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渭河盆地东南缘主要断裂晚更新世以来的活动性及灾害效应

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渭河盆地是中国中部地区一个重要的新生代断陷盆地, 也是一条重要的地震活动带, 属于汾渭地震带的一部分。中国西部政治、经济、文化中心西安就位于其上。渭河盆地东南缘活动断裂非常发育、地震活动频繁, 而且有 1556 年华县 8 级特大地震发生的背景。华县大地震是发生在高角度正断层上为数不多的强震之一, 并且其发震构造目前还存在争议。华山山前断裂为正断型活动断裂, 是研究正断型活动断裂与其灾害效应的典型实例。本论文通过对正断型断层活动与大地震及其灾害关系的研究, 为评价西安等重要城市群的稳定性提供科学依据。

本论文以详细的野外地质调查为基础, 将剖面测量、大比例尺填图、露头观测、光释光(OSL)测年、同位素 ^{14}C 测年、电子自旋共振(ESR)测年、室内编图等手段和方法有机结合, 深部资料和地表调查相结合, 探讨渭河盆地成因机制, 分析构成渭河盆地东南缘构造格局的 NE 走向的临潼–长安断裂、NW 走向的浐河断裂和近 EW 走向的华山山前断裂、渭南塬前断裂、秦岭北缘断裂以及铁炉子断裂的切割关系、几何学、运动学特征, 进而探讨渭河盆地东南缘主要活动断裂与相关地质灾害的关系。

1 临潼—长安断裂晚更新世以来活动性分析

临潼—长安断裂带位于渭河盆地东南部, 呈北东—南西向展布于铜人塬、白鹿塬、少陵塬和神禾塬等塬前, 主要由麻街—碾湾断裂和胡家沟—首帕张断裂两条次级断裂组成。塬面整体向西北倾斜, 塬前的黄土陡坎展布与临潼—长安断裂带的展布基本一致。临潼—长安断裂带以灞河、皂河为界, 可以分为北东、中、南西三段。沿断裂带也有过地震活动, 即: 公元前 35 元 7 月 9 日发生在断裂西北的铜人塬 $M_S5^3/_4$ 和 1568 年 4 月 11 日临潼的 $M_S5^1/_2$ 的两次中强地震。由于临潼—长安断裂带穿越西安东南部并有过地震灾害发生, 引起了众多学者对临潼—长安断裂活动特征的关注。一种观点认为晚第四纪以来临潼—长安断裂带北东段较西南部分活动性强; 另一种观点认为断裂带中段晚第四纪以来活动性较为强烈, 而断裂带北东段和西南段活动强度相对较低。

为了确定临潼—长安断裂带晚更新世以来的活动性, 本研究以黄土 S_1、L_{1S} 和 S_0 为确定垂直位移的标志和年代标尺, 通过 DEM 地貌分析、断层露头调查, 结合地壳形变资料, 断层切割黄土—古土壤的时间标尺、断层垂直断距与全新世以来的活动情况、地壳形变数据及古地震等分析表明: 晚更新世以来临潼—长安断裂带在灞河以东的铜人塬(北东段)活动性最强, 中段的白鹿塬、少陵塬活动强度其次, 西南部的神禾塬和沣峪口一带活动性较弱, 与 DEM 显示的现今断裂带上下盘的地貌差异有很好的吻合性。预测临潼—长安断裂带未来在北东段(铜人塬), 特别与渭河断裂结合部位发生地震的危险性较大。

2 华山山前断裂晚更新世以来活动性与华县大地震

华山山前断裂分布于华山北部山前, 沿华山山前呈北东—北东东—东南向延伸, 属正断层。沿断裂带, 发育清晰的断层三角面, 断面延续性较好, 地势变化大, 并分布多次地震, 特别是 1556 年的华县 8.0 级大地震。根据断裂走向、地貌类型和活动性, 由东向西可将华山山前断裂划分为东段(灵宝—孟塬段)、中段(杜峪—石堤峪段)和西段(石堤峪—

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流峪口段)三段。

华山山前断裂东段和西段在晚更新世有过强烈活动，在全新世活动不明显。华山山前断裂中段发育清晰的断层三角面、跌水、断层陡坎等构造地貌。根据野外露头调查、年龄测定，识别出华山山前断裂中段全新世的多次古地震事件，即 8 590~7 570 a BP 两次、7 570 to 6 180 a BP 一次、5 610 a BP、2 715 a BP(2 500~3 000 a BP)以及 AD1556a 等 6 次古地震事件。根据断裂切割洪积扇和第四纪地层计算得到华山山前断裂中段中长期倾滑运动速率约为(0.64±0.05) mm/yr，全新世倾滑运动速率约为1.67~2.71 mm/yr，华山山前断裂中段不但在晚更新世有过强烈活动，而且在全新世继续强烈活动。

在渭南赤水河东的河河漫滩的砂石采坑发现了两个渭南塬前断裂经过的露头剖面，两个剖面上均发现约(6 865 ± 80) calyrB.P.的地震楔，上覆于地震楔之上的全新世未见错动的地层测得的最大 ^{14}C 年龄为(3 123 ± 33) yrB.P.。指示(6 865 ± 80) calyrB.P.以后该断裂带未活动过，确切的说(3 123 ± 33) yrB.P.截至现在，该处断层未见明显活动。根据渭南塬前断裂切割第四纪地层和河流阶地，估算得到渭南塬前断裂中长期倾滑运动速率约为 0.32~0.42 mm/yr，全新世倾滑运动速率约为 0.58 mm/yr。

根据以上分析，华山山前断裂中段在全新世的活动速率远远大于渭南塬前断裂的全新世活动速率，并且华县 1556 年的地震破裂未从渭南塬前断裂经过。据此推断，华县大地震的发震断裂可能不是渭南塬前断裂，而与华山山前断裂中段有关。

3 华县莲花寺多期滑坡、崩塌研究

陕西华县莲花寺有一面积较大的混杂堆积物，其位于华山山前断裂带上，由于其特殊的构造位置和周边地区活跃的中强震的发生，对于其形成时间和成因机制存在较大的分歧。

为了查明陕西华县莲花寺混杂堆积物的成因和期次，在滑坡区进行了 1:5 万活动断裂填图，并结合黄土光释光年龄测定和混杂堆积物的特征，厘定了莲花寺混杂堆积物里包含两次古滑坡和两次地震诱发的崩塌等 4 次灾害事件。这就是说，陕西华县莲花寺滑坡具有 2 次早期滑动，后期又叠加了崩塌作用，即莲花寺的混杂堆积物里包含两次古滑坡和两次地震诱发的崩塌。根据覆盖在大套堆积物之上稳定堆积的黄土 5 个剖面的光释光年龄测定，得到陕西华县莲花寺黄土层之下的混杂堆积物不是 1072 或1556年地震造成的，而是形成于18.7万年前的两次古滑坡，是目前国内报道最老的高速远程古滑坡，并推测高速远程滑坡的诱因可能是华山山前断层的地震活动。散落地表的滚石与 1556 年华县大地震有关；混杂堆积的黄土之上有掩埋在浅层坡积物之间的杂乱滚石应该是 1072 年地震造成的滚石。

4 正断型活动断裂及其灾害效应

渭河盆地活动断裂主要表现为 EW 走向断裂系、NE 走向断裂系、NNE 走向断裂系、NW 走向断裂系；根据野外调查和擦痕测量，除铁炉子断裂为明显的左旋走滑性质外，其余断层均主要表现为正断层性质。渭河盆地东南缘甚至整个渭河盆地地质灾害非常发育，地裂缝、滑坡、崩塌和泥石流常有发生。断裂的活动方式不同，地质灾害分布的主要部位和灾害的类型也不一致。这些灾害的发育与分布与渭河盆地的活动断裂空间展布和活动方式具有一定的关系。

华山山前断裂带作为断距大并在晚第四纪以来强烈活动的正断层，其上下盘的灾害分布特征具有明显的不同。在断裂以北的上盘，主要分布着一些平行于断裂走向的地裂缝。上盘由于为地势平缓的平原区，人类居住密集、活动频繁。地震灾害发生时，断裂上盘的人类密集区也成为灾害最严重，损失最大的地区。华县 1556 年大地震发生时，造成的灾害主要分布在渭河平原区的人类活动密集区。在华山山前断裂带的下盘为华山山地区，主要的灾害类型为滑坡、崩塌和泥石流等灾害。崩塌主要发生在华山北坡的 45° 以上的陡峭斜坡上。

5 渭河盆地成因模式与孕震机制

渭河盆地不是某一应力场下一次构造作用形成的，它是在深部地幔上隆和浅部多阶段多方位拉张应力叠加作用下的产物。其深部动力学与地幔上隆和存在切穿 Moho 面的深断裂有关，为简单剪切模式。渭河盆地不但地幔上隆，而且存在低速高导层，主要断裂在低速高导层交汇，并存在莫霍断裂，是未来发生强震的重要地区。

6 论文研究意义

论文详细研究了渭河盆地东南缘的断裂活动特征以及几何学、运动学特征，对重点活动断裂晚更新世以来活动特征进行了详细分析，并探讨了正断型活动断裂的灾害效应，提出了渭河地堑动力学模式，对研究该地区的地壳稳定性、城市规划和经济建设提供了新的资料。

关键词: 渭河盆地; 活动断裂; 华县地震; 莲花寺古滑坡; 华山山前断裂; 灾害效应
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Activity of Main Faults since the Late Pleistocene and Related Geohazard Effects in Southeast of Weihe Basin

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Weihe Basin is not only one important Cenozoic rift basin, but also one significant seismically active belt belonged to Fenhe–Weihe seismic zone in central China. Xi'an city is located on Weihe Basin, and it is the center of political, economic and cultural of western China. There are many active faults and earthquakes in Weihe Basin. Huaxian county 8.0 earthquake in AD1556 is a key earthquake and occurred in the high angle normal faults of Weihe Basin. The seismogenic structure of Huaxian earthquake is still controversial. Huashan piedmont fault is one high angle normal faults and maybe related to Huaxian earthquake. Thus, Huashan piedmont fault is a typical example of study relationship of normal fault and its disaster activities. This paper provide scientific basis for the stability evaluation of Xi'an city to study the relationship between fault activity and its earthquake and others disaster.

This study is based on detailed geological survey, and combine many means and methods, such as profile measurement, large scale mapping, outcrop observation, OSL dating, ^{14}C isotope dating, ESR dating, indoor mapping. Using Geophysical data and surface survey, the author analysis the relation and the characteristics of geometry and kinematics of those faults of the Weihe Basin southeastern, and to explore the Weihe Basin formation mechanism and the relationship between activity faults and related geological disasters. In the end, the following conclusions and understanding can be got.

1 Activity of Lintong–Chang'an Fault Belt since the Late Pleistocene

Lintong–Chang'an fault belt consist of Majie–Nianwan fault and Hujiagou–Shoupazhang fault and distribute on the northwest of Tongren, Bailu, Shaoling, and Shenghe Loess Tableland with NE–SW trending in the southeastern of the Weihe Basin. Those loess tableland surfaces all tilted to the northwest. The position of loess scarp is basically the same as the distribution of Lintong–Chang'an fault belt. Lintong–Chang'an fault belt can be divided into northeast section, center section and southwest sections by Bahe River and Zaohe River. Many scholars pay attention to the activity of Lintong–Chang'an fault due to the fault belt across the southeastern Xi'an and there ever occurred two moderate earthquakes along the Lintong–Chang'an fault belt. A point of view is that the activity of the northeast section is stronger than the center section and the southwest section since the Late Quaternary; another view is that the activity of the center section is strongest among three sections.

By means of DEM geomorphological analysis, the fault outcrop survey and combined with the crustal deformation data, and the result shows that activity since the late Pleistocene of the northeastern section in Tongren Loess Tableland is the strongest in the Lintong–Chang'an fault zone, the central section in Bailu and Shaoling Loess Tableland is second and the southwestern section in Shenhe Loess Tableland and Fengyu area is the weakest. Author forecast there is earthquake risk in the future in Tongren Loess Tableland area in the northeastern section of Lintong–Chang'an fault belt.

2 Activity of Huashan Piedmont Fault since the Late Pleistocene and Huaxian 8.0 Great Earthquake

Huashan piedmont fault is normal fault with a NE～NEE～ES direction distributing in the northern of Huashan Mountain. Along the fault zone, there are clear fault triangular facets. The continuity of those fault triangular facets is good. The terrain of hanging wall and footwall changes great. There are many earthquakes along fault zone, especially the AD 1556 Huaxian 8.0 earthquake. According to the fault strike, landform and activity, Huashan piedmont fault can be division east section (Lingbao–Mengyuan section), center section (Duyu–Shidiyu section) and west section (Shidiyu–Liuyu section).

The East and West sections had strong activities during the late Pleistocene, but activity is not obvious during the Holocene. The center section has a strong activity during both late Pleistocene and Holocene. Long-term dip-slip rate of center section is about (0.64±0.05) mm/yr; the dip slip rate during Holocene is about (1.67~2.71) mm/yr. Along center section, there are still clear and complete fault triangular facets, waterfall and fault cliff. According to outcrop survey and geological-age determination, the author identify Holocene multiple paleo-seismic events in Huashan piedmont fault zone, namely twice between 8 590~7 570 a BP, 7 570 to 6 180 a BP, 5 610 a BP, 2 715 a BP or (2 500~3 000 a BP) and AD1556a etc.

In two trench of Chishuihe river of Weinan city, author discovers about (686.5 + 80) calyrB.P. earthquake event. The layers up earthquake wedge still keep intact and its oldest geological age is (3 123+33) yr B.P. North Margin fault of the Weinan Loess Tableland just passes the two trenches. This appearance indicates that North Margin fault of the Weinan Loess Tableland has not obvious activity after (3 123+33) yrB.P.. According to North Margin fault of the Weinan Loess Tableland cut the Quaternary strata and river terraces, author calculate and get dip-slip rate of North Margin Fault of the Weinan Loess Tableland. The long-term dip-slip rate of North Margin Fault of the Weinan Loess Tableland is about 0.32~0.42 mm/yr, and the dip-slip rate Holocene is about 0.58 mm/yr.

The dip-slip rate Holocene of Huashan piedmont fault is far greater than North Margin Fault of the Weinan Loess Tableland. The Huaxian 8.0 earthquake rupture has not passed the distribution area of North Margin Fault of the Weinan Loess Tableland. Based on those evidence, the following conclusions are obtained that North Margin Fault of the Weinan Loess Tableland is not seismic fault of 1556 Huaxian M_w8 earthquake, and seismic fault may be related with the center section of Huashan piedmont fault.

3 Study on the Origin and Times of Lianhuasi Mass Accumulation

There are mass accumulations on the hanging wall of Huashan piedmont fault in Lianhuasi area of Huaxian County Shaanxi Province. Due to its special tectonic location and strong earthquakes occurred surrounding areas, there are great arguments about its formation time and forming mechanism.

In order to find out cause of mass accumulation of Lianhuasi area, the author have made a geological mapping with 1:5 million scale and combined with loess OSL age, identify Lianhuasimass accumulation containing two ancient landslide and two collapse induced by earthquake. The accumulation under loess layer is not caused by AD1072 or AD1556 earthquake, and it is the oldest reported high-speed and long runout ancient landslide 18.7 million years ago. The inducement of ancient landslides may is one seismic activity on Huashan piedmont fault. The rolling stones Scattered on the surface is collapse accumulation caused by Huaxian 8.0 earthquake in AD1556. Those rolling stones buried shallow is caused by earthquake in AD 1072.

4 Normal Active Fault and Its Related Geohazard Effects

Active faults in the Weihe Basin are made up of EW trending fault system, NE—NNE strike fault system, NW trending fault system. Among of those faults, except Tieluzi fault is a left lateral strike-slip fault, the rest of the faults show normal fault. There are frequently geohazards in southeastern of Weihe Basin. Those geohazards include ground fissure, landslide, collapses and mud flow. The distribution of geologic hazards along a fault often varies with the type of the fault. Development and distribution of those disasters have certain relationship with the spatial distribution and activity way of active fault in Weihe Basin.

The Huashan piedmont fault is a highly active normal fault during the late Quaternary; however, the disasters that have occurred due to the fault have been distributed significantly differently among the hanging wall and footwall. Ground fissures parallel to the strike of the fault are mainly distributed on the northern (hanging) wall of the fault. The hanging wall area is a wide plain with a high population density. Therefore, during an earthquake, the hanging wall will incur the most damage and largest losses. The disasters caused by the Great Huaxian County Earthquake of 1556 were mainly distributed in the Weihe plain area, where human activity was concentrated. The footwall of the Huashan piedmont fault is the mountainous area of the Huashan Mountains; disasters that occur in the footwall mainly include landslides, collapses and mudslides. Collapses mainly occur on steep slopes with gradients of more than 45° on the northern slope of the Huashan Mountains.

5 The Formation and the Seismogenic Mechanism of Weihe Basin

The formation of Weihe Basin is not in only one structural stress field and is the product of the deep mantle uplift and shallow multi stage and multi direction under the action of tensile stress superposition. The mechanics model of formation is a simple shear model. Its deep dynamics related to mantle uplift and the deep fracture of the upper mantle and the Moho surface. Because Weihe Basin is not only the mantle uplift but have the low velocity layer, and the main fault convergence in the low velocity and high conductive layer and the existence of Moho fault, there is an important area of strong earthquakes risk in the future.

6 Research significance

In this paper, author detail the geometry and kinematic characteristics of those active faults since the Late Pleistocene in the southeastern margin of the Weihe Basin, discusses the normal fault and the geological hazard effects, and build the dynamics model of the Weihe Graben. Those researches are new data for crustal stability and urban planning and economic construction of Xi’an area.

Key words: Weihe Basin; active fault; Huaxian earthquake; Lianhuasi ancient landslide; Huashan piedmont fault; geohazard effects

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