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Invited review

Mid-continental earthquakes: Spatiotemporal occurrences, causes, and hazards

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A B S T R A C T

Large earthquakes in North China, Australia, Northwestern Europe, Central and Eastern United States, and other mid-continents show complex spatiotemporal patterns that do not fit existing earthquake models. Individual faults or fault zones tend to fall into long term (thousands of years or longer) dormancy after a cluster of ruptures, whereas large earthquakes seem to roam between widespread faults. These behaviors are characteristic of complex dynamic systems of interacting faults. In such systems, widespread faults collectively accommodate slow tectonic loading, and a major fault rupture both transfers stress to the neighboring faults and perturbs loading conditions on distant faults. Because of the slow tectonic loading, local stress variations from fault interaction or nontectonic processes, or changes of fault strength, could trigger mid-continental earthquakes. The precise spatiotemporal occurrence of large mid-continental earthquakes may be unknowable, an intrinsic limitation of complex dynamic systems, but their qualitative system behavior may be understood by a system approach. This approach would render some commonly used concepts, such as seismic cycles, recurrence intervals, characteristic earthquakes, and seismic gaps inadequate or irrelevant in mid-continents, and calls for rethinking of the probability estimates based on these concepts. It requires a better understanding of fault interactions on multiple spatial and temporal scales rather than focusing solely on the balance of tectonic loading and yield strength of individual faults or fault segments. It also indicates the need for paleoseismic and geodetic studies extending beyond areas where recent large earthquakes occurred, and for hazard assessments to reduce the biasing influence of the most recent large earthquakes that tend to dominate the short and incomplete earthquake records.

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"*The potential for earthquakes along the plate boundaries has been mapped with reasonable success. Our attention should now focus on the threat posed by unanticipated quakes located in the continental interiors*." (England and Jackson, 2011).

1. Introduction

Large earthquakes within plate interiors, although less common than earthquakes at plate boundaries, have killed more people than interplate earthquakes (Bilham, 2014). The deadliest earthquake in human history, the 1556 Huaxian earthquake (M 8.0) that killed 830,000 people (Min et al., 1995), occurred in the middle of continental China, as did the 1976 Tangshan earthquake (Mw 7.8) that claimed ~ 242,000 lives (Chen et al., 1988). Three of the largest historical earthquakes (M ≥ 7.0) in the continental US occurred during 1811–1812 in the New Madrid area of Missouri, in the middle of the North American continent (Hough and Page, 2011; Hough et al., 2000; Johnston and Schweig, 1996). The 2011 Virginia earthquake (M 5.8), which rattled the eastern seaboard and damaged the Washington Monument, serves as a fresh reminder of earthquake hazards in central and eastern US (Wolin et al., 2012).

"Unanticipated" is a key word differentiating interplate and intracontinental earthquakes. Most large interplate earthquakes are, or could be, anticipated, because plate tectonics predicts their general locations, and their abundance means that we often have earthquake records that seem adequate to *anticipate* where the next might occur. In continental interiors where faults are widespread (and often poorly mapped), which faults are *active* is often unclear, and earthquake records are short relative to long recurrence times, large earthquakes often come as surprises.

The complexity of mid-continental earthquakes and their challenge to current earthquake models have spurred intense interest and debates in recent years, both about their causes (e.g., Calais et al., 2016; Calais et al., 2010; Forte et al., 2007; Hough and Page, 2011; Landgraph et al., 2015; Li et al., 2005; Liu et al., 2011; Pollitz et al., 2001; Schweig and Ellis, 1994; Talwani, 2014) and the resulting hazards (Camelbeeck et al., 2007; Clark and McCue, 2003; Frankel et al., 2012; Grollimund and Zoback, 2001; Liu and Wang, 2012; Newman et al., 1999; Stein et al., 2011; Stein et al., 2012; Stein et al., 2015b). In this review we first briefly discuss the spatiotemporal history of large earthquakes in major mid-continents, focusing on common aspects of seismicity in North China, the central and eastern US, northwestern Europe, and Australia. We then discuss current models for the causes of these earthquakes, and argue that these models are inadequate for or inapplicable to mid-continental earthquakes. We suggest a paradigm shift to treat mid-continental earthquakes as resulting from complex dynamic systems of interacting faults, and to incorporate this view in hazard assessment.

2. Roaming earthquakes in mid-continents

Spatiotemporal patterns of seismicity form the basis for exploring their tectonic causes. The global distribution of seismicity, with earthquakes concentrating in narrow belts, played a key role in establishing plate tectonic theory (Isacks et al., 1968). Similar spatiotemporal patterns are, unfortunately, hard to identify in mid-continents from available earthquake records, which are incomplete and often too short relative to the low rates of tectonic loading. Nonetheless, a number of mid-continents, either because of exceptionally long historic records or low rates of erosion, give us some glimpse of the complex spatiotemporal behavior of mid-continental earthquakes.

2.1. North China

North China (or geologically the North China block), including the Ordos Plateau and the North China Plain, is part of the Achaean Sino-Korean craton within the Eurasian plate (Fig. 1). The eastern part of the craton was rejuvenated in the Mesozoic, producing widespread volcanism and crustal extension that formed the North China Plain (Liu et al., 2004; Liu and Yang, 2005). The western part of the craton is preserved under the Ordos Plateau, which is bounded by the Weihe rift to the south and the Shanxi rift to the east (Figs. 1–2).

The earthquake catalog in North China extends for nearly 3000 years (Min et al., 1995). It is likely complete for magnitude M ≥ 6 events since 1300 (Huang et al., 1994), a period that includes 49 M ≥ 6.5 events and at least four M ≥ 8 earthquakes. These large earthquakes appear to roam between widespread fault zones (Liu et al., 2011; Liu et al., 2014c). In 1303 the Hongdong earthquake (M 8.0) in the Shanxi rift killed >470,000 people. In the next 250 years, seismicity was active within the Shanxi rift (Fig. 2A). In 1556, the Huaxian earthquake (M 8.0) occurred in the Weihe rift, >300 km from the epicenter of the Hongdong earthquake (Fig. 2B). About 830,000 people perished, making it thedeadliest earthquake in human history. The next catastrophic earthquake, the 1668 Tancheng earthquake (M 8.5), occurred >700 km east of the rift systems, in the North China Plain (Fig. 2C). This earthquake ruptured the Tanlu Fault, a major Mesozoic fault that has had little Cenozoic deformation and few previous large earthquakes. GPS data show <1 mm/yr slip on the Tanlu Fault today (Liu et al., 2007). A decade later, another large event, the 1679 Sanhe-Pinggu earthquake (M 8.0), occurred ~40 km north of Beijing in a fault zone with limited previous seismicity and no clear surface exposure (Fig. 2C). Then, in 1695, an M ≥ 7.5 earthquake occurred in the Shanxi rift again, near the site of the 1303 Hongdong earthquake but on a different fault (Liu et al., 2014c).

In the past 300 years the Shanxi and Weihe rifts have been largely quiescent with only a few moderate earthquakes. Meanwhile, seismicity in the North China Plain increased, including three damaging earthquakes in the past century (Fig. 2D), all on previously unrecognized faults. The 1966 Xingtai earthquakes, five events with M 6.0–7.2 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 (a M 7.8 event followed by a M 7.1 event 17 h later) occurred on a blind fault, which had not shown even moderate seismicity in the 3000-year long Chinese catalog (Min et al., 1995; Yin et al., 2015).

Thus large earthquakes roamed between the Shanxi and Weihe rifts, and between these rifts and the North China Plain. No large earthquakes in North China ruptured the same fault segment twice in the past 2000 years (Liu et al., 2011). Prior to that time, paleoseismic studies, while limited and with large uncertainties, indicate episodic large earthquakes separated by thousands of years of quiescence on the same fault segments (Xu and Deng, 1996b).