Active tectonics and intracontinental earthquakes in China:
The kinematics and geodynamics

Mian Liu
Youqing Yang

Department of Geological Sciences, University of Missouri, Columbia, Missouri 65211, USA

Zhengkang Shen

State Key Laboratory of Earthquake Dynamics, Institute of Geology, China Earthquake Administration, Beijing 100029, China

Shimin Wang

Department of Geological Sciences, University of Missouri, Columbia, Missouri 65211, USA

Min Wang

Institute of Earthquake Science, China Earthquake Administration, Beijing 100036, China

Yongge Wan

School of Disaster Prevention Techniques, Yanjiao, Beijing 101601, China

ABSTRACT

China is a country of intense intracontinental seismicity. Most earthquakes in western China occur within the diffuse Indo-Eurasian plate-boundary zone, which extends thousands of kilometers into Asia. Earthquakes in eastern China mainly occur within the North China block, which is part of the Archean Sino-Korean craton that has been thermally rejuvenated since late Mesozoic. Here, we summarize neotectonic and geodetic results of crustal kinematics and explore their implications for geodynamics and seismicity using numerical modeling. Quaternary fault movements and global positioning system (GPS) measurements indicate a strong influence of the Indo-Asian collision on crustal motion in continental China. Using a spherical three-dimensional (3-D) finite-element model, we show that the effects of the collisional plate-boundary force are largely limited to western China, whereas gravitational spreading of the Tibetan Plateau has a broad impact on crustal deformation in much of Asia. The intense seismicity in the North China block, and the lack of seismicity in the South China block, may be explained primarily by the tectonic boundary conditions that produce high deviatoric stresses within the North China block but allow the South China block to move coherently as a rigid block. Within the North China block, seismicity is concentrated in the circum-Ordos rifts, reflecting the control of lithospheric heterogeneity. Finally, we calculated the change of Coulomb stresses associated with 49 major (M ≥ 6.5) earthquakes in the North China block since 1303. The results show that ~80% of these events occurred in regions of increasing Coulomb stresses caused by previous events.

Keywords: earthquakes, China, GPS, geodynamics, modeling.

INTRODUCTION

In King Jie’s 10th year of the Xia Dynasty (1767 B.C.), an earthquake caused interruption of the Yi and Lo Rivers. In the capital of Zhengxuen, buildings cracked and collapsed.

—State Records: Zhou Dynasty

This is one of the earliest written records of earthquakes in China. The Chinese catalog of historic earthquakes shows more than 1000 M ≥ 6 events since A.D. 23 (Ming et al., 1995). At least thirteen of these events were catastrophic (M ≥ 8). The 1556 Huaxian earthquake reportedly killed 830,000 people, making it the deadliest earthquake in human history (Ming et al., 1995). Modern earthquakes in China are intense and widespread. The best-known event is perhaps the 1976 Tangshan earthquake (M = 7.8), which killed ~250,000 people and injured millions (Chen et al., 1988).

The intense seismicity in China cannot be readily explained by plate tectonics theory, which predicts that earthquakes are concentrated within narrowly defined plate-boundary zones. As shown in Figure 1, most earthquakes in China occur within the interior of the Eurasian plate. In western China (approximately west of 105°E), seismicity is closely associated with the roughly E-W–trending fault systems resulting from the Indo-Asian collision. East of ~105°E, the influence of Indo-Asian collision is less clear. Major active fault zones there trend NE and NEE due to subduction of the Pacific plate under the Eurasian plate (Deng et al., 2002; Zhang et al., 2003). Active crustal motion on these faults, however, may be influenced by the Indo-Asian collision (Tapponnier and Molnar, 1977; Zhang et al., 2003). Most earthquakes in eastern China occur within the North China block, a geological province including the Ordos Plateau and surrounding rifts, the North China Plain, and the coastal regions. These events are commonly regarded as intraplate earthquakes because the North China block is in the interior of the Eurasian plate, within the Archean Sino-Korean craton, and thousands of kilometers away from plate boundaries. Because the North China block is one of the most densely populated areas in China, with vital economic and cultural centers, understanding earthquake hazards there is a pressing societal need.

Neotectonic studies in China, especially in the North China block, have been intensive in the past decades. Extensive global positioning systems (GPS) measurements in China have greatly

![Figure 1. Seismicity in China and neighboring regions. Blue dots are the epicenters of historical earthquakes before 1900 A.D., and red dots are those from 1900 to 1990. The green fault-plane solutions are from the Harvard catalog (1976–2004) without scaling. Solid lines are active faults.](image-url)
refined our knowledge of crustal kinematics. In this paper, we first summarize and analyze the GPS and neotectonic data in China to outline the crustal kinematics. We then explore the driving mechanisms and their interplay with lithospheric structures in controlling seismicity in China.

TECTONICS AND CRUSTAL KINEMATICS

Neotectonics

Neotectonic studies have shown a strong influence of plate-boundary processes on the diffuse crustal deformation in China and surrounding regions (Tapponnier and Molnar, 1977, 1979; Wesnousky et al., 1984; Ye et al., 1985; Burchfiel et al., 1991; Avouac and Tapponnier, 1993; Xu et al., 1993; Allen et al., 1998; Zhang et al., 1998, 2003). Figure 2 shows a simplified map of the major tectonic units and their Quaternary crustal motions based on fault slips and other neotectonic data (Ma, 1989; Deng et al., 2002). West of ~105°E, Quaternary tectonics is clearly controlled by the Indo-Asian collision, which has caused roughly N-S crustal contraction over a broad region extending from the Himalayan front all the way to the Altai Mountains. Deformations are largely localized within the roughly E-W-oriented fault zones that separate the region into a hierarchy of tectonic units (Geological Institute, 1974). Within each unit, deformation is relatively coherent. The first-order tectonic units include the Himalayan-Tibetan Plateau, the Tarim block, and the Tianshan mountain belt.

The Himalayan-Tibetan Plateau is bounded on the southern side by the Indo-Eurasian plate-boundary fault zone, where Holocene slip rates are as high as 15–18 mm/yr (Lavé and Avouac, 2000) and seismicity is intense. The northern side of the plateau is marked by the sinistral Altyn Tagh–Qilian–Haiyuan fault system. Estimates of Holocene slip rates on these faults vary significantly among previous studies: ~4–30 mm/yr on the Altyn Tagh fault and ~3–19 mm/yr on the Haiyuan fault (Peltzer et al., 1989; Peltzer and Saucier, 1996; Deng et al., 2002; Lasserre et al., 2002). The Tarim Basin is a rigid block with little internal deformation or seismicity (Avouac et al., 1993; Lu et al., 1994; Allen et al., 1999; Molnar and Ghose, 2000; Kao et al., 2001; Yang and Liu, 2002). The Tianshan mountain belt has been rejuvenated by the Indo-Asian collision since the Tertiary.

Figure 2. Simplified map of major geological units in continental China and their relative motion (mm/yr) with respect to stable Siberia, based on Quaternary fault-slip rates and other neotectonic data (after Ma, 1989; Deng et al., 2002). Thin lines are active faults. WG—Weihe graben; SG—Shanxi graben; YR—Yinchuan rift; HR—Hetao rift; BB—Bohai Basin.
Across the Tianshan mountain belt, active crustal shortening is 15–7 mm/yr estimated from balanced crustal sections. The amount of shortening decreases from west to east along the mountain belt (Deng et al., 2002). The Tianshan mountain belt is bounded by thrust and strike-slip faults with intense seismicity, manifesting the far-field impact of the Indo-Asian collision.

East of ~105°E, Cenozoic fault systems are predominantly oriented NNE and NWW, reflecting the influence from both the Indo-Eurasian collision and subduction of the Pacific and the Philippine Sea plates (Deng et al., 2002; Zhang et al., 2003). The rates of Quaternary crustal deformation are much lower than in western China. Major deformation and seismicity occur within the North China block. The western part of the North China block includes the stable Ordos Plateau and the surrounding rift systems: the Yinchuan rift basins to the west, the Hetao rift zone to the north, the Shanxi graben to the east, and the Weihe graben to the south. These rift zones initiated perhaps as early as the Miocene but developed mainly during Pliocene time (Zhang et al., 1998). Neotectonic evidence shows 2–6 mm/yr lateral motions on these fault zones (Deng et al., 2002) and about ~1.2 mm/yr extension across the Shanxi graben (Zhang et al., 1998). Historic records show three M = 8 and more than 30 M ≥ 6 earthquakes in these rift zones. East of the Ordos system, there is the North China Plain, which is a region of Mesozoic-Cenozoic rift basins and uplift structures crosscut by a system of NNE- and NW-orientated fault zones, on which many large modern earthquakes have occurred, including the 1976 Tangshan earthquake. The North China Plain is separated from the Bohai Basin and other coastal regions (collectively called the Jiaoliao block for the northern part and the Sulu block for the southern part) by the Tanlu fault zone, a major structure in east Asia and the locus of numerous large earthquakes, including the 1668 M = 8.5 Tancheng event.

North of the North China block, there is the relatively stable Siberian shield, where the major Quaternary crustal deformation is extension across the Baikalf rift zone. Within China, this region is called the Dongbei or Mongolian-Alashan block; here, the Quaternary crustal deformation and seismicity are weak. The South China Block is south of the North China block and is separated from it by the Qingling-Dabie fault zone and from the Tibetan Plateau by the Longmanshan–Xianshuhe–Red River fault system. Within the South China block, Quaternary deformation is minor, and seismicity is quiescent relative to the North China block.

GPS Measurements

Extensive GPS measurements in the past two decades have provided many details of crustal motion in China and surrounding regions. These studies include: Bilham et al. (1997) and Paul et al. (2001) for the central Himalayas, Abdurakhmatov et al. (1996) and Reigber et al. (1999) for the central and western Tianshan, King et al. (1997) and Chen et al. (2000) for the east borderland of the Tibetan Plateau, Shen et al. (2000) for North China, Calais et al. (1998) for the Lake Baikal area, Bendick et al. (2000) and Shen et al. (2001) for the central Altyrn Tagh fault, Shen et al. (2001) and Reigber et al. (2001) for the Tarim Basin and Qaidam Basin, Wang et al. (2001) and Zhang et al. (2004) for the interior of Tibetan Plateau, Banerjee and Bürgmann (2002) for western Himalayas and the Karakoram fault, Michel et al. (2001) for the Sandaland block, Vigny et al. (2003) for the Sagaing fault, Calais et al. (2003) for Mongolia, and Chen et al. (2004) for southern Tibet. A consistent regional GPS velocity field over continental China has emerged from the Crustal Motion Observation Network of China (CMONOC), established in 1998 by the State Seismological Bureau of China (now the Chinese Earthquake Administration). The CMONOC is composed of 25 continuous stations and ~1000 survey mode stations. The survey mode stations were observed in 1999, 2001, and 2004, with 3–5 24 h sessions per site and at least a couple of dozens of stations surveyed simultaneously. Station velocities obtained on the 1999 and 2001 data are shown in Figure 3. Additional GPS data sets from Bilham et al. (1997) and Paul et al. (2001) across the central Himalaya, and from Wang et al. (2001) along a north-south profile across eastern Tibet, were used in Figure 3 to fill in regions where the CMONOC network has no coverage.

The composite data set provides a detailed picture of crustal deformation for most parts of continental China. The general pattern of crustal motion and deformation is remarkably consistent with that derived from neotectonic studies (Fig. 2), with some noticeable differences. Present convergence between the India and Eurasia plates is ~36 mm/yr at the west Himalaya syntaxis and 40 mm/yr at the east Himalaya syntaxis, respectively (Paul et al., 2001); these rates are significantly lower than the ~50 mm/yr relative motion predicted by the NUVEL-1 model (DeMets et al., 1990, 1994), which was based on marine magnetic data for the past 3 m.y. Nearly half of the convergence is absorbed across the Himalayas (Bilham et al., 1997; Wang et al., 2001), and the rest is partitioned between rather uniform shortening across the Tibetan Plateau (Wang et al., 2001) and Tianshan (Abdrakhmatov et al., 1996). The Tarim Basin rotates clockwise as a rigid block relative to Siberia at a rate of ~9 nanoradian/yr (Shen et al., 2001).

Along the major strike-slip fault zones within and around the Tibetan Plateau, the GPS measured slip rates are considerably lower than those derived from neotectonic studies, although some of the neotectonic estimates are disputed (Deng et al., 2002). For the Altyrn Tagh fault, the GPS data indicate ~9 mm/yr on the central segment (Bendick et al., 2000; Shen et al., 2001) and ~7 mm/yr on the western (Karokash) segment (Shen et al., 2001), in comparison with 20–30 mm/yr from geological estimates (Tapponnier et al., 2001; Peltzer et al., 1989). Northeast of the plateau, ~7 mm/yr transpressional slip was determined across the Haiyuan fault (Shen et al., 2001), much slower than the 19 mm/yr slip determined geologically (Lasserre et al., 2002). Southwest of the plateau, GPS and InSAR (Interferometric Synthetic Aperture Radar) studies measured ~5 mm/yr and ~1 mm/yr left-slip across the Karakoram
fault, respectively (Banerjee and Bürgmann, 2002), compared to ~11 mm/yr slip estimated from geomorphic studies (Chevalier et al., 2005). Such discrepancies may result from errors in the derived geological rates. Estimates by Chinese workers on some of these faults are much lower, closer to the GPS values (Zhang et al., 2003). On the other hand, some of the discrepancy may reflect the time scale–dependent crustal rheology and deformation (Liu et al., 2000; He et al., 2003).

Consistent with neotectonic data, GPS data indicate weak crustal deformation in east Asia. Extensive GPS measurements have been recorded for the North China block because of the intense seismicity and dense population there. By analyzing GPS data collected from a network during 1992–1996, Shen et al. (2000) found that regional deformation in North China is dominated by left-lateral slip (~2 mm/yr) across the E-SE–trending Zhangjiakou-Penglai seismic zone and extension (~4 mm/yr) across the N-NE–trending Shanxi rift. However, extension across the Shanxi graben is not clear in the more complete data sets (He et al., 2003). GPS sites within the South China block are sparse because of the weak neotectonic activity and low seismicity. In general, the GPS data show low velocity gradients within the South China block, attesting to its stability. In the Lake Baikal region, GPS measurements since 1994 reveal ~4 mm/yr crustal extension across the Baikal rift in the NW-SE direction, normal to the elongated direction of the lake (Calais et al., 1998, 2003). In northeast China, GPS measurements are sparse, and the crustal motion seems insignificant.

Figure 4 shows the calculated horizontal strain rates based on an interpolated GPS velocity field (Shen et al., 2003). The highest strain rates, besides those along the Himalayas, are along the Xianshuihe fault, consistent with the high (~10 mm/yr) slip rates from GPS data (Wang et al., 2003a). Other regions of high strain rates include the Tibetan Plateau and the Tianshan-Altai mountain belts. East of 105°E, high
rates are found around the Ordos block and in the North China Plain. The strain rates in South China are not well constrained because of the scarcity of GPS sites.

GEODYNAMICS

The GPS and neotectonic studies of continental China provide useful kinematic constraints for understanding the geodynamics of crustal deformation and seismicity. In this section, we present a suite of geodynamic models of different spatial scales, constrained by the GPS and neotectonic data, to explore (1) the major driving forces and critical boundary conditions for active crustal deformation in China and neighboring regions, (2) the cause of the contrasting seismicity between the North China and South China blocks, (3) intraplate seismicity in the circum-Ordos rift zones, and (4) Coulomb stress evolution and the triggering effects associated with major earthquakes in North China.

Driving Forces for Diffuse Asian Continental Deformation

As shown in Figure 2, China and the surrounding Asian continent are under the influence of tectonic processes from two plate boundaries: the indentation of the Indian plate into the Eurasian plate, and subduction of the Pacific and the Philippine Sea plates along the eastern margins of the Eurasian plate. Some workers have suggested a dominant role of the Indo-Asian collision in Cenozoic continental deformation in Asia (Molnar and Tapponnier, 1975; Tapponnier and Molnar, 1979; Tapponnier et al., 1982), but the temporal-spatial extent of the collisional effects is controversial. Others have argued that subduction along the eastern margins of the Asian continent has played a critical role in early Tertiary rifting and volcanism in eastern China (Northrup et al., 1995; Ren et al., 2002; Zhang et al., 2003). Numerous studies have attempted to reproduce the present crustal motions in various viscous thin-shell models.
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(Kong and Bird, 1996; Flesch et al., 2001). However, the relative roles of major driving forces and their temporal-spatial impacts through the Cenozoic remain uncertain.

To explore the roles of driving forces, tectonic boundary conditions, and lithospheric structure in active tectonics in China and surrounding regions, we have developed a preliminary three dimensional (3-D) finite-element model (Fig. 5). Main driving forces in the model include (1) the plate-boundary force from the Indo-Asian collision, (2) the plate-boundary force related to subduction around the east margins of the Asian continent, and (3) the gravitational buoyancy forces resulting from lateral mass variations within the Asian lithosphere and mantle, primarily reflected by topographic loading in the Tibetan Plateau. Although the effects of gravitational spreading of the Tibetan Plateau are sometimes lumped together with plate-boundary forces as an integral part of the Indo-Asian collision, there are major differences between these two. The plate-boundary force is related to the rate of plate convergence, which has been roughly steady state for the past ~50 m.y. (Molnar and Tapponnier, 1975; Patriat and Achache, 1984). The gravitational buoyancy force arises from the isostatically compensated topography, which has increased with time. Thus, we treat these two forces separately in the model.

The model assumes a power-law viscous fluid rheology, with the strain rate proportional to the cubic power of stress (Brace and Kohlstedt, 1980; Kirby and Kronenberg, 1987). Because of the large region modeled here, we constructed the 3-D finite-element model in spherical geometry to include the effects of the curvature of Earth’s surface. The topographic loading is calculated using digital topography data, assuming local isostasy. The model crust sits on a viscous foundation. The vertical resistant force on the base of the crust is proportional to the vertical displacement of the crust and is a function of the effective viscosity of the underlying mantle. The indentation rate of the Indian plate into Asia is from the NUVEL-1A model (DeMets et al., 1990,

Figure 5. Finite-element mesh and boundary conditions of the continental-scale model. Areas of dark blue, pink, and light blue are the relatively stiff Tarim block, the Ordos Plateau, and the Sichuan Basin, respectively.
A crustal effective viscosity in the range of $10^{22} - 10^{23}$ Pa s is necessary for spreading, are highly sensitive to the rheology of the crust.

The predicted strain rates, particularly those from gravitational spreading, are highly sensitive to the rheology of the crust. A crustal effective viscosity in the range of $10^{22} - 10^{23}$ Pa s is necessary to fit the GPS and neotectonic strain rates. These values are consistent with previous estimates of long-term continental deformation in Asia (England and Houseman, 1986; Flesch et al., 2001). A fixed boundary along the eastern margins of the Asian continent is used in both cases in Figure 6 to isolate the effects of the Indo-Eurasian plate-boundary force and the gravitational buoyancy force. Replacing this with a velocity boundary condition based on the GPS data has little impact on the predicted deformation field, suggesting that active tectonics in Asia are largely controlled by the plate-boundary force from the Indo-Asian collision and the gravitational buoyancy forces arising from the high topography of the Tibetan Plateau and surrounding regions. However, the situation may have been quite different in the early Cenozoic, when much of the Tibetan Plateau was not uplifted and the eastern margin of the Asian continent was dominated by back-arc spreading, possibly related to deceleration of the Pacific-Eurasian plate convergence and trench rollback (Northrup et al., 1995).

Figure 7 shows the results for a preferred model of present active tectonics driven jointly by the combined forces of Indo-Asian collisional, gravitational spreading of the Tibetan Plateau, using present kinematic boundary conditions along the eastern margins of the Asian continent. The predicted uplift occurs mainly in and around the Tibet Plateau, and the horizontal velocities are generally comparable with the GPS data. This requires an $8^\circ \times 8^\circ$ window to cover all regions shown in Figure 8B. Within each window, linear regression is used to calculate the average velocity gradient. We then iterate with finer windows of $4^\circ \times 4^\circ$, $2^\circ \times 2^\circ$, and $1^\circ \times 1^\circ$ to refine the strain rates in areas where the sites are sufficiently dense. The result shows a better correlation with seismicity. The Ordos Plateau is shown as a stable block with low strain rates. High strain rates are found in the North China Plain and around the Ordos Plateau. The South China block has low strain rates.

To explore the impact of the observed crustal kinematics and lithospheric structure on seismicity in the North China block and South China block, we developed a 3-D finite-element model to calculate the long-term stress states and strain energy in these regions. The North China block is subdivided into the Ordos Plateau, the North China Plain, and the Sulu block because of their distinct tectonic histories. Displace-
Figure 6. (A) Predicted surface horizontal (arrows) and vertical (background color) velocities caused solely by the compressive force on the Indo-Eurasian plate boundary. (B) Predicted surface horizontal and vertical velocities caused solely by gravitational spreading of the Tibetan Plateau and other regions of high topography. In both cases, a cubic power-law rheology was used: $\sigma = B \varepsilon^{\frac{1}{3}}$, $B = 10^{13}$ Pa $s^{\frac{1}{3}}$. 
Figure 7. (A) Predicted surface vertical (background) and horizontal (arrows) velocities for a preferred case of combined driving forces (rheological parameters same as those in Fig. 6). (B) Surface horizontal maximum and minimum compressive stresses for the case in A.
ment boundary conditions, simplified from the GPS data, are applied to the edges of the model domain. The model crust has two layers with viscoelastic rheology.

Figure 9A shows the predicted stresses and the long-term strain energy, which is given by the product of the stress and strain tensors. Here, we assume a uniform crust for the North China block and South China block and no internal faults; thus, the higher shear stress and strain energy in the North China block than in the South China block are caused solely by the imposed kinematic boundary conditions. The North China block is compressed in the NE-NEE direction between the expanding Tibetan Plateau and the stable Alashan-Mongolian shield, while it moves relatively freely in the SE direction—hence the relatively large differential stresses and strain energy. Conversely, the South China block moves southeastward rather uniformly as a coherent block, resulting in little differential stresses and strain energy except near its margins. The contrast is more evident in Figure 9B, where we considered a stiff Ordos Plateau and a weak North China Plain and Sulu block as indicated by geophysical data (Ma, 1989; Liu et al., 2004). The internal fault zones that bound those tectonic units are simulated as rheological weak zones (Liu et al., 2002; Liu and Yang, 2003). The general patterns of stresses and strain energy are similar to those in Figure 9A, but some details of the model results, including the low strain rates within the Ordos Plateau, and the NW-SE extension near the Shanxi graben, fit the observations better (Xu and Ma, 1992; Zhang et al., 2003).

Figure 9C shows the estimated seismic energy release since 23 A.D. derived from Chinese catalogs of historic earthquakes and modern events. We used the Gutenberg-Richter energy formula (Lay and Wallace, 1995) and approximated all magnitudes as Ms. The strain energy was averaged over a 20-km-thick seismogenic crust. The seismically released energy is two orders of magnitude lower than the predicted long-term strain energy (Fig. 9B), presumably because not all energy is released by earthquakes. The spatial pattern of seismic energy release is quite comparable with that in Figure 9B, although the records of historic events may be incomplete. This suggests that the intense seismicity in the North China block reflects a long-term pattern of stress accumulation and release that will continue into the future.

The Circum-Ordos Seismic Zones

Within the North China block, seismicity is clearly controlled by the heterogeneous lithospheric structure, best shown in the Ordos Plateau and the surrounding rift systems (Fig. 8A). The interior of the plateau has been stable through the Cenozoic. Deformation and seismicity are concentrated within the
Figure 9. (A) Predicted steady-state strain energy (background color) and the deviatoric stresses (“beach balls”) for a case of homogeneous crust (Young’s modulus: 70 GPa; Poisson ratio: 0.25; viscosity: $5 \times 10^{23}$ Pa s). The Tibet Plateau was assumed to be weaker (viscosity: $3 \times 10^{22}$ Pa s). The three-dimensional stress states are represented by the lower-hemisphere stereographic projection; the maximum ($\sigma_1$) and minimum ($\sigma_3$) principal stresses bisect the white and shaded quadrants, respectively. (B) Results of a model of heterogeneous crust: the upper crustal viscosity is $1 \times 10^{23}$ Pa s for the North China Plain (NCP) and the Sulu blocks and $1 \times 10^{22}$ Pa s for the rest of the region. The lower crustal viscosity is $5 \times 10^{22}$ Pa s for most regions but is $1 \times 10^{23}$ Pa s for the Sulu block and the Tibetan Plateau. All fault zones are simulated as weak zones (viscosity: $1 \times 10^{22}$ Pa s). (C) Calculated seismic energy release since 23 A.D. based on the Chinese earthquake catalog.
surrounding rift zones. The Shanxi graben, on the eastern side, is an over 700-km-long echelon of extensional basins that mainly developed in the Pliocene and Quaternary (Xu and Ma, 1992; Zhang et al., 1998). Nineteen $M \geq 6$ historic earthquakes occurred here, including two $M = 8$ events, the 1303 Hongdong and the 1695 Linfen earthquakes. The Weihe graben, on the southern side of the plateau, is structurally connected to the Shanxi graben. The Weihe graben had a number of destructive earthquakes, including the deadly 1556 Huaxian earthquake ($M = 8$). Abundant ground fissures and Quaternary faulting indicate that this region is tectonically active today (Li et al., 2003). On the western and northern side of the plateau, there is the Yinchuan-Hetao rift, which also has experienced intense seismicity. The Liupanshan thrust belt on the southwestern side of the Ordos Plateau is the transition zone between the Tibetan Plateau and the North China block. Formation of the thrust belt started during the Pliocene, contemporaneous with left-slip motion on the Haiyuan fault (Zhang et al., 1991), best known for the 1920 Haiyuan earthquake ($M = 8.7$).

Although both neotectonics (Xu et al., 1993; Zhang et al., 1998) and historic seismicity indicate that the circum-Ordos rift zones have been active, only a few moderate-sized events have occurred in the past two hundred years, mainly near the northeastern side of the plateau (Fig. 8A). The GPS data, while indicating relative high strain rates around the Ordos Plateau (Figs. 4 and 8B), permit alternative interpretations. For example, based on the CMONOC GPS data collected between 1992 and 1996, Shen et al. (2000) found a 4 mm/yr extension rate across the Shanxi graben. However, using the same data set but with updated measurements extending to 2001, He et al. (2003) found no clear velocity jump across the Shanxi graben. This discrepancy with geological evidence of active extension across the graben may reflect data errors, or more likely, the time scale–dependent crustal rheology and deformation (Liu et al., 2000; He et al., 2003).

To explore the effects of time scale–dependent crustal kinematics and heterogeneous lithospheric structure, we built a local-scale geodynamic model similar to the regional-scale model for the North China and South China blocks (Fig. 10). In this local-scale model, the circum-Ordos rifts are simulated as rheological weak zones with finite widths. Figure 10 shows the predicted stresses and strain rates within the upper crust under the boundary load derived from interpolated GPS velocities. The lower maximum shear stress in the circum-Ordos rifts and other fault zones results from the lower viscosity assumed for these fault zones. The predicted stress states, such as the widespread extensional stresses in much of the North China Plain and the Mongolian shield, and the lack of thrust faulting in the Liupanshan region and northeastern Tibetan Plateau are inconsistent with Cenozoic structures and neotectonic data. To better fit the geological structures, we found it necessary to

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**Figure 10.** (A) Predicted stress states (“beach balls”) and maximum shear stress (background color) for the local-scale model. The boundaries of the model domain are loaded by imposed velocities interpolated from the global positioning system (GPS) data. (B) Predicted strain rates (background color) and the direction of maximum horizontal compressive stress (black bars), compared with the observed stress orientations interpolated from the World Stress Map (http://world-stress-map.org). HY—Haiyuan fault; YH—Yinchuan-Hetao rifts; KL—Kunlun fault; WH—Weihe graben; SX—Shanxi graben; LM—Longmanshan fault; QLDB—Qinling-Dabie fault zone.
increase the velocity on the western side of the model domain, especially along the northeastern front of the Tibetan Plateau (Fig. 11). These requirements seem consistent with the fact that GPS velocities on the major strike-slip faults in this region are systematically lower than the geologically estimated slip rates. Thus, GPS site velocities, which are measured during a period of a few years and reflect the instantaneous velocity field, may not be representative of the long-term geological rates of crustal motion. Similar observations have been made in other regions (Liu et al., 2000; Friedrich et al., 2003). Note that in both cases the predicted direction of maximum horizontal compressive stresses is generally comparable to those observed, indicating that the directions of long-term crustal motion are close to those indicated by the GPS data. The fits are generally better in the western part of the model domain, perhaps reflecting the dominance of compressive stresses from the expanding Tibetan Plateau. The relatively poor fit in the North China Plain may reflect the effects of other processes, such as subduction and basal drag associated with mantle flow (Liu et al., 2004), which may be important there but are not included in this model.

Stress Evolution and Triggering of Large Earthquakes in North China

Intracontinental seismicity in China is spatially correlated to regions of high strain rates (Figs. 4 and 8B). The temporal patterns of these earthquakes, however, remain poorly understood. The Weihe and Shanxi grabens have experienced more than 30 M ≥ 6 events in the past 2000 yr, but instruments have recorded no major events there in the past century, and modern seismicity in the North China block has been concentrated in the North China Plain (Fig. 1). Some explanations for the spatial-temporal evolution of seismicity may be provided by the changes of the Coulomb stresses associated with earthquakes, which have been shown to have significant influences on earthquake sequences in both interplate (King et al., 1994; Stein, 1999) and intraplate settings (Li et al., this volume). Shen et al. (2004) simulated the Coulomb failure stress change (ΔCFS) in North China since 1303 using 49 destructive events (M ≥ 6.5) from the Chinese catalog of historic earthquakes.

The ΔCFS on a fault plane is calculated as

\[ Δ\sigma = Δτ + μΔσ_n, \]

where \( Δτ \) is the change of shear stress on the fault plane, \( Δσ_n \) is the change of normal stress (\( Δσ_n > 0 \) indicates an increase in tension), and \( μ \) is the frictional coefficient (\( μ = 0.4 \) for this study). Positive \( Δσ \) moves a fault toward failure, and vice versa. The stress evolution was calculated using the viscoelastic codes by Zeng (2001). The earthquakes used in the simulation are shown in Figure 12. The locations, magnitudes, and intensity data are from the Chinese earthquake catalog (Ming et al., 1995). Because most of the earthquakes occurred on faults buried under sediments, we first derived an empirical relationship between the earthquake ground-shaking intensity distribution (and magnitude) and earthquake rupture parameters using modern instrumentally recorded strong earthquakes in North China, and then we used this empirical formula to infer fault rupture parameters of historical earthquakes, including the rupture length and the amount of slip. The

Figure 11. Results of the local-scale model similar to Figure 10, except faster eastward velocities (3 mm/yr higher than the global positioning system [GPS] velocities) are assumed along the eastern side of the Tibetan Plateau.
earthquake rake angles were derived from geologically determined fault parameters and seismically estimated orientations of regional tectonic stresses. Earthquake ruptures were assumed to span 2–20 km based on focal-depth distribution of small- to medium-sized earthquakes in the region. The incremental secular loading stresses were assumed to be depth invariant, and were calculated from the GPS velocity field assuming linear elasticity of the media (Shen et al., 2003).

The initial values of $\Delta CFS$ were assumed to be zero everywhere, and the simulations started with the 1303 Hongdong earthquake ($M = 8.0$). The stress evolution was then calculated with secular loading and for each of the sequential earthquakes using the geologically derived rapture parameters. Figure 13A shows one snapshot of the $\Delta CFS$ field after the 1888 Bohai earthquake and before the 1910 Huanghai earthquake. The $\Delta CFS$ was evaluated on vertical fault planes trending N40°E, which is the dominant fault geometry of the region. The triggering effects are suggested by the spatial correlation between regions of positive $\Delta CFS$ and the loci of major earthquakes since 1880. The 1976 Tangshan earthquake occurred in an area of increased $\Delta CFS$ that was the result of the 1679 Sanhe-Pinggu earthquake ($M = 8$) and secular tectonic loading, with an accumulated $\Delta CFS$ of ~1.8 bar. Our analysis shows that for all 49 earthquakes with $M \geq 6.5$ that have occurred since 1303 in North China, 39 out of the 48 subsequent events occurred in regions of positive $\Delta CFS$; the triggering rate is 81.3%. Figure 13B shows present $\Delta CFS$, modified from that in Figure 13A mainly by the 1910 Huanghai earthquake and 1976 Tangshan earthquake. The high risk areas include the Bohai Basin, the west segment of the northern Qinling fault, western end of the Zhangjiakou-Penglai seismic zone, and the Taiyuan Basin in the Shanxi graben.

**DISCUSSION**

Diffuse continental deformation has challenged one of the basic tenets of plate tectonics theory that predicts deformation and seismicity concentrations within narrowly defined plate-boundary zones, and this has been propelling a fundamental transition from kinematic descriptions of tectonic plates toward a dynamic understanding of lithospheric deformation (Molnar, 1988). Some of the intracontinental deformation reflects diffuse plate-boundary zones. Space-geodetic measurements show that many plate-boundary zones are characterized by diffuse deformation, and the diffuse plate-boundary zones are not limited to continents (Gordon and Stein, 1992). Other intracontinental deformation occurs within plate interiors, often associated with certain lithospheric heterogeneities, and shows no clear link to plate-boundary processes.

The active tectonics and seismicity in China provide some of the best examples of both diffuse plate-boundary zone deformation and intraplate tectonics. The Tibetan Plateau and most parts of western China are extreme examples of diffuse plate-boundary

![Figure 12. Large earthquakes (M $\geq$ 6.5) in North China since 1303 that were used in the modeling of Coulomb stress changes and their triggering effects.](image-url)
zones, where continuous crustal deformation extends thousands of kilometers into the Asian continent from the Indo-Asian plate boundary. The deformation styles and orientations of geological structures are coherently related to the collisional plate-boundary processes. On the other hand, although the Indo-Asian collision may have influenced tectonics in eastern China and southeast Asia, those areas are not part of the diffuse Indo-Eurasian plate-boundary zone, as shown by their different type and style of deformation. While western China was under tectonic compression through much of the Cenozoic, eastern China experienced widespread rifting and basaltic volcanism (Ye et al., 1985; Ren et al., 2002; Liu et al., 2004). Thus, earthquakes in eastern China are commonly regarded as intraplate events. Crustal deformation in the North China block, however, differs significantly from typical seismic zones within stable continents, such as the New Madrid seismic zone in central United States (see Li et al., this volume, and references therein), because the North China block has been thermally rejuvenated since the late Mesozoic and is no longer a stable continental block and the strain rates are one order of magnitude higher than those in the central and eastern United States (Newman et al., 1999; Gan and Prescott, 2001). Moreover, unlike the central and eastern United States, where seismicity shows no clear link to plate-boundary processes (Li et al., this volume), active crustal deformation and earthquakes in the North China block are strongly influenced by the compressive stress from the Indo-Asian collision and gravitational spreading of the Tibetan Plateau.

Figure 13 (on this and following page). (A) Predicted Coulomb stress changes in 1910. Stars and circles denote the epicenters of the subsequent $M \geq 6.5$ and $6.5 \geq M \geq 5$ earthquakes for 1910–1976, respectively.
We have shown that the GPS site velocities provide a satisfactory first-order delineation of the regions of high strain rates and seismicity that is consistent with neotectonic data. However, along major strike-slip faults in western China, the GPS observed slip rates are consistently lower than those inferred from neotectonic studies. Although errors from processing GPS data collected from campaign-style measurements may not be excluded, the systematic discrepancy more likely results from different time scales represented by the GPS and neotectonic data (Liu et al., 2000). The GPS data, typically collected over a period of a few years, measure an instantaneous velocity field. During the period of GPS measurements, the faults are often partially or entirely locked. The neotectonic data, on the other hand, represent long-term, average slip rates that include both coseismic and interseismic displacements. Over dip-slip faults, the GPS velocity gradient is expected to be gentle if the fault is locked during the period of GPS measurements. The lack of a clear GPS velocity gradient across the Shanxi graben is consistent with the fact that no major earthquakes have occurred within the graben in the past 200 yr.

The analyses of crustal kinematics and dynamics presented in this study provide a geodynamic framework for understanding the variable distributions of seismicity in continental China. Both kinematics and lithospheric structures exert strong influences on seismicity. The Ordos Plateau and the Tarim block, for example, are located within regions of high rates of relative crustal motions; their lack of seismicity results mainly from their high...
lithospheric strength. The seismic quiescence within the South China block, on the other hand, may be largely attributed to the kinematic boundary conditions that allow the South China block to move coherently as a rigid block.

The seismic zones in China are well defined by seismicity, neotectonics, and, to some extent, space-geodesy. The temporal patterns of the seismicity, however, remain poorly understood. For example, the Weihe and Shanxi grabens have experienced abundant large earthquakes in the past 2000 yr, but they have not seen major earthquakes in the past 200 yr. Modern seismicity within the North China block seems to have shifted to the North China Plain. We have attempted to explore the triggering effects of large earthquakes by modeling the associated Coulomb stress changes. Given the complexity of earthquake physics and incomplete knowledge of crustal structures in North China, we found it interesting that over 80% of M ≥ 6.5 events occurred in regions of increased Coulomb stresses caused by previous earthquakes. These results, albeit intrinsically limited, provide helpful information for future seismic hazard assessments in this part of China where population is dense and economy is booming.

CONCLUSIONS

1. Neotectonic data, mainly based on Quaternary fault slips, and GPS measurements indicate that the diffuse intracontinental deformation in China and surrounding regions and the associated seismicity are strongly influenced by the Indo-Asian collision. The effects of indentation of the Indian plate are largely limited to western China (west of 105°E). In contrast, the compressive stress arising from gravitational spreading of the Tibetan Plateau has a broader impact on active tectonics in much of central and east Asia. The subduction zones around the eastern margins of the Asian continent contribute little to the intracontinental deformation in the Asian continent at present but may have played a major role in the early Cenozoic, when most of the Tibetan Plateau was not fully uplifted and back-arc spreading was intense along the eastern margins of the Asian continent.

2. GPS data indicate that more than half of the present-day convergence (36–40 mm/yr) between the Indian and Eurasian plates is spread evenly across the Tibetan Plateau and the Tianshan, making western China and surrounding regions one of the widest diffuse plate-boundary zones. Seismicity in this part of the Asian continent is intense and is generally associated with crustal motion on a system of roughly E-W–oriented strike-slip and thrust faults driven by N-S-directed crustal shortening. Seismicity in eastern China is characterized by intense seismicity in the North China block and relative quiescence in the South China block. Geodynamic modeling suggests that this contrasting seismicity is primarily caused by the crustal kinematics and tectonic boundary conditions. The North China block experiences high deviatoric stresses because it is squeezed between the stable Siberian shield and the expanding Tibetan Plateau, while the crust is moving relatively freely southeastward. The South China block, facilitated by the surrounding strike-slip fault systems, moves more coherently as a rigid block, resulting in low internal deformation and seismicity.

3. Within the North China block, deformation and seismicity are largely controlled by the lateral heterogeneities of the lithospheric structure. High strain rates and intense seismicity within the circum-Ordos rifts result mainly from the weakness in the crust and perhaps mantle lithosphere in these rifts. In the North China Plain, seismicity is associated with a system of conjugate NNE and NWW faults. The predicted long-term strain energy pattern agrees with the spatial pattern of seismic strain energy released during the past 2000 yr, suggesting that the intense seismicity in North China is a long-term process that will continue in the future. However, the temporal pattern of large earthquakes within the North China block remains unclear. Preliminary calculations of earthquake-triggered Coulomb stress changes show that ~80% of large (M ≥ 6.5) earthquakes have occurred within regions of increased Coulomb stresses. At present, the high-risk regions include the Bohai Basin, the western segment of the northern Qilining fault, the western end of the Zhangjiakou–Penglai seismic zone, and the Taiyuan Basin in the Shanxi graben.

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