大陆活化克拉通与裂谷地堑地区的地震构造模型

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摘 要

经常观察到这样的现象:活化的克拉通在其演化的不同阶段经历过裂谷作用.在这些地区有分割的地堑构造,有些地堑已变成现代的活跃地震带,如中国山西临汾地堑,中国河北邢台地堑和美国的新马德里地堑。大量资料表明,这些地区的地震成因与许多地质、地球物理条件有关,而不仅仅是活动断层。以临汾地堑为例,地震发生过程涉及到下列因素:(1)地堑周围强度较大的变质岩,这些岩体在区域应力场作用下产生应力积累;(2)地堑内5—15km深度发震层内强度较低的介质,地震发生时发震层介质发生破裂,释放能量,辐射出地震波;(3)发震层之下的异常低阻层或低速层,它对震源过程具有延性的调节作用;(4)地堑两侧的断裂带,它具有糜棱岩化特征,对孕震过程具有控制作用.这些因素结合构成发震构造模型,它能解释大陆活化克拉通与裂谷地堑地区发生地震的原因。应用数值模拟对所提出的模型进行了检验。

关键词: 克拉通 裂谷地堑 地震构造模型

SEISMOTECTONIC MODELS FOR THE CONTINENTAL AREAS ASSOCIATED WITH REACTIVATED CRATONS AND RIFTING GRABENS

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Abstract

It is often observed that there are separated graben structures in the reactivated cratons where rifting occurred during different periods of their evolution. Some of these grabens behave as present－day active seismic zones, such as the Linfen graben, Shanxi, China; the Xingtai graben, Hebei, China; and the New Madrid graben, the United States. Increasing data have demonstrated that the causes of earthquakes in these areas are involved with many geological and geophysical conditions besides the active fauting. As a typical case, studies on the Linfen graben show that the seismogenic process is associated with the following factors: (1) The metamorphic rocks with greater strength around the graben, in which stress is built up under the action of the regional tectonic stress field. (2)The medium of the seismogenic layer with lower strength at the depth range of 5－15 km within the graben, which ruptures during the seismic source process to release energy and radiate seismic waves. (3)The abnomal layer with low velocity or low resistance beneath the seismogenic layer, which has the ductle adjusting function to the seismic source process. (4)The fault zones along the both sides of the graben, which are characterized by mylonitization and have controlling effects on the process of earthquake brewing. The combination of these elements offers seismogenic models which can explain the causes of some seismic zones in the continental areas associated with reactivated cratons and refting grabens. Numerical modeling has been used to test the proposed models.

Key Words: Craton; Rifting graben; Seismotectonic model

1 INTRODUCTION

The earth is a deformable body, and the ultimate cause of earthquakes is material deformation driven by relative displacements arising from large－scale plate motions. Such deformation processes occur in a wide variety of geological environments and have different styles of faulting.

Characterization of seismogenic faults in intrapladte **areas**, such as Eastern China and the central and eastern United States, is a formidable problem because of general absense of the relationship between seismicity and geological structures with clear surface expression.

Some hypotheses have been proposed to explain the causes of intraplate earthquakes. The most viable one is the 'zone of weakness model' which was originally suggested by Sbar and Sykes (1973) and Aykes (1978). Sccording ɔ this model, contemporary earthquake activity is caused by reactivation of ancient faults and other boundaries within the crystalline crust which are presently subjected to the action of an appropriately directed regional stress field. Although increasing evidences from the continental interiors support this model, many problems remains in some details, such as the special occurrence of earthquakes with regard to specific geological structures and their mechanism.

Jonston and Kanter(1990) found that some major earthquakes occurred in association with Mesozoic/Cenozoic continental rifts imbedded in the stable continental regions. This evidence provides an important tectonic framework for the 'zone of weakness model'. In this study direction we will develop more specific seismotectonic models for the continental areas associated with reactivated cratons and rifting grabens. Examples include the Xingtai area, Hebei, China; the Linfen area, Shanxi, China and the New Madrid seismic zone, the United States. Numerical modeling is used to analyse the stress localization which can justify the proposed seismogenic models. Attempts are also made to explain physically why earthquakes are more likely to occur in rifting grabens than in adjacent areas.

2 GEOLOGICAL SETTINGS

The Xingtai area is situated in the North China plain, southwest Beijing, where four major earthquakes (M=6.8, 6.7, 7.2, 6.2) occurred in 1996. The Linfen area at the south of the Shanxi plateau is also most seismically active (M=8, 1303; M=8, 1695). Both the areas are geologically parts of the North China precambrian plateform, which is the most ancient and completely cratonized part of China. During Cenozoic time this stable block experienced a series of extentional events which fragmented the craton to form a number of intracratonic grabens (Ma et al., 1982). The Shanxi graben is associated with the central extention of the uplifting Shanxi plateau, while the North China plain is characterized by rifting, regional subsidence and igneous activity in the grabens. Epicenters of major earthquakes are located within the grabens for both the areas (Fig. 1). Fault plan solutions of all four Xingtai events show primarily strike-slip faulting with right-lateral slip on NNE trending planes, while seismic reflection data reveal the existence of listric normal faults in the grabens. Geodetic data imply long-term vertical crustal movement and predominant horizontal displacements of coseismic deformation for the Xingtai area.

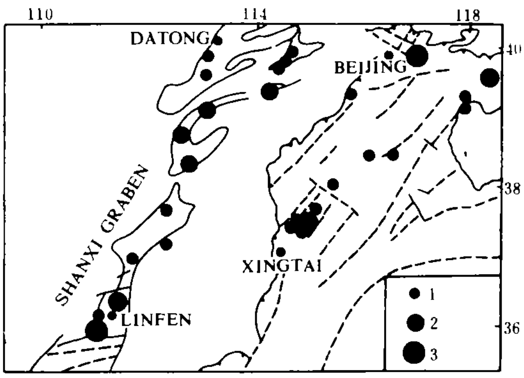

Fig. 1 Sketch map showing the tectonics of Eastern China and the locations of the Xingtai and Linfen areas.
1. M=6.0−6.9; 2. M=7.0−7.9; 3. M=8

The New Madrid seismic zone is the site of the devastating earthquakes in 1811−1812. It is located at the central midcontinent which is a part of the North American plate. This area is at present a relatively stable craton. However, it has had a long, complicated history of tectonic activity including Precambrian rifting and igneous activity. Along the New Madrid seismic zone, geophysical data have outlined a NE trending crust rift at depth of 5km and greater beneath the modern surface. This rift is thought to have been first activated in late Precambrian and (or) early Paleozoic time and also shows the contemporary seismicity to be closely associated with faults within the rift zone. Expression of faults or other tectonic features that might be responsible for the seismicity is concealed by the sediments of the Upper Mississippi embayment. The focal mechanisms consistently show right-lateral strike-slip motion on NE trending fault planes(Fig. 2) (Zoback et al. .1980).

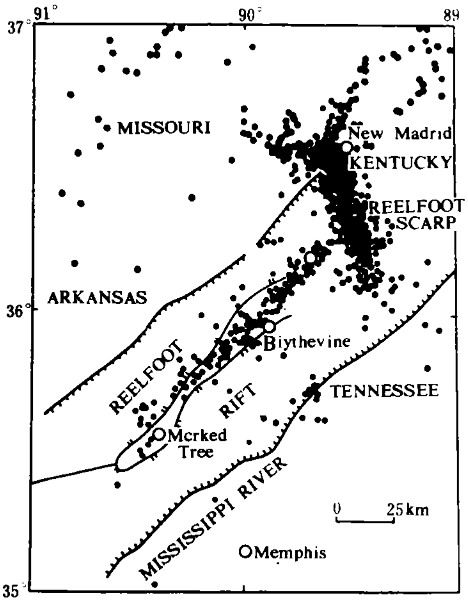

Fig. 2 Geological setting and seismicity of the New Madrid seismic zone of the United States.

The above three examples represent the continental areas associated with reactivated cratons and rifting grabens. They are far away from the direct influence of plate boundary tectonics. The pattern of seismicity defines a main concentration of activity within the rifts or grabens, while there are also transverse faults, uplifts and seismic zones intersecting with the main trend of grabens. Fault plane solutions of earthquakes show the uniform stress field over large regions which is characterized by horizontal compression and reflects the deformation style of deep seated crust. On the other hand, geological and geodetic data demonstrate that vertical crustal movement is predominant for tectonics, which is consistent with normal faults and extentional deformation on the surface.

3 SEISMOTECTONIC MODELS

The synthesis of earthquake, geophysical, geodetic and geological data enables us to deduce the tectonic framework of the seismic regions associated with reactivated cratons and rifting grabens within continents. We propose the seismtectonic models for the Xingtai and Linfen areas, China, respectively (Fig. 3,4). The model for the New Madrid seismic zone suggested byy Hinze et al. (1982) is also cited (Fig. 5) . With these models we can offer the following explanations:

(1)For some relatively stable continental interiors, major earthquakes may result from reactivation of pre-existing zones of weakness due to localized stress build up. This is in response to the action of the ambient stress field whicl is generally uniform over large regions and originated from the contemporary plate motion.

(2)The pre-existing zones of weakness are mostly located within the Cenozoic grabens or acient rifts. They are the results of rifting processes of cratons during different geological times and characterized by extensional deformation near the surface.

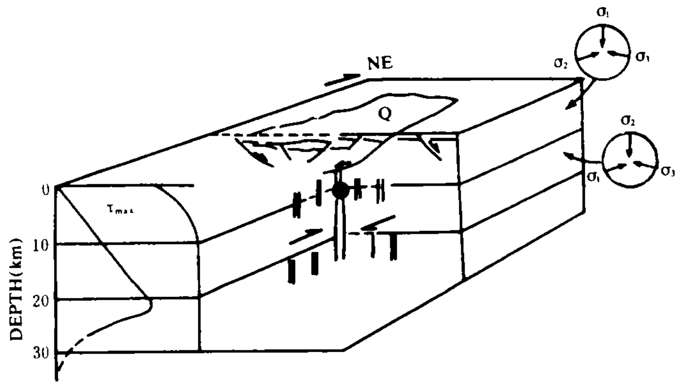

Fig. 3 Seismotectonic model for the Xingtai area, China.

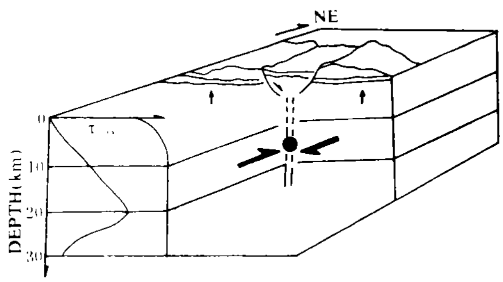

Fig. 4 Seismotectonic model for the Linfen area, China.

(3) The main shocks are caused by strike-slip motion on a steeply dipping fault suitably oriented with respect to the present-day maximum horizontal stress. Sometimes co-seismic components of normal faulting have been observed, while aftershocks may behave with reverse fault motion.

(4) The greatest concentration of seismic activity is along the axis of the graben or rift. The epicenters of major events are usually near the intersection of two main faults which are approximately perpendicular to each other. At the edges of the graben there are relative uplifts of older and rigider blocks which may constrain active grabens.

(5) The physical origin of earthquakes in these areas not only lies in the deformation processes of any active fault zones, but also is associated with many structural factors in addition to faults. For example, the seismogenic process of the Linfen area is related to the following conditions: (a) The metamorphic rocks with greater strength around the graben, in which stress is built up by the action of the regional tectonic stress field. (b) The medium with lower strength of seismogenic layer at the depth of 5—15km within the graben, which ruptures during the seismic source process to release energy and radiate seismic waves. (c) The abnormal layer with low velocity or low electric resistance beneath the seismogenic layer, which has the ductile adjusting function to deformation of the upper crust, and (d) The fault zones along the both sides of the graben, which are characterized by mylonitization and impose controlling effects on the process of earthquake brewing within the graben.

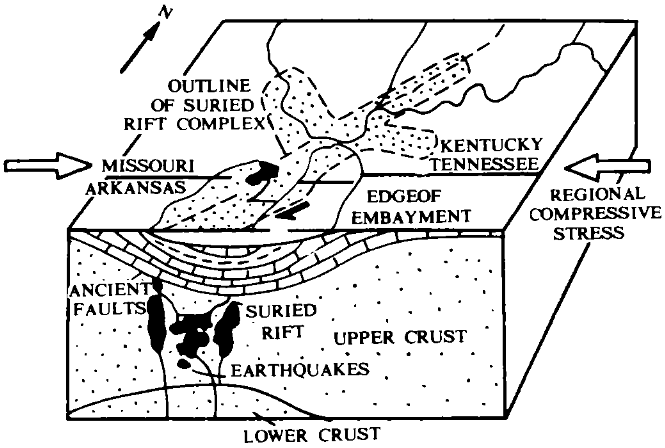

Fig. 5　Schematic block diagram of New Madrid rift complex region (after Hinze et al. , 1988).

4　NUMERICAL MODELING

We have carried out numerical modeling to test the proposed seismotectonic models. Our purpose is to explain the mechanism of stress accumulation within the seismogenic layer of the crust. A 3-D finite element model was designed for the stress modeling (Fig. 6). Mechanical parameters were assigned to elements which make the upper part of the model behave elastically and the lower part plastically. A pair of horizontal compressive forces were applied on the boundaries to simulate the regional tectonic stress. The finite element program ADINA (Bathe, 1975) was adopted to calculate stresses. First, the normal distribution of the maximum shear stress at depth of 15km was obtained with horizontally homogeneous model. Then this normalized shear stress was subtracted from the corresponding results of modified models to show changes of stress due to heterogeneity.

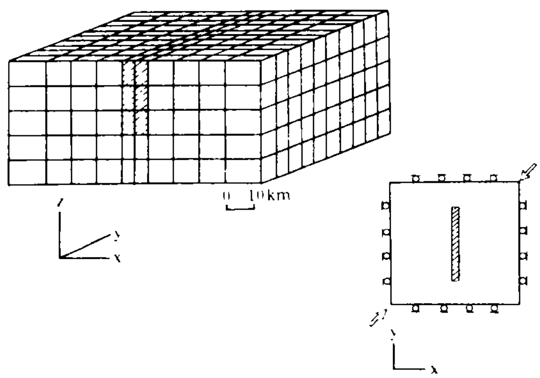

Fig. 6　The 3-D finite element model. Shaded part shows the position of the zone of weakness in the crust.

When the weak zone was assigned by a lower Young's modulus (1/10 of the initial model), a zone of stress decrease in line with the applied load was observed. On the both ends of the weak zone, however, the maximum shear stress was increased by 50% relative to the normal model (Fig. 7a). If the model with a weak zone was added a rigid constraint on the side boundary, a stronger stress concentration appeared near the weak zone (Fig. 7b). These results demonstrate that the local crust inhomogeneity could lead to redistribution of tectonic stress. The zone of weakness in the crust may be the important cause of localized stress accumulation, although the weak zone itself would be the potential site of seismic rupture.

5 CONCLUSIONS

A summary of data and interpretation that pertain to tectonic framework of continental areas associated with reactivated cratons and rifting grabens is given in this paper. The seismotectonic models for the Xingtai and Linfen areas, China are proposed in comparison with the New Madrid seismic zone of the United States. They could help to delineate critical information that is needed for understanding the causes of intraplate earthquakes.

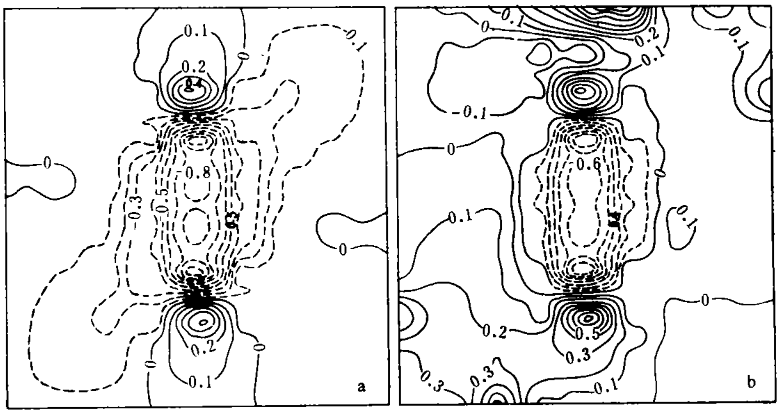

Fig. 7 Calculated maximum shear stress changes in normalized form.
(a) Model with weak zone;
(b) Model with weak zone and rigid constraint at one side boundary.

In the interiors of some continents, such as Eastern China and the eastern United States, it is hard to relate large earthquakes to mapped active faults on the surface. Most epicenters are located within the grabens or rifts. Increasing evidences support the hypothesis that continental crust weakened by rifting is a necessary precondition for major seismogenesis in the stable continents. The zones of weakness in the graben or rift can become the potential sites of seismic rupture under the action of the regional tectonic stress.

The results of 3-D numerical modeling offer a test to the proposed models. They demonstrate that the existence of weak zone in the crust is an important reason of localized stress concentration. The relatively rigid proporties near the ends of the weak zone, as observed uplift blocks at the edges of grabens, make major contributions to stress accumulation associated with seismogenic processes. This means that the active grabens or reactivated acient rifts whthin the continent, and combined with appropriate tectonic stress determine the locations of major intraplate earthquakes. It should be of great importance for efforts at long-term forecasting of earthquakes hazards.

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