ms = 8.5 earthquake of Zayu, 1950. The intersections between the NS-trending normal faults and NW-trending strike-slip faults are often the places for strong earthquakes. The Dumxung earthquake of magnitude 8 in 1954 occurred in this kind of tectonic setting. Boundaries on the Qiangtang and Bayan Har blocks are characterized by left-lateral strike slip faults. Earthquakes along these boundaries are also strike slip earthquakes, such as the magnitude 7.9 Mani earthquake of 1997 and the magnitude 9.1 Kunlun earthquake in 2001. Oblique thrusts of the Qilian block onto the Alxa block is partitioned into thrust faulting perpendicular to and left lateral strike-slip along the Qilian Mountains that control occurrences of the 7 earthquakes of magnitude over 7 along the northern margin of the Tibetan Plateau.

The Chuandian block is located in the southeastern corner of the Tibetan Plateau. There have been 23 earthquakes with magnitude over 7 in and around the block[24]. The western boundary of the block is the Red River fault. Northern part of the fault has large extension component that results in pull-apart basins. Three earthquakes with magnitude 7 occurred along northern part of the fault. No historical earthquake of magnitude 7 occurs along the southern part of the fault. Earthquakes however appear to shift to another fault just north of it, the Chuxiong-Jianshui fault[24]. The northeastern boundary of the block is the Xianshuihe-Xiaojiang fault. 17 earthquakes with magnitude over 7 occur along this boundary.

Boundaries on both southern and northern Tianshan are foreland fold and thrust belts. Earthquakes associated with them are also thrust or reverse type earthquakes. Most of the large earthquakes occur along the fold and thrust belts, such as the magnitude 7.7 Manas earthquake in 1906 and the magnitude 8 Artux earthquake in 1910. Earthquakes in the Tianshan block are often "folding earthquakes"[46], of which the surface deformation is characterized by broad anticline uplift without large-scale surface rupture.

There is no historical earthquake of magnitude 6 in the interior of Ordos block. There are, however, 19 historical earthquakes of magnitude over 7 around the block[42]. Among these earthquakes, the 1303 Hongdong earthquake of magnitude 8 took place along the eastern boundary of the block, the 1556 Huaxian magnitude 8 earthquake occurred on the Huashan range-front fault along the southern boundary, and the 1739 Pinglou magnitude 8 earthquake and the 1920 Haiyuan magnitude 8.5 earthquake occurred along the western boundary of the block.

The western boundary of the North China Plain block is the Shanxi normal fault and graben system along which there have been 7 historical earthquakes of magnitude over 7. The Tanlu fault along its eastern boundary generated the 1668 Tancheng earthquake. The intersections between the NWW-trending Zhangjiakou-Bohai fault zone and the NNE-trending faults are often the focus of major earthquakes in the northern boundary. For example, the 1976 destructive Tangshan earthquake occurred in the intersection area between the Zhangjiakou-Bohai fault and the NNE-trending Cangzhou fault (fig. 1). Some earthquakes of magnitude 7 also occur along the boundaries of sub-blocks in the interior of the North China Plain block, such as the 1937 Cixian earthquake in Shandong Province and the 1966 Xingtai earthquake in Hebei Province.

Taiwan Province is located in the intersection between the Philippine Sea plate and the Eurasian plate. It is part of the earthquake and volcanic belt surrounding the Pacific Ocean, and is one of the most seismically active areas in the world. The earthquakes in Taiwan are plate margin or margin related events that are characterized by high frequency of occurrences and intense magnitude. The Chichi earthquake of 1999 was associated with an 80 km long surface rupture and 8 m vertical coseismic displacement.

Except major earthquakes that occurred along the boundaries of blocks and block regions, other regions are often tectonically stable and seismically quiet without historical earthquakes of magnitude 7 and over. Deep earthquakes (depth between 300 and 600 km) occur beneath the Northeast China block, but their associated hazards are often negligible due to the great depths.

4 Conclusion

(1) Late Cenozoic deformation of China is characterized by movement and interaction of active tectonic blocks. Boundaries between blocks are the highest gradient of differentia movement. The areas of several blocks that intersect and interact are the areas of high earthquake activity, especially the areas of several block regions interact each other.

(2) Earthquakes are results of abrupt releases of accumulated strain energy that reaches the threshold of strength of the earth’s crust. Boundaries of tectonic blocks are the locations of most discontinuous deformation and highest gradient of stress accumulation, thus are the most likely places for strain energy accumulation and releases, and, devastating earthquakes.

(3) Almost all earthquakes of magnitude greater than 8 and 80%—90% of earthquakes with magnitude over 7 occurred along or near boundaries of different tectonic blocks. This fact indicates that differential movements and interactions of active tectonic blocks are the primary reasons for the occurrences of devastating earthquakes.

Acknowledgements This work was supported by the National Key Basic Research Program G1998040701. We are grateful for many useful discussions with and comments from Ding Guoyu, Ma Zongjin, Chen Rong, Mei Shirong, Zhang Xiankang, Chen Xiaofei, Li Yanxin, Ren Jinwei, Wu Zhongliang, and Wu Jianchun among others during the preparation of this paper.

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