

2000 years of migrating earthquakes in North China: How earthquakes in midcontinents differ from those at plate boundaries

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ABSTRACT

Plate-tectonic theory explains earthquakes at plate boundaries but not those in continental interiors, where large earthquakes often occur in unexpected places. We illustrate this difference using a 2000-year record from North China, which shows migration of large earthquakes between fault systems spread over a large region such that no large earthquakes rupture the same fault segment twice. However, the spatial migration of these earthquakes is not entirely random, because the seismic energy releases between fault systems are complementary, indicating that these systems are mechanically coupled. We propose a simple conceptual model for intracontinental earthquakes, in which slow tectonic loading in midcontinents is accommodated collectively by a complex system of interacting faults, each of which can be active for a short period after long dormancy. The resulting large earthquakes are episodic and spatially migrating, in contrast to the more regular spatiotemporal patterns of interplate earthquakes.

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INTRODUCTION

Most of the world's large earthquakes occur along the boundary faults between tectonic plates. Steady relative motion of these plates loads the boundary faults at constant rates, leading to quasi-periodic release of strain energy by earthquakes. This process forms the basis of our current understanding of earthquakes and assessment of their hazards. Hence, small recent earthquakes are often viewed as indicating steady stress buildup leading to the next large one, whose timing may be estimated from fault slip rates and the time since the last large earthquake, based on some recurrence intervals.

This seemingly straightforward approach, however, fails in midcontinents, where large earthquakes often pop up in unexpected places. The devastating 2008 Wenchuan earthquake (Mw 7.9) in Sichuan Province, China, for example, occurred on the Longmanshan fault, which had little instrumentally recorded seismicity and only moderate earthquakes in the past few centuries (Burchfiel et al., 2008; Wang et al., 2010). The 1976 Tangshan earthquake (Mw 7.8), which killed nearly 240,000 people, occurred on a previously unknown fault in North China.

Establishing the spatiotemporal patterns of midcontinental earthquakes is thus a critical step toward understanding the cause of these enigmatic earthquakes and the hazard they pose. A major difficulty is that large midcontinental earthquakes are infrequent, so their patterns are not well described by the short earthquake records available in most regions. This problem should be less challenging in North China (Fig. 1), where the historic earthquake record extends more than 2000 years (Ming et al., 1995).

In this study, we show that the complex spatiotemporal pattern of earthquakes in North China does not result from their random occurrence

in isolated faults but reflects long-range migration between mechanically coupled fault systems in the continental interior.

SPATIOTEMPORAL MIGRATION OF LARGE EARTHQUAKES IN NORTH CHINA

North China, consisting of the Ordos Plateau and the North China Plain, is part of the Archean Sino-Korean craton within the Eurasian plate (Fig. 1). The Ordos Plateau is a rigid block bounded by the Weihe rift to the south and the Shanxi rift to the east (Fig. 2). The North China Plain has a complex system of basement faults hidden under a thick cover of Quaternary sediments. Since the Mesozoic, the North China craton has been rejuvenated, producing volcanism, rifting, and large earthquakes (Liu et al., 2004; Liu and Yang, 2005).

The earthquake catalog for the area, which appears to be complete for magnitude (M) ≥ 6 events since A.D. 1300 (Huang et al., 1994), includes 49 major events with $M \geq 6.5$ and at least four earthquakes with $M \geq 8$. The earthquake catalog and an animated map showing the epicenters are provided in the GSA Data Repository.¹

The catalog shows long-distance migration of large earthquakes. Before A.D. 1302, large earthquakes in North China were concentrated along the Weihe and Shanxi rifts and scattered over the North China Plain (Fig. 2A). In 1303, the Hongdong earthquake ($M = 8.0$) occurred within the Shanxi rift, killing more than 470,000 people. In the next 250 years, seismicity was active within the Shanxi rift (Fig. 2B). Then, in 1556, the Huaxian earthquake ($M = 8.3$) occurred in the Weihe rift, more than

¹GSA Data Repository Item 2011080, earthquake catalog and slides animation of earthquake epicenters, is available at www.geosociety.org/pubs/ft2011.htm, or on request from editing@geosociety.org, Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

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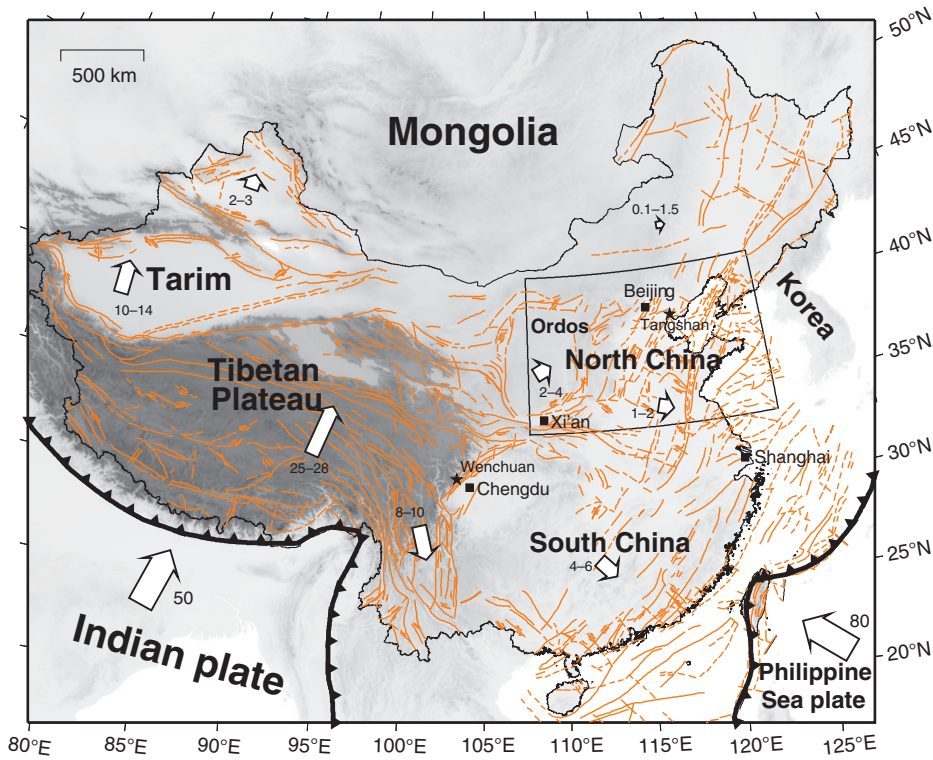
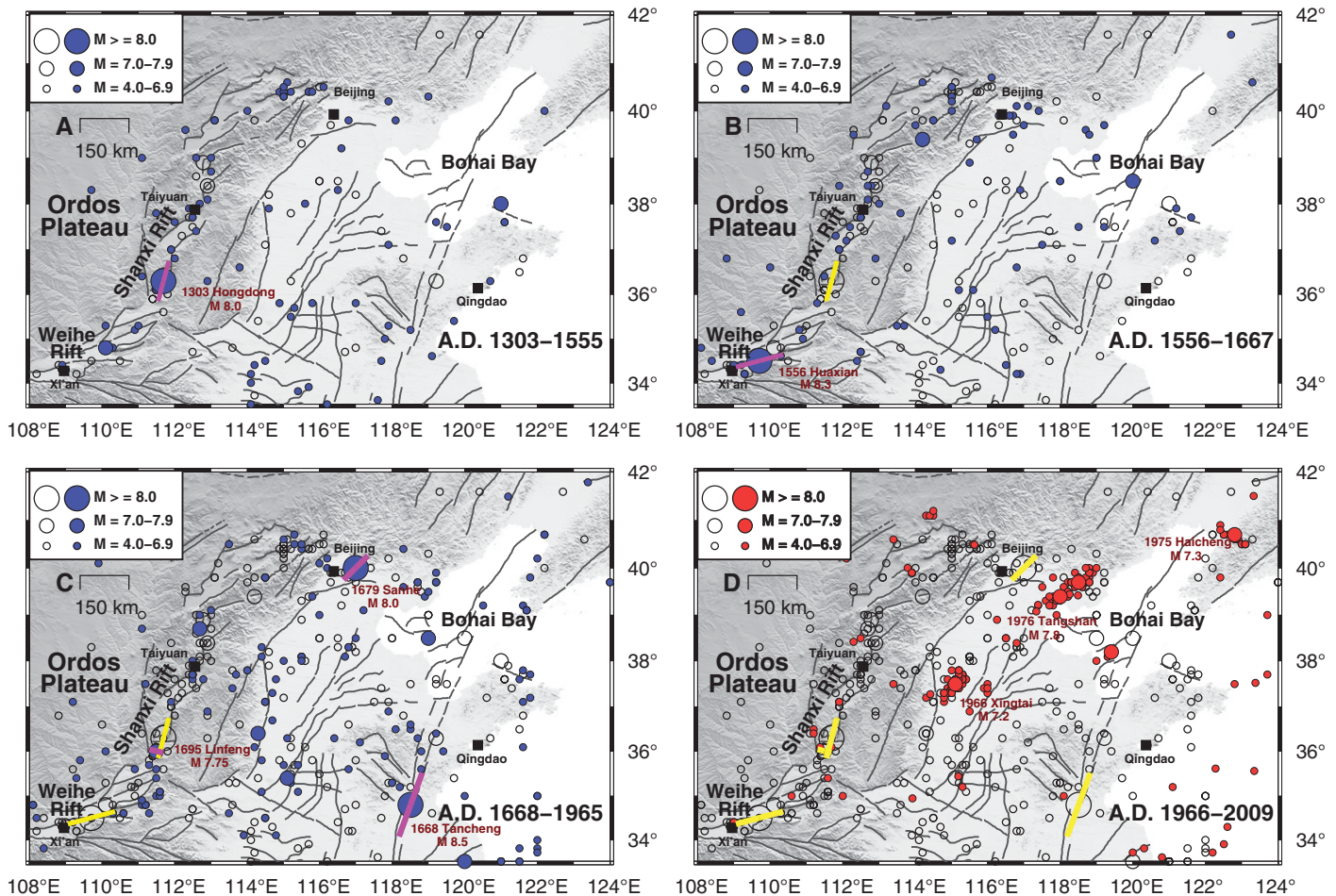


Figure 1. Topography and tectonic setting of North China (boxed) and neighboring regions. Thin orange lines are active faults. Arrows show crustal motion (mm/yr) relative to the stable Eurasian plate (Liu et al., 2007).

Figure 2. Earthquake history of North China. Solid circles are the locations of events during the period indicated in each panel; open circles are the location of events from 780 BCE to the end of the previous period (A.D. 1303 for panel A). Red dots are epicenters of instrumentally recorded earthquakes. Bars show the rupture lengths for selected large events during (magenta) and before (yellow) the period indicated in each panel (after Liu et al., 2007).



300 km away from the epicenter of the Hongdong earthquake (Fig. 2B). About 830,000 people perished, making it the deadliest earthquake in human history. The next catastrophic earthquake, the 1668 Tancheng earthquake ($M = 8.5$), did not occur within the rift systems but more than 700 km to the east, in the North China Plain (Fig. 2C). This earthquake ruptured the Tanlu fault zone, which had shown little deformation through the late Cenozoic and few previous large earthquakes. Only a decade later, another large event, the 1679 Sanhe-Pinggu earthquake ($M = 8.0$), occurred only 40 km north of Beijing, in a fault zone with limited previous seismicity and no clear surface exposure (Fig. 2C). Then, in 1695, a $M = 7.75$ earthquake occurred in the Shanxi rift again, near the site of the 1303 Hongdong earthquake but on a different fault.

Since then, the Shanxi and Weihe rifts have been largely quiescent for more than 300 years, with only a few moderate earthquakes recorded. Meanwhile, seismicity in the North China Plain has apparently increased, including three damaging earthquakes in the past century (Fig. 2D). These recent earthquakes occurred on previously unrecognized faults. The 1966 Xingtai earthquakes, a sequence of five events ranging from $M 6.0$ to $M 7.2$ within 21 days, occurred in a buried rift with no surface fault traces. The 1975 Haicheng earthquake ($M = 7.3$) occurred in a region with no major surface fault traces and little previous seismicity, and the 1976 Tangshan earthquakes ($M = 7.8$ and $M = 7.1$) occurred on a blind fault, which had not shown even moderate seismicity in the previous centuries (Fig. 2D).

Thus, the spatiotemporal occurrence of earthquakes in North China is much more complex than that at plate boundaries. Large earthquakes have migrated between the Shanxi and Weihe rifts, and between these rifts and the North China Plain. Such long-distance migration of earthquakes cannot be all attributed to stress triggering due to earthquake-induced changes of the Coulomb stress (Liu et al., 2007), which occurs mainly near the ruptured fault segment (Stein, 1999). No large earthquakes in North China have ruptured the same fault segment twice in the past 2000 years. For seismicity prior to that time, paleoseismic studies, while limited and with large uncertainties in dating results, nonetheless indicate episodic large earthquakes separated by thousands of years of quiescence on the same fault segments (Xu and Deng, 1996). Similar behavior is observed in other midcontinents such as the central and eastern United States, Australia, and northwest Europe (Newman et al., 1999; Crone et al., 2003; Camelbeek et al., 2007).

MOMENT RELEASE AND MECHANICAL COUPLING BETWEEN FAULT SYSTEMS

Are the complex spatiotemporal patterns of earthquakes in North China simply random effects of long recurrence times on different faults? Or could these migrating earthquakes reflect mechanical coupling between remote fault systems? One way to answer these questions is to examine the seismic moment release on these fault systems. For a dynamically coupled system of fault zones, the total moment release rate should stay around a certain level, with the moment release rate of individual fault zones being complementary (Dolan et al., 2007). We estimated moment release in North China using the earthquake catalog, treating the magnitudes of historic events as surface wave magnitude M_s and converting them to moment magnitude M_w using a M_s - M_w relationship based on instrumental events in China (Wang et al., 2010). The moment (M_0) in Newton-meter was then calculated from $M_w = (2/3)\log(M_0) - 6.03$.

The moment release between the Weihe and Shanxi rifts seems to be complementary: increases in one correspond to decreases in the other (Fig. 3A). Hence, these rifts are not independent from each other but are somehow mechanically coupled. Similar correlation exists between the Shanxi-Weihe rift system and the faults within the North China Plain (Fig. 3B). The appar-

ently increasing moment release since ca. A.D. 1399 is probably due to the catalog being more complete for the more recent periods.

A CONCEPTUAL MODEL FOR MIDCONTINENTAL EARTHQUAKES

These spatiotemporal patterns of earthquakes in North China illustrate some fundamental differences between earthquakes in midcontinents and those at plate boundaries. Faults at plate boundaries are loaded at constant rates by the steady relative plate motion. Consequently, earthquakes concentrate along the plate boundary faults, and some quasi-periodic occurrences may be expected, although the actual temporal patterns are often complicated (Fig. 4A). However, in midcontinents, the tectonic loading is shared by a complex system of interacting faults spread over a large region (Fig. 4B), such that a large earthquake on one fault could increase the loading rates on remote faults in the system (Li et al., 2009). Because the low tectonic loading rate is shared by many faults in midcontinents, individual faults may remain dormant for a long time and then become active for a short period. The resulting earthquakes are therefore episodic and spatially migrating.

Most natural faults probably fall between the idealized end-members in Figure 4. The Shanxi and Weihe rifts are major fault systems accommodating the eastward extrusion of the Asian continent, driven by the Indo-Asian collision (Tapponnier and Molnar, 1977; Xu and Ma, 1992; Zhang et al., 2003). As such, their slip rates (2–4 mm/yr) are relatively constant, high by intraplate standards, and not sensitive to influences from ruptures within the North China Plain. Thus, seismicity is concentrated within the rift zone, with some quasi-periodicity. Within the North China Plain, however, tectonic loading is shared by a complex system of faults, and the slip rates are low (<2 mm/yr) and perhaps variable. Hence, large earthquakes migrate between faults (Fig. 4B). Similar patterns are found in other midcontinents. In the central and eastern United States, which deforms even more slowly, faults often show clustered earthquakes for a while and then become dormant for thousands of years. The Meers fault in Oklahoma, for example, had a major earthquake around 1200 yr ago but is inactive today (Crone et al., 2003). The New Madrid seismic zone, which experienced several large earthquakes in the past few thousand years, including at least three $M \geq 6.8$ events in 1811–1812, shows no significant surface deformation (Calais and Stein, 2009). Hence, the deformation rate must vary significantly over time, and the recent cycle of large earthquakes may be ending (Newman et al., 1999; Calais and Stein, 2009; Stein and Liu, 2009).

DISCUSSION

The long-range interactions between faults in midcontinents explain a long-standing paradox: the rupture processes of intraplate earthquakes are no different from those for interplate earthquakes, yet intraplate earthquakes are much less regular in space and time. Whereas the basic physics of earthquakes—stress buildup and release on faults—are the same on all faults, the network of faults in midcontinents forms a complex system (Stein et al., 2009) whose behavior differs significantly from that of a single fault. Similar situations also arise at plate boundaries that consist of a system of faults (Rundle et al., 2006; Dolan et al., 2007).

Complex systems, whose behavior cannot be fully understood from studies of their individual components, are a major challenge in many aspects of the physical, biological, and social sciences (Gallagher and Appenzeller, 1999). Realizing that midcontinental earthquakes behave as a complex system does not immediately answer many questions about these earthquakes or make assessing their hazards any easier. However, it provides a more holistic framework for addressing these questions. Hence,

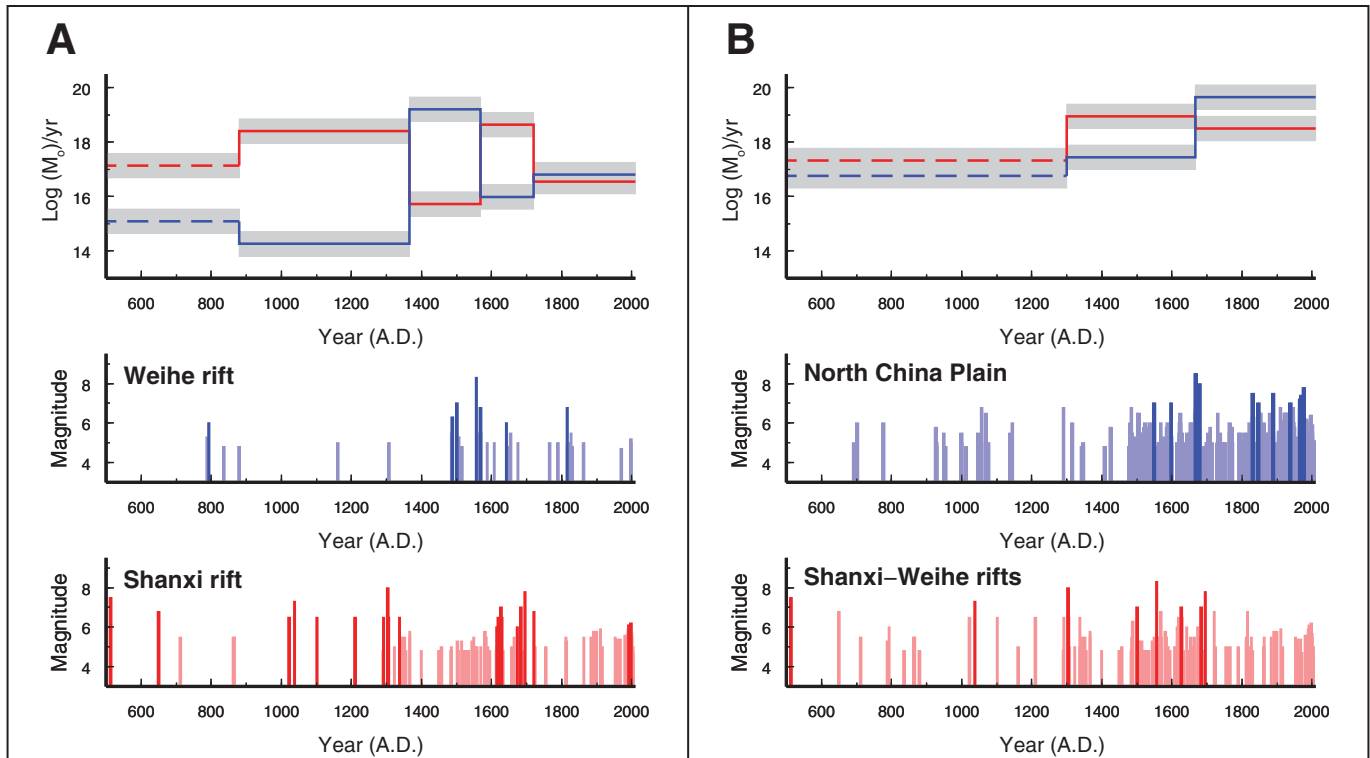


Figure 3. (A) Bottom two panels show occurrence and magnitude ($M \geq 4.0$) of earthquakes in the Shanxi and Weihe rifts. Top panel compares the time-averaged rate of seismic moment release (Newton-meter/yr) between the two rifts (colors are correlated with those in the bottom panels). Dashed lines are for older intervals, wherein some events are likely unrecorded. Gray bands indicate uncertainties associated with an estimated ± 0.3 error in the magnitudes, which were based on the maximum intensity and the radius of the affected area (Ma, 1989). (B) Similar to (A) for the comparison of moment release between the North China Plain and the Weihe-Shanxi rift system.

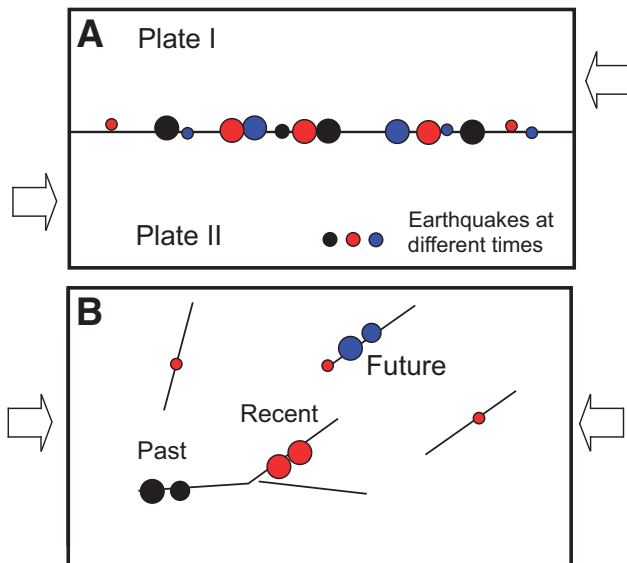


Figure 4. Cartoon showing the difference between earthquakes (A) at plate boundary faults and (B) in midcontinents. The plate boundary fault is loaded at a constant rate by the steady relative plate motion, causing quasi-periodic earthquakes to concentrate along the plate boundary. The midcontinent is loaded from the far field, and the loading is shared by a complex system of interacting faults. Hence, on each fault, the loading rate may be variable, and earthquakes may shut off on one fault and migrate to another.

the present methods of earthquake hazard assessment, which are based on the assumption of quasi-periodic earthquakes on recently active faults, need modification to describe the complex earthquakes in midcontinents. The combination of high-precision global positioning system measurements, detailed paleoseismic studies, and more realistic computer simulation of fault interactions in midcontinents should help show which faults with past large earthquakes are shutting off for some time, and which apparently dormant faults are awakening and quietly building up stress for future large earthquakes.

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