

引用格式: 张波, 王爱国, 姚赞胜, 等, 2025. 2023 年积石山 M_s 6.2 地震的地震裂缝及其成因机制 [J]. 地质力学学报, 31 (2): 211–222.
DOI: [10.12090/j.issn.1006-6616.2024114](https://doi.org/10.12090/j.issn.1006-6616.2024114)

Citation: ZHANG B, WANG A G, YAO Y S, et al., 2025. Earthquake-induced fissures and their formation mechanisms in the 2023 M_s 6.2 Jishishan Earthquake [J]. Journal of Geomechanics, 31 (2): 211–222. DOI: [10.12090/j.issn.1006-6616.2024114](https://doi.org/10.12090/j.issn.1006-6616.2024114)

2023 年积石山 M_s 6.2 地震的地震裂缝及其成因机制

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Earthquake-induced fissures and their formation mechanisms in the 2023 M_s 6.2 Jishishan Earthquake

Abstract: [Objective] Seismic fissures, landslides and mudflows are common secondary hazards of earthquakes. Following the occurrence of moderately strong earthquakes, detailed investigations of landslides and mudflows are usually conducted, but earthquake-induced fissures often receive less attention, because the characteristics and causes of earthquake-induced fissures are controlled by a combination of factors. The 2023 M_s 6.2 Jishishan Earthquake formed an extensive and dense earthquake-induced fissure zone in the Jishishan Mountain front and the interior of the Linxia Basin, but there are large differences in the understanding of the genetic mechanisms of earthquake-induced fissures. [Methods] In order to better understand the characteristics and genetic mechanisms of earthquake-induced fissures in the Jishishan Mountains, 246 fissures were systematically investigated by field observation, statistical analysis, and drone photogrammetry; then, the distribution, characteristics and genetic mechanisms of the earthquake-induced fissures were analyzed. Combined with relevant published studies, the following new findings are made. [Results] First, the 2023 M_s 6.2 Jishishan Earthquake formed a large number of fissures in the VII-VIII degree zone, which can be generally divided into two categories: tectonic-related fissures and non-tectonic fissures, and the non-tectonic fissures are further divided into ridge gravity fissures, landslide-related fissures, and valley fissure-sand liquefaction combinations on the basis of the topography associated with these fissures. Second, the tectonic-related fissures developed along the eastern margin fault of the Jishishan Mountains, with fissure widths at the cm-mm level. The tectonic-related fissures extend through fault planes, joints, and other weaknesses of the Jishishan fault zone, clearly showing that the more than 100 m wide fracture zone (i.e., weak zone in the upper crust) of the eastern margin fault of the Jishishan Mountains dominates the distribution of the earthquake-induced fissures. Meanwhile, the tectonic-related fissures tend to develop at weaknesses in man-made structures, such as road seams and bridge joints; this “weakening-preferred” behavior indicates that these fissures are generated by seismic shaking effects on the fracture zone along the fault, rather than direct rupture by the earthquake-causing fault. Thus, the tectonic micro-fissures are not the surface ruptures mentioned above. Third, the non-tectonic fissures mainly developed in the loess-covered area around the Dahejia-Kexinmin-Ganhetan villages north of the epicenter, where the topography is hilly, predominantly tableland and valleys; ridge (tableland) gravity fissures are large in scale,

基金项目: 中国地震局地震科技星火计划 (XH23040A, XH19045Y); 科技部第二次青藏高原综合科学考察研究专题 (2019QZKK0901); 国家自然科学基金项目 (42372267, 42072246, 41602225); 中国地震局地震预测研究所基本科研业务费专项 (2021IESLZ06)

This research is financially supported by the Spark Program of Earthquake Technology of China Earthquake Administration (Grant Nos. XH23040A and XH19045Y), the Second Tibetan Plateau Scientific Expedition and Research Program (STEP), Ministry of Science and Technology (Grant No. 2019QZKK0901), the National Natural Science Foundation of China (NSFC) Projects (Grant Nos. 42372267, 42072246, and 41602225), and the Basic Scientific Research Special Project of the Institute of Earthquake Forecasting, China Earthquake Administration (Grant No. 2021IESLZ06).

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收稿日期: 2024-11-01; 修回日期: 2025-02-17; 录用日期: 2025-02-19; 网络出版日期: 2025-02-24; 责任编辑: 吴芳

extend far along the ridge, and exhibit a combination of reticulation, parallelism, or an echelon style; landslide-related fissures on the slopes are comparatively smaller in scale and confined to the landslide area; valley fissures are comparable in scale to tectonic micro-fissures and generally formed in association with sand liquefaction; the fissure widths decrease from dm scale on the ridges (tableland) to mm scale in the valleys. Fourth, the tectonic-related micro-fissures healed naturally within approximately half a year, while the healing of the ridge gravity fissures lasted much longer; some landslide-related fissures may take a long time to heal naturally and may even form permanent displacements that pose a serious threat to people and require repair. [Conclusion] By reviewing and analyzing the distribution, types, and genetic mechanisms of earthquake-induced fissures in the 2023 $M_s6.2$ Jishishan Earthquake, and taking into account the magnitude, the epicenter depth, and minor surface displacements, it is speculated that no surface ruptures formed during the Jishishan Earthquake. [Significance] An overview of the earthquake-induced fissures of the Jishishan Earthquake is of great significance for understanding the causal mechanisms of secondary earthquake disasters, analyzing seismotectonics, and proposing disaster mitigation strategies.

Keywords: earthquake-induced fissures; Jishishan Earthquake; eastern margin fault of Jishishan Mountains; geological hazards of earthquakes; surface rupture

摘要: 2023年积石山 $M_s6.2$ 地震在地表形成了大量的地震裂缝,但对地震裂缝的成因认识存在较多分歧。为了更好地认识中强地震中地震裂缝的发育特征及其成因机理,采用野外观测、统计分析、无人机摄影测量等方法,系统调查积石山地震形成的246条地震裂缝,总结其发育特征和成因机理。研究显示:2023年积石山 $M_s6.2$ 地震在 VII—VIII 度区内形成了大量的地震裂缝,总体可分为构造微裂缝和非构造裂缝两类,非构造裂缝又包括山脊重力裂缝、滑坡边缘裂缝和沟谷裂缝-沙土液化组合。构造微裂缝沿积石山东缘断裂发育,宽度为厘米~毫米 (cm~mm) 级,通过断层面、节理面等介质软弱部位,表现为构造对裂缝的控制作用,裂缝同时具有“趋弱”的特点,说明此类裂缝不是断层直接错动地表而形成。非构造裂缝主要发育在震中北侧的黄土丘陵和台塬-沟谷区,山脊(台塬)部位的裂缝规模大、延伸远,从山脊(台塬)向下经山坡至沟谷,裂缝宽度从分米(dm)级降低为毫米(mm)级。构造微裂缝经过约半年时间已基本自然愈合,非构造裂缝的愈合时间远长于构造微裂缝的愈合时间;一些滑坡边缘裂缝可能难以自然愈合而形成永久位移,而对人类造成严重威胁的裂缝,需要人为修复。对2023年积石山 $M_s6.2$ 地震裂缝的分布、类型和成因机制的分析表明,2023年积石山 $M_s6.2$ 地震没有形成地表破裂带。对积石山地震的地震裂缝的综合研究对于地震次生灾害的研究、灾害损失减轻和地震构造分析具有重要意义。

关键词: 地震裂缝; 积石山地震; 积石山东缘断裂; 地震地质灾害; 地表破裂

中图分类号: P694 **文献标识码:** A **文章编号:** 1006-6616(2025)02-0211-12

DOI: 10.12090/j.issn.1006-6616.2024114

0 引言

地震裂缝是指地震震动在地表产生的裂缝,是一种常见的地震次生灾害,中强地震发生后,通常会在地表形成多种成因的地震裂缝,造成严重的人员伤亡和财产损失(张业成等, 2012)。与地震构造明确相关的地震裂缝,如走滑型地表破裂带上的雁列状地震裂缝,受到较多关注。如2021年青海玛多 $M_s7.4$ 地震和2022年青海门源 $M_s6.9$ 地震在地表形成了典型的雁列状的张裂缝-挤压鼓包组合,指示走滑为主的破裂特征(刘璐等, 2022; 刘小利等, 2022; Li et al., 2023; 陈锡锐等, 2023; 袁道阳等, 2023)。未形成地表破裂的中强地震,地震裂缝的分布和发育受构造、地貌、第四系分布等多种因素

的影响,地震裂缝的裂开机制复杂,并且难以通过地震裂缝的研究获得地震构造的性质和参数,因此现有研究对此类地震裂缝的关注较少。

2023年甘肃省积石山 $M_s6.2$ 地震就是1次未形成广泛认可的地表破裂带的地震,地震裂缝广泛分布在积石山山前和临夏盆地内部。学者们在讨论积石山地震的同震地质灾害(泥石流、滑坡、沙土液化、地震裂缝等)时,将地震裂缝当作一类常见的地震次生灾害,由地表震动引起(郭富赟等, 2024; 刘传正等, 2024; 刘帅等, 2024; 徐岳仁等, 2024; 许强等, 2025)。有学者(杨传成等, 2024)发现了雁列状地震裂缝,认为其与构造活动相关。也有学者(Chen et al., 2024; 苏瑞欢等, 2024)提出,一些发育在断层附近的地震裂缝可能是断层断错地表现,代表着此次地震的地表破裂带。积石山 $M_s6.2$ 地震

后中国地震局组织了地震科考队,在科考交流中出现了地震裂缝是否为地表破裂带的争议,引发了人们对中强地震地表破裂的识别标志的重新思考和讨论(张军龙等,2024)。

积石山地震裂缝的成因主要有2种观点:一是地表震动引起了广泛分布的地震裂缝,二是由断层错动引起的地震裂缝。地震裂缝成因的不同观点来源于分析不同地形地貌部位、不同表现形式和组合形态的地震裂缝,但研究局限于地震构造、地震地质灾害两个不同学科的调查研究,分析数据或集中在断裂沿线,或分布在主要地质灾害点附近,缺少对地震裂缝成因机制的整体把握。

总体上,积石山地震裂缝分布广、类型多、数量庞大、成因复杂,有必要专门对地震裂缝开展综合研究。因此,文章通过收集和调查积石山地震Ⅶ—Ⅷ度区内共246条地震裂缝的分布规律、类型和发育特点等,分析不同地震裂缝的成因机制,形成关于积石山地震裂缝成因的科学认识;结合多学科研究结果,回答积石山地震中部分裂缝是否为地表破裂的问题。研究结果也可为减轻地震裂缝相关的次生灾害提供参考。

1 研究背景

2023年积石山 M_s 6.2地震发生在临夏盆地内部(震中坐标:35.713°N,102.835°E;鞠慧超等,2024),震源机制解显示为逆冲型地震(王丽霞等,2024)。震中西侧的积石山高逾4000m,主要由加里东期岩浆岩、前震旦系构成;临夏盆地与积石山的高差超过1000m,由新近系和上覆厚层黄土组成。裂变径迹热年代学表明,约8Ma时积石山开始发生构造隆起,约3.6Ma时隆升加快,形成“地形雨”效应(郑德文等,2006)。随着积石山的隆起,积石山东缘断裂发生逆冲活动并向临夏盆地内部扩展,形成积石山东缘断裂和临夏盆地内部的活动褶皱(银川沟背斜),同时盆地内部发生多次5级左右的中等强度地震(国家地震局震害防御司,1995;袁道阳等,2007;张波,2012)。2023年积石山 M_s 6.2地震发生以前,关于积石山东缘断裂的新活动特征研究较少,张波(2012)根据大峡河一带的三级阶地断错,推测断裂最新活动时代为晚更新世。苏瑞欢等(2024)通过地质地貌调查,在临夏盆地内部新发现了大河家断裂、赵木川断裂和大墩村断裂,上述断裂的发现使拉脊山断裂与积石山东缘断裂在平面

上相连。

根据GNSS(Global Navigation Satellite System, GNSS)和InSAR(Interferometric Synthetic Aperture Radar, InSAR)观测结果,2023年积石山 M_s 6.2地震的地表同震变形微弱,多为0~10cm(陈鹏等,2025;平孜菲等,2025;张文婷等,2025)。微弱的地表变形未形成广泛认可的地表破裂带,一些学者在局部段发现了地表破裂带,表现为地震裂缝(局部雁列排列)和陡坎,具有cm级的挤压逆冲和右旋位错特征(Chen et al., 2024; 苏瑞欢等, 2024)。也有一些学者发现了雁列式地震裂缝,推测其可能与构造活动相关(杨传成等,2024;张军龙等,2024)。

2 数据和方法

文章汇总了甘肃省地震局、青海省地震局的246条地震裂缝数据(图1)。由于大多数裂缝尺度很小(宽度为cm~mm级),从震后卫星影像上难以识别,因此裂缝数据主要通过实地调查得到。幸运的是,震前积石山地区曾有严重降雪,地面被冰雪覆盖,地震裂缝因断错冰雪表面而清晰可见。尤其是地震裂缝与硬化公路交切区,地震裂缝极其清楚,公路边缘、护坡、排水沟、车道标志线等皆为清晰的标志。在未与硬化公路交切区,由于地表松散、低矮植被(灌木等)多,规模小的裂缝难以追索,因而无法得到地表裂缝的长度。通过观察每条裂缝的发育特征,测量典型裂缝的宽度和走向,结合裂缝点的地质地貌,分析地震裂缝的成因机制。

3 研究结果

3.1 地震裂缝分类

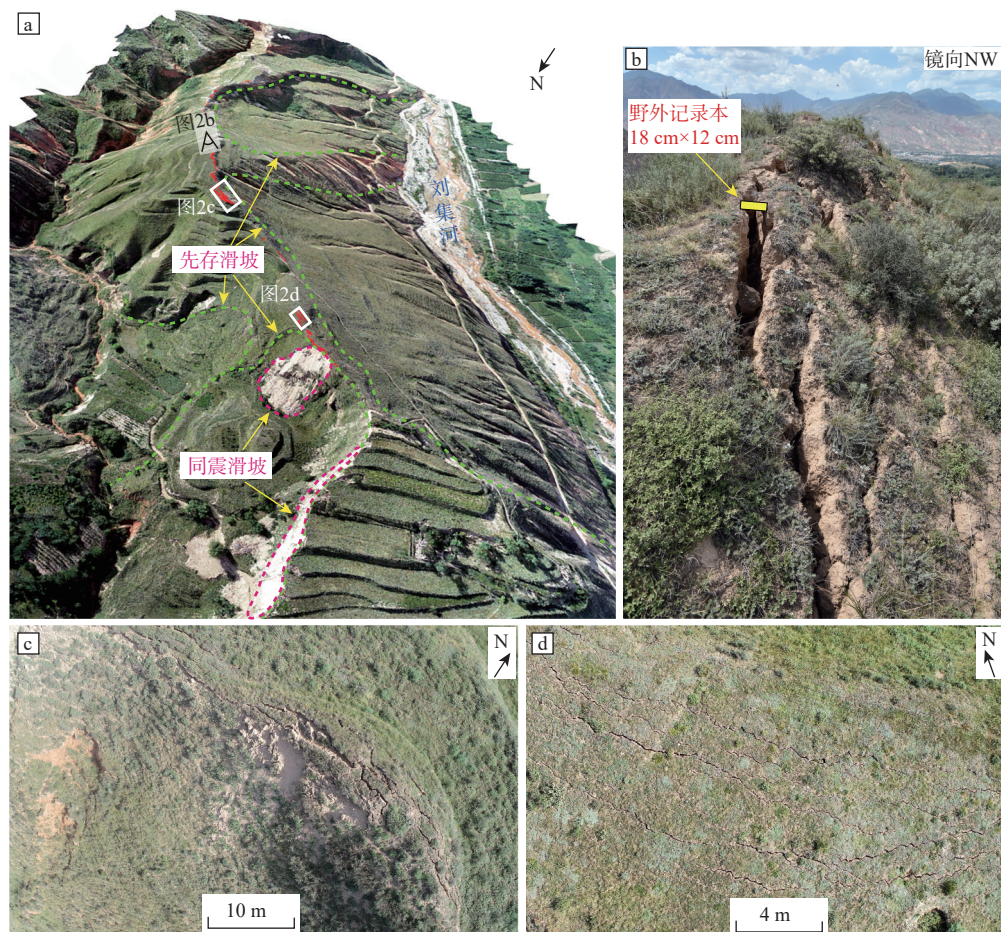
地震裂缝分布总体呈北北西—南北走向,南至积石山山前的雷积沟一带,北至民和峡门村一带。震中以北的大河家—克新民—甘河滩一带尤为密集。根据裂缝的分布、规模、表现和地质地貌特征,地震裂缝可分为2类:非构造裂缝和构造微裂缝。

3.2 非构造裂缝

通常发育在远离断层区域,主要沿山脊、或伴随滑坡出现、或为裂缝—沙土液化组合等。

3.2.1 山脊重力裂缝

主要分布在临夏盆地内部、震中以北的黄土覆盖区,这一带为黄河及其支流的冲洪积阶地、黄土台地、临夏盆地顶部堆积区,阶地或台地上堆积的



a—克新民村南山脊上的张裂缝带,红色实线代表张裂缝带,红色虚线代表积石山地震的同震滑坡,绿色虚线代表先存的大型滑坡边界;
b—宽0~70 cm的张裂缝;c—网状排列的张裂缝;d—平行排列的张裂缝

图2 克新民村南沿山脊的张裂缝

Fig. 2 Fissures developed along the ridge south of the Kexinmin Village

(a) Ridge fissure zone south of the Kexinmin village, red solid lines are tensional fissures, red dashed lines indicate coseismic landslides, and green dashed lines mark the boundaries of pre-existing large landslides; (b) 0~70 cm wide fissure; (c) Gridded fissures; (d) Parallel fissures

滑坡相伴生,当滑坡下滑时后缘拉张形成张裂缝。裂缝带局部段表现为西高东低(图3c),与顺坡向滑动不一致,推测与下方公路的人工护坡有关。一方面,由于护坡部位相对稳定,那么其可能会对周围土体产生一个“固定点”的效果,使原本应该顺坡向下移动的部分土体由于受到阻挡,导致局部区域发生反坡向滑动;另一方面,护坡处的基础比周围土体相对牢固,可能会导致护坡和周围土体的差异沉降,促使部分土体反坡向移动以适应新的应力条件,形成了“西高东低”的裂缝(图3c)。

3.3 构造微裂缝

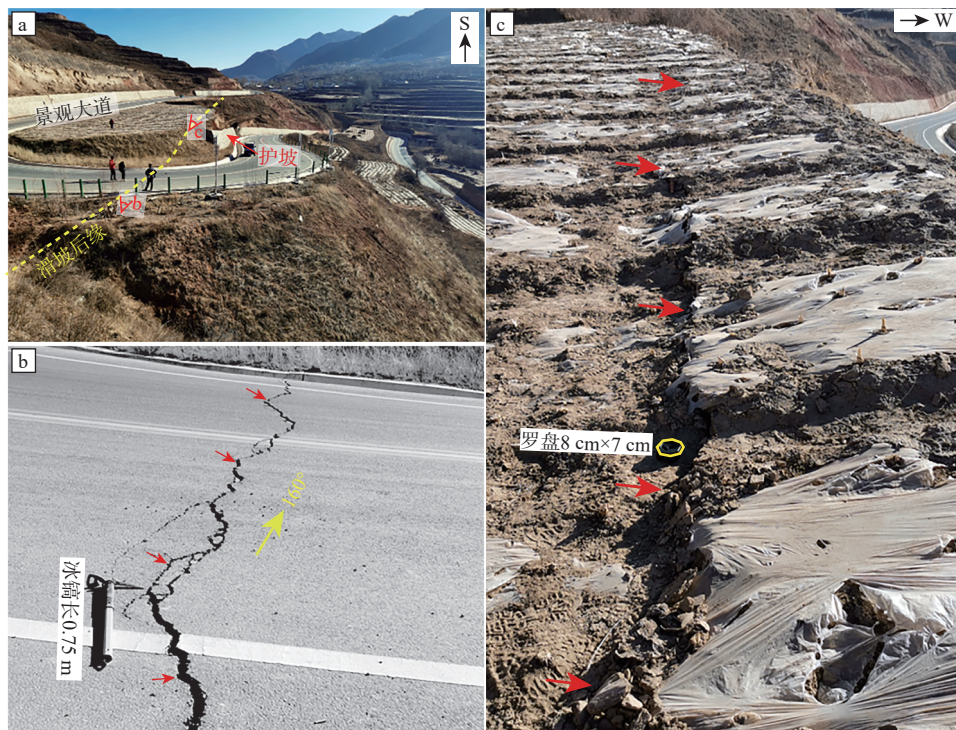
构造微裂缝主要沿积石山东缘断裂分布,在震中西侧的尕护林至大山庄一带尤其密集(图1,图4a—4c),其最显著的特点是贯穿了冰雪覆盖的硬化路面。构造微裂缝总体沿断裂发育,且裂缝走向统计

结果与断裂走向一致,表现出明显的构造相关性。

除了断裂附近贯穿冰雪路面(图4a—4c)或地表(图4d)的微裂缝以外,也有多处地震裂缝与构造相关。尕护林以西,裂缝沿基岩中的构造节理发育(图5a),开裂面新鲜,且该裂缝与图4a中冰雪地面上的地震裂缝相连;黄草坪和关门村一带,裂缝沿基岩中的先存断层出现,开裂面新鲜,坡底伴随着小规模崩塌堆积(图5b、5c);关门村一带先存断层的上盘还出现了“X”型裂缝,开裂面新鲜(图5d)。地震裂缝沿节理面、断层面等构造软弱部位发育的情况,体现了构造(积石山东缘断裂)对地震裂缝的控制作用。

3.4 裂缝的愈合

裂缝愈合对人类生产生活具有重要意义,裂缝愈合问题却少有讨论。通过对典型地震裂缝的多



a—尹家山以东的裂缝；b—张裂缝贯穿景观大道；c—局部“西高东低”的张裂缝

图3 尹家山以东的滑坡边缘裂缝

Fig. 3 Landslide edge-related fissures east of the Yinjiashan Village

(a) Fissures east of the Yinjiashan Village; (b) Extensional fissures cutting a road; (c) Locally developed uphill-facing fissure scarp

次调查,发现孕护林一带的构造微裂缝(宽5 cm;图6a)在震后半年已经完全自然愈合(图6b)。贯穿硬化公路的微裂缝,已在积石山灾后重建工作中被人类修复。克新民村的山脊重力裂缝,地震半年后几乎没有变化,自然愈合的时间远超构造微裂缝。与滑坡伴生的裂缝,由于滑坡的不定期滑动,裂缝可能继续生长和扩展,甚至形成永久位移。

裂缝自然愈合速度受气候、环境、人类作用、构造、植被等多因素控制。对一些难以快速愈合甚至继续发展的非构造裂缝,人为修复是一项重要的工作,从而保证基础设施的安全性和人类生命财产安全。

3.5 非构造裂缝与构造微裂缝对比

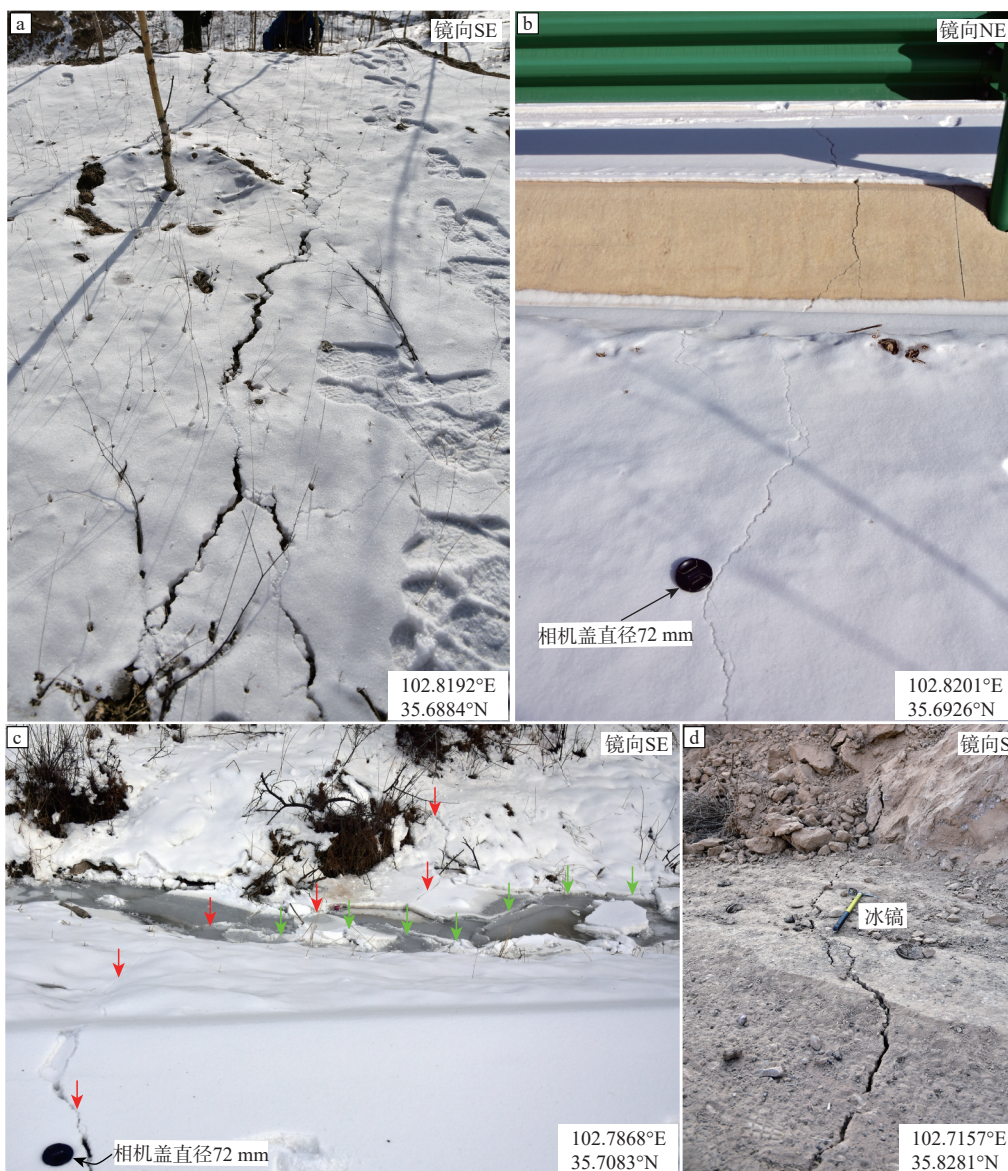
通过调查研究,结合杨传成等(2024)在黄河阶地上发现的裂缝-沙土液化组合,得到了积石山地震的地表裂缝分类及其发育特征(表1),并从裂缝规模(宽度)、组合形式、发育部位、延伸方向、愈合速度等方面对比了非构造裂缝(共3类)和构造微裂缝。总体而言,非构造裂缝规模大、延伸远、组合形式复杂、愈合慢,沿山脊、台地、山坡、谷地等各类地形部位普遍发育,从山脊(台地)到谷地(地形从高到低)裂缝规模逐渐减小;而构造微裂缝规

模小,常以单条出现,沿断层面、节理面等构造软弱部位发育,愈合速度快,最宽的构造微裂缝经半年时间可完成自然愈合。

4 讨论

4.1 非构造裂缝的成因机制

文章详细介绍了山脊重力裂缝和滑坡边缘裂缝,克新民村的山脊重力裂缝的规模与青海省民和县寨子山处的雁列式裂缝相当(杨传成等,2024)。裂缝组合呈网状、带状或雁列状。克新民、寨子山等地的山脊重力裂缝,多为地震动导致山体松动而形成,受山脊上相对较高的重力势能控制。同时,由于山脊被数米乃至数十米的松散黄土覆盖,地震动放大效应显著,形成规模相对较大的地震裂缝(刘传正等,2024)。滑坡边缘裂缝在极震区(Ⅷ度)内广泛发育,文中重点介绍了尹家山一带贯穿景观大道的滑坡后缘裂缝,并详细分析了局部反向陡坎的成因。结合杨传成等(2024)在大河家水电站附近(黄河河谷)发现的微裂缝和沙土液化组合,总结了非构造裂缝的3种类型:山脊重力裂缝、滑坡边缘裂缝和谷底微裂缝和沙土液化的组合,分别发育在



a—尕护林以西的地震裂缝; b—尕护林西北的构造裂缝贯穿冰雪路面; c—黄草坪以北地震裂缝贯穿冰面; d—达帮沟以北黄土中的地震裂缝

图 4 沿积石山东缘断裂的构造微裂缝

Fig. 4 Tectonic-related micro-fissures observed along the eastern margin fault of Jishishan Mountain

(a) Tectonic fissures west of the Gahulin Village; (b) Tectonic fissures cutting a road northwest of the Gahulin Village; (c) Tectonic fissures cutting ice and snow; (d) Tectonic fissures developed in loess north of the Dabangou Village

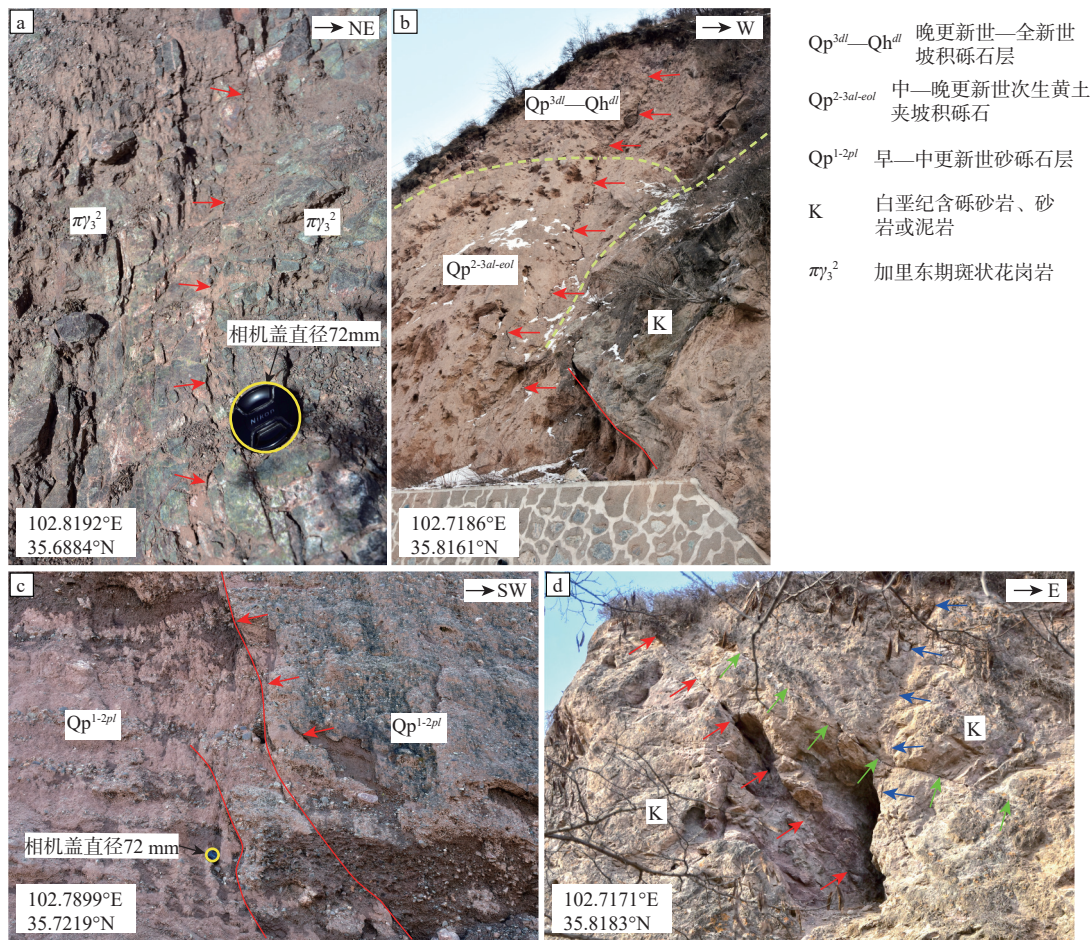
山脊、山坡和河(沟)谷等不同的地形地貌部位。

裂缝发育的地形地貌部位决定了裂缝的规模。山脊重力裂缝规模最大、延伸最远;滑坡边缘裂缝受控于滑坡几何形态,规模小于山脊重力裂缝;河(沟)谷内的裂缝规模最小,常与沙土液化等现象共生。总体上,随着地形地貌部位下降,地震裂缝的规模越小(图 7)。地震裂缝规模的空间差异与苏瑞欢等(2024)发现的房屋破坏和地震地质灾害程度的空间分布不谋而合,共同反映了地震动强度的空间差异。因此,非构造裂缝主要发育在临夏盆

地内部、震中以北的厚层黄土覆盖区,由地震动产生重力滑动,具有典型的场地放大效应。

4.2 构造微裂缝的成因机制

与非构造裂缝相比,构造微裂缝规模小得多(多<1 cm),且不受重力和滑坡的直接影响。文中积石山地震的构造微裂缝沿积石山东缘断层发育,而节理、断层面等部位,体现了构造对裂缝的控制作用。与积石山地震类似的是,在 1989 年的 Loma Prieta M_s 7.1 地震中,地震裂缝通过了地层层面(Ponti and Wells, 1991)。节理、断层面和地层面本质上都



红色实线代表先存断层；箭头代表裂缝；黄色虚线代表地层界线

a—裂缝沿节理发育；b—关门村一带裂缝沿先存断层面发育；c—黄草坪一带裂缝沿先存断层面发育；d—沿断层面的裂缝和断层上盘的“X”形裂缝

图5 沿先存断裂和节理发育的裂缝

Fig. 5 Fissures developed along pre-existing fault planes and joints

(a) Fissure developed along rock joints; (b) Fissure developed along an old fault plane near the Guanmen Village; (c) Fissure developed along an old fault plane near Huangcaoping; (d) Fissure developed along an old fault plane and X-fissure formed on the hanging-wall of the fault plane. Red solid lines represent pre-existing faults; arrows indicate fissures; yellow dashed lines show strata boundaries.

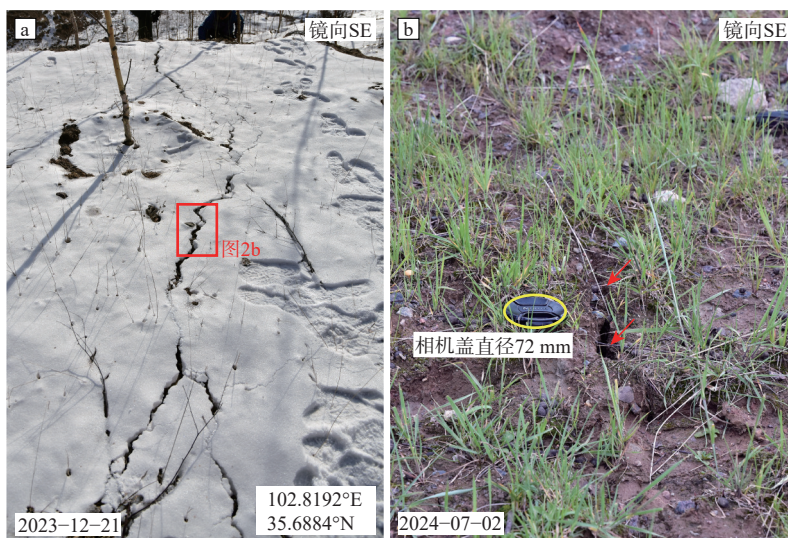
是地壳中的构造软弱带，体现了构造对地震裂缝的控制作用。积石山东缘断裂的断层带较宽，如桦林谷一带出露的断层破碎带的宽度 >100 m(图 8a)，可见破碎程度不一的基岩、断层角砾、断层泥以及多条倾向多变的次级断层(图 8b、8c)。受积石山地震的强震动影响，构造软弱带(积石山东缘断裂)内形成了大量的微裂缝，沿断裂带发育，体现断裂对裂缝的控制作用(图 7)。黄草坪一带，景观大道穿过断裂带处发育了密集的地震裂缝，公路边缘的接缝(介质软弱带)普遍“袭夺”公路主体上的裂缝，使裂缝在公路边缘发生跃迁、拐弯、分叉等现象。

以上现象表明，介质软弱带(断裂带或人造建筑接缝部位)可以控制构造微裂缝。对于人造建筑

(公路接缝、桥梁箱体之间、桥体和外围接缝处等)，应注意一些关键部位的连接性和整体性，从而减轻地震灾害损失。

4.3 裂缝对构造的启示

积石山东缘断裂较宽的构造微裂缝带，说明积石山东缘断裂的破碎带(介质软弱带)宽度大，是1条具有复杂构造背景和长期演化历史的断裂带(郑德文等, 2006; Lease et al., 2012; 张波, 2012)。既然构造微裂缝在几何分布上受限于断裂带，那么这些裂缝是否为断层错动引起？通过此次研究认为该构造微裂缝不是断层断错地表现。依据一，构造微裂缝普遍“趋弱”，即裂缝切过公路到边缘时，具有向公路接缝、护坡接缝、桥体边缘等软弱



a—震后第 3 天拍摄的宽 5 cm 的地震裂缝; b—自然愈合后的地震裂缝

图 6 构造微裂缝的快速愈合

Fig. 6 Rapid natural coalescence of tectonic micro-fissures

(a) Photo showing 5 cm wide tectonic fissures taken 3 days after the Jishishan Earthquake; (b) Natural coalescence of tectonic fissures

表 1 积石山地震的地表裂缝分类及其特征

Table 1 Classification and characteristics of fissures induced by the Jishishan Earthquake

裂缝类型	宽度	组合	发育部位	方向性	恢复速度
非构造裂缝	山脊重力裂缝	带状、网状、雁列	山脊、台地	沿山梁	慢
	滑坡边缘裂缝	围椅状、雁列	边坡	滑坡边缘	慢
	沟谷裂缝-沙土液化	带状、雁列	沟谷		较快
构造微裂缝	cm~mm	单条	沿断层、节理等构造软弱带	沿断层	1年内

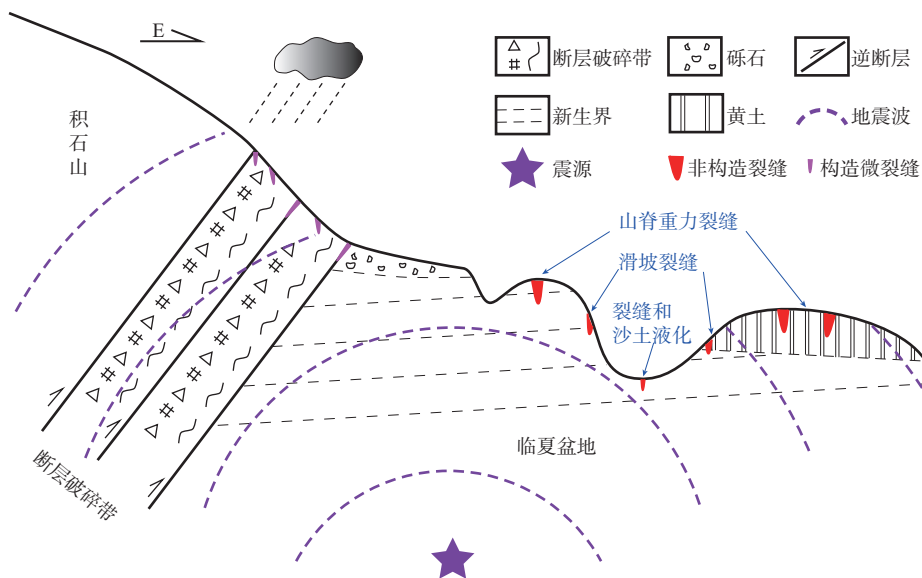


图 7 积石山地震的裂缝分布及成因机制

Fig. 7 Distribution and formation mechanism of fissures induced by Jishishan Earthquake

部位发展的趋势,这种“趋弱”的特点,体现裂缝本身动能的不足,与深部断层断错沿线一切地质地貌体的特征相悖。依据二,地震地质、大地测量、地

震精定位等多学科研究表明,2023年积石山 M_s 6.2 地震的发震构造应在临夏盆地内部,在几何上与积石山东缘断裂不匹配(鞠慧超等, 2024; 苏瑞欢



a—桦林谷出露宽>100 m的断层破碎带；b—断层破碎带中的西倾断层面；c—断层破碎带中的东倾断层面

图8 积石山东缘断裂宽逾百米的断层破碎带

Fig. 8 Over 100 m wide fracture zone of the eastern margin fault of the Jishishan Mountains

(a) Outcrop of an over 100 m wide fracture zone in the Hualingu valley; (b) West-dipping fault plane exposed in the fracture zone; (c) East-dipping fault plane exposed in the fracture zone

等, 2024; 王世广等, 2024; 张文婷等, 2025)。

雁列式裂缝是走滑剪切不连续破裂的典型标志 (Segall and Pollard, 1980; 刘璐等, 2022; 刘小利等, 2022; 袁道阳等, 2023), 2023年积石山 M_s 6.2地震形成的雁列式裂缝 (杨传成等, 2024; 张军龙等, 2024) 是否能作为逆冲型破裂的标志尚不清楚, 也未见相关力学机制上的探讨。因此, 文章倾向的观点是2023年积石山 M_s 6.2地震没有产生地表破裂带, 构造微裂缝只是地震动叠加在介质软弱带 (积石山东缘断裂带) 上的表现 (图7)。

5 结论

通过系统总结2023年积石山 M_s 6.2地震的地

裂缝分布、类型及其成因机制, 得到如下结论:

(1) 积石山地震形成的地表裂缝主要包括两大类: 构造微裂缝和非构造裂缝, 非构造裂缝又包括山脊 (台塬) 重力裂缝、滑坡相关裂缝和沟谷裂缝-沙土液化组合。

(2) 构造微裂缝沿积石山东缘断裂的断层破碎带发育, 裂缝通过断裂带内的断层面、节理面等介质软弱部位, 体现构造对裂缝的控制作用; 但裂缝同时具有“趋弱”特点, 说明构造微裂缝不是地震地表破裂带。

(3) 非构造裂缝主要发育在震中北侧的黄土覆盖区, 山脊部位规模大, 从山脊 (台塬) 经山坡向下到沟谷, 裂缝规模逐渐减小。

(4) 构造微裂缝经过自然修复可快速愈合, 非

构造裂缝的自然愈合时间远大于构造微裂缝, 局部滑坡相关裂缝可能难以自然愈合而形成永久位移, 对人类造成严重威胁的裂缝, 需要人为修复。

致谢: 山东省地震局杨传成高级工程师、青海省地震局盖海龙高级工程师提供部分地震裂缝数据; 与秦满忠副研究员、田勤俭研究员开展了有益的讨论。在此一并表示感谢!

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