Identification of Paleoeartquakes and Coseismic Slips on a Normal Fault Using High-Precision Quantitative Morphology: Application to the Jiaocheng Fault in the Shanxi Rift, China

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The quantitative morphology of bedrock fault surfaces combined with aerial surveys and field identification is a useful approach to identify paleoearthquakes, obtain coseismic slips, and evaluate the seismogenic capacity of active faults in bedrock areas where traditional trenching methods are not applicable. Here, we report a case study of the Jiaocheng Fault (JCF) in the Shanxi Rift, China. Although several studies have been conducted on the JCF, its coseismic slip history and seismogenic capacity are still unclear. To address these problems, we investigated two bedrock fault surfaces, Sixicun (SXC) and Shanglanzhen (SLZ), on the JCF’s northern segment using quantitative morphological analysis together with aerial and field surveys. Quantitative fractal analysis based on the isotropic empirical variogram and moving window shows that both bedrock fault surfaces have the characteristics of vertical segmentation, which is likely due to periodic earthquakes, the coseismic slip of which can be determined by the height of the segments. Three seismic events at SXC, with a coseismic vertical slip of 1.74, 1.65, and 1.99 m, and three seismic events at SLZ, with a coseismic vertical slip of 1.32, 2.35, and 1.88 m, are identified. Compared with the previous studies, these three seismic events may occur in the Holocene, but it requires absolute dating ages to support, which is also the focus of our future work. Considering the seismologic capability (M > 7.5) and the relationship between the recurrence interval of ~2.6 kyr and elapsed time of more than 3 kyr, the seismic hazard of the northern and middle segments of the JCF requires immediate attention.

1. Introduction

Full understanding of the behavior and history of an active fault is the key to assessing seismic hazards and reducing the impacts from earthquake disasters [1]. A reasonable seismic hazard assessment mainly depends on the integrity of seismic records [2]. Considering the relative shortness and general absence of historical earthquake records, paleoearthquake research is the most effective way to extend the history of earthquakes and produce more complete seismic records [3]. The main aim of paleoearthquake research is to obtain the information relating to the activity of prehistoric earthquakes, especially the number, timing, and size [4]. The traditional method to study an active fault is based on the analysis of displaced Quaternary sediment through the trenching technique [5, 6], which has been widely applied to paleoseismology, becoming a major contributor to paleoseismic studies in continental deformation zones [7–9]. For
normal faults in terrestrial environments, the number of paleoearthquakes can be relatively easy to acquire by determining the relationship of cutting and coverage between faults and strata in the trench. Meanwhile, ages of paleoearthquakes can be accurately bracketed by dating geomorphic surfaces, displaced deposits, and colluvial wedges [10]. However, since multiple seismic slips often result in complex deformation, the Quaternary stratigraphic markers are not easy to find, and interfaulting sedimentation and erosion are therefore difficult to reconstruct. The accurate coseismic displacement of a single paleoearthquake event is therefore usually difficult to measure via the trench technique [4, 11, 12]. Therefore, it is necessary to develop a new identification technique to obtain accurate coseismic slips on normal faults.

Bedrock normal fault scarps are long-lived tectonic landforms of repeated surface faulting in active extensional terrains [13–15]. A well-preserved bedrock fault scarp can record a detailed paleoearthquake history and important paleoearthquake information concerning accurate coseismic slips and earthquake recurrence intervals [16–20], and it has become an attractive target for paleoseismological studies [21]. Over the last two decades, a great number of studies have been conducted to extract paleoearthquake information from bedrock normal faults in the grabens of the U.S.A. [16, 22, 23], Israel [24, 25], Greece [17, 26–28], and Italy [29–31], using cosmogenic nuclide exposure dating and other physical and chemical indicators. However, only a few studies have applied these techniques to bedrock normal faults in China [32, 33].

Absolute and relative age dating methods have been used to obtain the seismic history of bedrock normal scarps. The absolute dating technique mainly refers to in situ cosmogenic nuclide exposure dating, which is most frequently applied to paleoearthquake analysis of normal fault scarps [16, 17, 25–27, 31, 34–36]. Not only can absolute dating obtain the number of individual earthquakes but also it can determine the corresponding age and slip rate by measuring the in situ cosmogenic nuclide concentrations along the fault scarp [18, 19, 30, 37–41]. The difficulties associated with this technique are that it can be prohibitively expensive, requiring a large amount of time, manpower, and materials to prepare and analyze samples at the sampling intervals required to identify seismic events [22, 23, 32].

Relative dating techniques assume that the degree of weathering is a function of the exposure time of bedrock fault surfaces and that the time-dependent weathering phenomena are quantifiable [23]. These methods obtain the number and coseismic slips of individual earthquakes by microroughness measurements [15, 29], observing discoloration by the naked eye [42], photogaphic analysis [29], pit depth measurements [43], rebound value tests using a Schmidt hammer [22], lichen size measurements [44], rare earth element analysis [28, 35, 45], measurements of optically stimulated luminescence residual signals [46], or terrestrial laser scanning (TLS) [47]. In particular, TLS has become a well-established tool for identifying weathering bands and extracting potential paleoearthquake information [20–22, 48] since it can rapidly obtain three-dimensional morphologic data with high spatial and temporal resolution [49–56]. This method can conveniently determine certain seismic parameters, such as the number of events and coseismic slips, and is suitable for a fault with clear earthquake ages but unclear coseismic slips [32, 33, 57].

Here, we focus on the JCF, an active normal fault located on the western flank of the Shanxi Rift at the eastern boundary of the Ordos block, which is a stable continental block in northern China (Figures 1(a) and 1(b)). The Taiyuan Basin is mainly controlled by the JCF and is considered the most inactive section of the Shanxi Rift with no historical record of earthquakes of magnitude 7 or greater since 2 kyr [58] (Figure 1(b)). The greatest earthquakes to hit this area are the Taiyuan M6½ earthquake, which occurred in 1102 CE, and the Pingyao M6½ earthquake, which occurred in 1614 CE [59] (Figure 1(c)). However, this does not mean that the basin is not a strong earthquake hazard, as this depends on the activity of the basin boundary fault over longer time scales. Previous surveys based on the traditional trenching method and knickpoint analysis have shown that the JCF experienced 3 paleoearthquake events during the Holocene [58, 60, 61], but the accurate coseismic slip of each paleoearthquake event is still not clear due to a lack of stratigraphic markers, a complex deformation history, and signs of strong erosion, making it difficult to estimate the seismic capacity of the fault. The Taiyuan Basin, which is adjacent to the JCF, is one of the most densely populated regions in China, with a total population exceeding 8 million. Therefore, it is urgent to accurately obtain the coseismic slip and calculate the magnitude of each paleoearthquake event if we are to evaluate the potential hazard of regional seismic events to the local populace. The JCF occupies bedrock at a large number of sites, and there are many well-preserved bedrock fault scarps available for study.

In this study, to obtain accurate coseismic slips and the seismic capacity of the JCF, we apply aerial survey, weathering band interpretation, and quantitative morphology analysis. First, aerial survey and field work were conducted on two bedrock fault scarps to ascertain the geomorphological information needed to choose suitable study sites. Second, we scanned two well-preserved bedrock fault surfaces and obtained high-precision 3D morphology data using terrestrial laser scanning (TLS). Third, the fault surface morphologies were quantified as fractal dimensions (D), calculated using the isotropic empirical variogram method and a moving window operation [33], and the morphologic bands were identified using the fractal results. We ascribed the morphologic bands for each fault surface band to individual earthquake events and obtained the coseismic slip and magnitude of each event. Finally, combined with the results of previous paleoseismic studies, we constructed an earthquake history of the JCF, determined the fault rates, and assessed the regional seismic potential.

2. Geological Setting

The JCF is an active boundary fault in the central Shanxi Rift between the Lvliang Mountain and piedmont Taiyuan Basin, extending approximately 125 km north from Nitun Town to
Fengyang City, with a general strike of NE-SW and dips to the SE at 40° to 80° [62]. The northern end and southern end of the JCF are, respectively, cut off by the Shilingguan uplift and Linshi uplift, which are roughly developing from east to west [61]. The mountain-basin height difference is about 800 m [60]. In the footwall, the Lvliang Mountain is an asymmetrical tight anticline with a core of Paleozoic and Mesozoic limestone and sand-shale covered by Quaternary loess in certain areas. Since the Pliocene, with continued motion along the normal fault dominated by NW-SE extension, this anticline has been tilted to form a block mountain [63]. In the hanging wall, the Taiyuan Basin is filled with sediments that range in age from the Pliocene to the Holocene, where the sedimentary center is inclined to the eastern side of the JCF indicating strong fault activity [64, 65] (Figure 1(c)).

The JCF is divided into a northern, a middle, and a southern segment according to its geometry and activity:
In this study, orthophotos of bedrock fault scarps and ground control points (GCP) were acquired by GPS differential measurement (point position correlation and correction in the orthophotos) to produce a digital 3D model of the bedrock fault surfaces and the surrounding topography. The morphological information of two bedrock fault scarps, e.g., morphological parameters such as degree of bedrock fault surfaces, was extracted based on the acquired digital 3D model. The visual interpretation was conducted mainly based on structural integrity and surface condition of bedrock fault surfaces, according to the principles derived from Tye and Stahl in 2018 [22]. The structural integrity is classified into three levels, nearly intact, macro-fragmented, and blocky, and the surface condition is also classified into three levels, smooth with striations and light-colored, rough associated with deeply colored erosion pits, and crushed with thick vegetation (Figure 2(b)). This provided basic information for target bedrock fault surfaces and a reference for subsequent morphology acquisition.

Next, the surface morphologies of the two fault scarps along the JCF were obtained with the aim of relating variations in surface morphology to paleoseismic activity using terrestrial laser scanning (TLS). The TLS, also known as terrestrial light detection and ranging (t-LiDAR), is a useful survey technique suitable for acquisition of very detailed and precise measurements of slip-surface geometry from well-preserved bedrock fault scarps [47]. As a noncontact sensing technique for reconstructing, monitoring, and observing geological and geomorphic phenomena and their related hazards, the fundamental principle of t-LiDAR is to generate a coherent laser beam with little divergence by stimulated emission [57]. In our study, we scanned the two fault surfaces to obtain high-precision and high-resolution morphologies of bedrock fault surfaces using a close-range t-LiDAR (Trimble GX 3-D scanner; Figure 3(a)). The space between two adjacent scan points ranged from 1.6 to 5 mm, with a change in the distance between the scanner and fault surface of 5 to 300 m. The distance between the farthest point and the center of the scanner is less than 15 m, which permits a point cloud with a high resolution of 2 mm. We chose a high-quality but time-consuming scanning mode to ensure that the scanner stored the data, and each data point was collected twice to guarantee high data quality. In the field, the well-preserved fault surface areas without vegetation or deposit cover were selected for scanning to allow complete data acquisition. We obtained high-precision and high-density 3D point clouds of the two fault surfaces with little divergence. The mean distance between adjacent points was 2 mm across the 3D point clouds. The original scan data were pre-processed by RealWorks Survey Advanced 6.1, Surfer 12, and Global Mapper 17 software packages. First, the point cloud dataset, with space coordinates X, Y, and Z, was moved and rotated to maintain the relative position of the scan points by the RealWorks Survey Advanced 6.1 software (Figure 3(c)).

### Table 1: Segment information for the Jiaocheng Fault (JCF).

| Segment marks | Northern segment | Middle segment | Southern segment |
|---------------|------------------|----------------|-----------------|
| Geometric characteristics | Changeable strike; clear but uncontinuous geometric trace | A general strike of NE-SW; protruding arc toward the NW | A general strike of NE-SW; unobvious fault trace |
| Piedmont tectonic geomorphology | A well-developed faulted bedrock and an alluvial fan | A well-developed faulted alluvial fan | A faulted loess platform |
| Active duration | NH-Qh | NH-Qh | NH-Qp2 |
| The latest active era | Qh | Qh | Qp2 |
| Paleoearthquake events | 3 same seismic events occurred on the northern and southern segments in the Holocene | No seismic events known |
| Ages of seismic events | 8.36-8.56 kyr; ~5.91 kyr; 3.06-3.53 kyr | / |
| Seismogenic capacity | $M > 7$ (northern and southern segments together) | / | / |

The northern segment of the JCF is characterized by a series of well-developed triangular facets and bedrock fault scarps caused by dominant normal-slip faulting. Although the bedrock fault scarps cannot be studied by the traditional trenching method, they remain useful records of previous earthquakes, providing a potential target for obtaining accurate coseismic slips via quantitative morphology analysis.

### 3. Methods

#### 3.1. Field Survey and Fault Surface Morphology Acquisition

In the field, we conducted an aerial survey, visual interpretation of weathering bands, and morphology acquisition. First, a small unmanned aerial vehicle was used to acquire high-precision, high-resolution topographic data [66–68]. In this study, orthophotos of bedrock fault scarps and their surroundings were collected by a Dajiang Inspire sUAV carrying a GSI, an inertial navigation system, and an 8 mm fixed-focus high-definition camera (upper panel in Figure 2(a)). The 3D coordinates of control points (GCP) were acquired by GPS differential measurement for point position correlation and correction in the orthophotos (lower panel in Figure 2(a)). Indoor splicing, creating dense point clouds, generating grids, and pasting texture of collected images were conducted by professional imaging processing software Agisoft Photoscan Professional Edition 1.2.0, which was then used to produce a digital 3D model of the bedrock fault scarps and the surrounding topography. The morphological information of two bedrock fault scarps, e.g., length, continuity, and slope variation, was extracted based on the acquired digital 3D model. Next, the weathering degree of bedrock fault surfaces was estimated by a method of visual interpretation. The visual interpretation was conducted mainly based on structural integrity and surface condition of bedrock fault surfaces, according to the principles derived from Tye and Stahl in 2018 [22]. The structural integrity is classified into three levels, nearly intact, macro-fragmented, and blocky, and the surface condition is also classified into three levels, smooth with striations and light-colored, rough associated with deeply colored erosion pits, and crushed with thick vegetation (Figure 2(b)). This provided basic information for target bedrock fault surfaces and a reference for subsequent morphology acquisition.
Figure 2: Aerial survey and principles of visual interpretation. (a) Aerial survey by the small unmanned aerial vehicle and ground control point measurement for obtaining topographic data around bedrock fault scarps. (b) The visual interpretation principles of weathering degree.

Figure 3: Workflow for the obtained surface morphology of the bedrock fault scarp. (a) Scanning by terrestrial light detection and ranging (t-LiDAR) to obtain the high-precision surface morphology of the bedrock fault scarp. (b) A high-precision and high-density three-dimensional (3D) point cloud dataset obtained using the t-LiDAR (original scan data in the side view). (c) The 3D point cloud dataset was levelled (levelled scan data in the front view). (d) The levelled point cloud dataset of the fault surface was interpolated from (c) into a DEM dataset. (e) The DEM dataset was cut from (d) into a regular rectangle.
The originally inclined fault surface scanning data was levelled, such that after transformation, the x-axis was the strike line of the fault surface, the y-axis was the dip line of the fault surface, and the z-axis was the fluctuation direction of the fault surface. Then, we interpolated the point cloud datasets of the levelled irregular fault surface into DEM datasets with a cell size of 2 mm × 2 mm (Figure 3(d)) using a natural neighbor method in Surfer 12. Finally, the DEM datasets were cut into a rectangle with Global Mapper 17 (Figure 3(e)).

Here, we selected two well-preserved bedrock fault outcrops on the northern segment for analysis: site 1 at Sixicun (SXC) and site 2 at Shanglanzhen (SLZ) (Figure 1(c)). Both study sites considered here consist of limestone in the footwall of the JCF, roughly 22 km apart. The fault trace is clear and continuous with no branch faults near the two study sites and ground deformation concentrated on the studied fault scarps (Figures 4(a) and 5(a)). Thus, the associated coseismic slips recorded on the fault surface can be treated as representative.

The bedrock fault surface at site 1 lies at the northern end of the northern JCF segment. According to our interpretation of the 3D digital model, the bedrock fault scarp extends for hundreds of meters along an NNE-SSW strike at the foot of the Lvliang Mountain, with the fault surface generally dipping to the SEE at 60°. The scan area was selected to be at a sufficient distance from several small gullies at the foot of the mountain. Furthermore, the chosen site is far from any trace of anthropogenic activity, such as dams or buildings, preventing any interference from these sources (Figure 4(a)). The field survey shows that the footwall of the bedrock fault mainly consists of brecciated limestone and that the bedrock fault scarp in the central segment displays the most complete level of preservation. According to visual interpretation in the field, the bedrock fault displays three weathering bands: (1) the lower part of the fault surface (weathering band 3) where the bedrock fault surface is relatively intact and small fissures are observable at the surface, (2) the middle part of the fault surface (weathering band 2) where the structure of the bedrock fault surface starts to become blocky, with erosion pits and comparatively large fractures on the surface, and (3) the upper part of the bedrock fault surface (weathering band 1) where the bedrock fault surface becomes crushed with thick vegetation (Figure 4(b)). A well-preserved area was scanned using t-LiDAR, and the collected point cloud data was processed to generate a DEM dataset with a cell size of 2 mm × 2 mm (Figure 4(c)).

The bedrock fault surface at site 2 lies in the central part of the northern segment of the JCF. The SLZ fault scarp at site 2 is approximately 10 m high and dips to the SE at 70°. The bedrock fault scarp gradually degrades and retreats
upward at \(~7.5\) m, with the lower 7.5 meters showing enough preservation to allow scanning (Figure 5(a)). The study site is located away from rivers and fans so there is little associated erosion or deposition at the base of the scarp, which ensures that the lower surface has been well-preserved. Segments along the strike of the bedrock fault scarp affected by anthropogenic activity were avoided to ensure the reliability of collected morphologic data. Several morphologic features were observed in the field at different heights of the fault surface due to varying degrees of weathering and exposure time (right panel of Figure 5(b)): (1) the lower part of the fault surface (weathering band 3) is characterized by a relatively intact bedrock fault surface with small tensional fractures and slickenlines observable at the surface, (2) the middle part of the fault surface (weathering band 2) is characterized by a rough bedrock fault surface with pits, and (3) the
upper part of the fault surface (weathering band 1) has a broken bedrock fault surface covered by weathered debris (Figure 5(b)). Like site 1, a well-preserved area was scanned using t-LiDAR to obtain point cloud data and then DEM datasets with a cell size of 2 mm × 2 mm (Figure 5(c)). The slickenlines (Figure 5(d)) at the base of the fault surface indicate that the slip direction is approximately vertical, confirming the nearly pure normal faulting exhumation of the JCF.

### 3.2. Fractal Dimension Quantifying the Surface Morphology.

The fault surface buried under the ground has initial morphology [69]. After the surface is exhumed by an earthquake event(s), weathering is the main control over its surface morphology, which may result in vertical segmentation of the morphology along the bedrock fault surface [32, 57]. Natural fault surfaces have either a self-similar or self-affinity morphology features which can be expressed as fractal dimension \( D \) [53, 70]. Here, we calculated the \( D \) value distribution of the fault surfaces by combining the isotropic empirical variogram with the moving window operation.

As an effective method to calculate the fractal dimensions of the DEM field [71, 72], the essence of the variogram is to describe how the statistical variation of mean differences \( r(t) \) varies with the distance, \( t \), between the points:

\[
r(t) = ct^K.
\]

For the surface fractals, the fractal dimension \( D \) has the following relationship with the fractal index \( K \) [73]:

\[
D = \frac{3-K}{2},
\]

where \( D \) reflects the complexity of a natural surface [74, 75], and this value ranges between 2 and 3 [76–78].

We chose three moving windows with a size of 66 mm × 66 mm, 130 mm × 130 mm, and 258 mm × 258 mm to calculate the fractal dimensions of the bedrock fault surface, according to the principles proposed by Sung et al. in 1998 [79]. The window moves along the whole DEM dataset of the fault surface. After these processes, we obtained a pair of result: a raster image displaying the distribution of fractal dimensions and a scatter plot displaying the average fractal dimensions on each horizontal row. To further determine the weathering bands on the fault surfaces, Student’s \( t \)-test was applied to identify any morphologic segment along the fault scarp. For more details, please see He et al. [32] and Zou et al. [33].

### 4. Results and Discussion

#### 4.1. Defining Morphological Segments and Their Heights.

Identification of weathering bands is a meaningful step as far as the coseismic slip, seismic intensity, and seismic hazard assessment are concerned [18, 28]. In the fractal analysis results, the raster images (left panels of Figures 6(a)–6(c) and Figures 7(a)–7(c)) show the spatial distribution of fractal values on the fault surfaces. Since the main purpose in this study was to reconstruct the seismic slip history of bedrock fault scarps, we focused on vertical changes in morphology and presented the data as scatter plots (right panels of Figures 6(a)–6(c) and 7(a)–7(c)). There are three obvious morphologic bands for both the SXC and SLZ bedrock fault surfaces as defined by visual identification and Student’s \( t \)-test (Figures S1 and S2 in supplementary material) presented in the scatter plots of average fractal dimension versus scarp height.

For the SXC bedrock fault surface, the fractal dimension results from all three window sizes are consistent. There are two abrupt changes in surface morphology located at heights of 2.3–2.8 m and 4.7–5 m, separating the scatter dots into three segments with heights of 2 m (\( H_1 \)) for segment 1 (the upper band), 1.9 m (\( H_2 \)) for segment 2 (the middle band), and 2.3 m (\( H_3 \)) for segment 3 (the lower band) (Figure 6).

For the SLZ bedrock fault surface, a stair-like change can be clearly identified, and the fractal results also display a three-segment morphology. The morphology of the SLZ

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**Figure 6:** Results of the 2D fractal method for the SXC bedrock fault surface. The fault surface has three pairs of results shown in (a), (b), and (c), which are generated by moving windows with three different sizes (66 × 66 mm, 130 × 130 mm, and 258 × 258 mm), respectively. In each pair, the raster image (left) has contours showing the spatial distribution of fault surface 2D fractal dimension values, while the scatter plots (right) display the variability of the mean fractal with surface height. For each scatter plot, the light blue circles are the average value of each horizontal row in the fractal raster image with their associated standard deviation. The red vertical lines represent the average value of \( D \) for each segment. The gray dashed lines represent discontinuities between segments (see text for details).

| Window size | Fractal dimension | Window size | Fractal dimension | Window size | Fractal dimension |
|-------------|-------------------|-------------|-------------------|-------------|-------------------|
| 66 mm × 66 mm | D = 2.3216, \( \sigma = 0.0331 \) | 130 mm × 130 mm | D = 2.3976, \( \sigma = 0.0362 \) | 258 mm × 258 mm | D = 2.2603, \( \sigma = 0.0300 \) |

\[ D = \frac{3-K}{2}, \]

where \( D \) reflects the complexity of a natural surface [74, 75], and this value ranges between 2 and 3 [76–78].

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fault surface has two slow discontinuous intervals located at heights of 2-3 m and 5.5-6.1 m which divide the fault surface into three segments with heights of 1.4 m ($H_1$) for segment 1 (the upper band), 2.5 m ($H_2$) for segment 2 (the middle band), and 2 m ($H_3$) for segment 3 (the lower band) (Figure 7). To quantify the morphology of each segment, the mean and the standard deviation of fractal dimensions were calculated for each segment (Tables 2 and 3), which can act as a quantitative indicator of fault surface morphology. The fractal results between SLZ and SXC bedrock fault surfaces are consistent, and both demonstrate three obvious segmentation features on the bedrock fault surfaces. The slight difference lies in the discontinuity between neighboring segments, in that the SLZ fault surface shows a wide transition zone while the SXC fault surface displays a narrow transition zone (gradual change) in the morphology (Figure S3). It is therefore inferred that the small fluctuations observed may reflect the nonuniformity in rock composition along the fault surface. The above is only one possible explanation, but regardless of the reason, such small discrepancies should not affect the overall segmentation of seismic events.

4.2. Determination of Paleoseismic Events, Coseismic Slip, and Magnitude. Comparing the fractal results of the fault surfaces (Figures 6 and 7) with the possible exposure models [33] allows the exhumation history of the bedrock fault surfaces on the JCF to be defined as follows. A segment of the fault surface is exhumed by a strong fault activity (rupture earthquake), the height of which is equal to the coseismic slip. Then, it suffers from the same weathering processes as before and thus has nearly the same fractal dimension. A series of seismic events may form multiple morphological segments on the bedrock fault surface between two adjacent seismic events, and long-term erosion under weak hydrodynamic conditions at the base of the fault scarp forms a transition zone (gradual change) in the morphology (Figure S3).

The geological background of the fault surfaces provides strong evidence for this pattern. According to the previous trench studies, there have been three earthquake ruptures

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**Table 2: Characteristic fractal dimensions ($D$) and heights of bedrock fault surface bands of the Sixicun (SXC) bedrock fault surface.**

| Fault surface | Window size | Fractal dimension ($D$) | Standard deviation ($\sigma$) |
|---------------|-------------|-------------------------|-----------------------------|
|               | Band 1      | Band 2                  | Band 3                      |
|               | Fractal dimension |                   | Standard deviation ($\sigma$) |       |
| SXC           | 66 mm       | 2.5331                  | 2.2361                      | 0.0419 |
|               | 130 mm      | 2.3204                  | 2.2122                      | 0.0355 |
|               | 258 mm      | 2.3581                  | 2.2681                      | 0.0391 |

| Band height (m) |                   | Standard deviation ($\sigma$) |       |
|-----------------|-------------------|-----------------------------|-------|
| (a)             | 66 mm             | 0.0419                      |       |
| (b)             | 130 mm            | 0.0355                      |       |
| (c)             | 258 mm            | 0.0391                      |       |

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**Figure 7:** Results of the 2D fractal method for the SLZ bedrock fault surface. The fault surface has three pairs of results shown in (a), (b), and (c), which are generated by moving windows with three different sizes (66 × 66 mm, 130 × 130 mm, and 258 × 258 mm), respectively. See Figure 6 and text for details.
on the JCF since the Holocene [58, 61]. In addition, the JCF is located between the Taiyuan Basin and the Lvliang Mountains. The resistance to erosion is different between the hanging wall, consisting of Paleozoic and Mesozoic limestone, and the footwall, consisting of loose Quaternary deposits, such as loess. The latter is easily influenced by the weak hydrodynamic conditions; therefore, exposure of the fault scarp is likely to be controlled by both seismic activity of the fault and the erosion of loose deposits on the hanging wall. Previous studies indicate that the average sedimentary rate near Shansi area is 0.078 mm/yr [80] to 0.15 mm/yr. Considering that the average recurrence interval of 3 seismic events of the aimed fault is 2.58 m.yr [58, 61], the sediment thickness during the interseismic period could be 20-38 cm. The average coseismic slip is about 2 m of the aimed fault in this study, so the sediment thickness during the interseismic period accounts for about 10-20% of the average coseismic slip of the aimed fault. It is important to distinguish erosion processes and seismic events in places where erosion processes may exist, especially in loess areas. Since there is no large gully developed around the study sites (SXC and SLZ) and the scan areas were selected to be at a sufficient distance from small gullies at the foot of the mountain (Figures 4(a) and 5(a)), the two bedrock fault scarps could not be affected by strong erosion. Accordingly, we can exclude the existence possibility of intermittent strong erosion which is easily confused with the effect of seismic events. Since the weak hydrodynamic erosion is usually a continuous process, the segmentation could not be produced by such a process. When the statistical method was used to divide the segments, some gradual changes in the fractal curve were observed (Figures S1 and S2), confirming that the transition zones between adjacent segments are caused by the gradual erosion of loess during the interseismic period, dominated by weak hydrodynamics.

In a model where the morphological segments of the fault scarp are mainly the result of repeated seismic events, the three morphological segments of the SLZ and SXC fault scarps would represent seismic events, and the coseismic slips can be estimated by the heights of these segments. The length of surface rupture \((L)\) and the displacement \((D)\) on continental faults are the most commonly used parameters for estimating the magnitude of paleoearthquakes [4, 81]. However, the length of surface rupture for a prehistoric earthquake is usually not easy to obtain. The coseismic displacement not only reflects the seismic energy release but also is positively correlated with the magnitude of the earthquake [81]. Therefore, in this study, the coseismic displacements obtained by the morphological analysis of bedrock fault surfaces can be used to estimate magnitude. Based on the results from the fractal analysis method, the three segments, segment 1, segment 2, and segment 3, on the SXC bedrock fault surface are considered to represent three earthquakes, E1, E2, and E3, with respective coseismic slips of 2 m, 1.9 m, and 2.3 m in the dip direction. The corresponding magnitudes, calculated by the empirical formulas between magnitude \((M)\) and displacement \((D)\) for normal faults in North China, as proposed by Liu and Wang in 1996 [82], are estimated to be \(M_{S7.5}\), \(M_{S7.5}\), and \(M_{S7.6}\), respectively (Figure 8(a)). According to the fault dip of 60° measured in the field, the vertical coseismic slips of E1, E2, and E3 are 1.74 m, 1.65 m, and 1.99 m, respectively. Similarly, morphology segments 1 to 3 identified on the SLZ fault surface are considered to indicate earthquakes E1, E2, and E3 with respective coseismic dip slips of 1.4 m, 2.5 m, and 2 m, coseismic vertical slips of 1.32 m, 2.35 m, and 1.88 m, and magnitudes of \(M_{S7.4}\), \(M_{S7.6}\), and \(M_{S7.5}\). In the profile of the SLZ fault scarp, there is an obvious slope break at 7 m, and the surface of the fault scarp starts to degrade and retreat above this height, which may indicate earlier event(s); however, they have not been obtained in this study (Figure 8(b)).

The southern segment is inactive since the late Pleistocene [64], and the northern and middle segments have the characteristics of synchronous seismic activity [58, 60]. To show the seismic capacity of the whole aimed fault, the coseismic displacement \((D)\) and total length \((L, \sim 105 \text{ km})\) of the northern and middle segments are comprehensively considered to estimate the magnitude. The magnitudes of earthquakes E1, E2, and E3 identified on the SXC fault surface, calculated by the empirical formulas between magnitude \((M)\) and length multiplied by displacement \((L D)\) for normal faults in North China, as proposed by Liu and Wang in 1996 [82], are estimated to be \(M_{S7.8}\), \(M_{S7.8}\), and \(M_{S7.9}\), respectively (Figure 8(a)). Similarly, the corresponding magnitudes of earthquakes E1, E2, and E3 identified on the SLZ fault surface are estimated to be \(M_{S7.7}\), \(M_{S7.9}\), and \(M_{S7.8}\), respectively, by the empirical formula \(M = LD\) (Figure 8(b)). Previous studies indicate that the northern and middle segments of the JCF have a seismogenic capacity of \(M > 7\) based on the estimated coseismic slips from the trenching method [58, 62]. This study suggests that the northern and middle segments are able to produce earthquakes together with magnitudes greater than 7.5, which is basically consistent with the previous studies.

The distance between the two study sites SXC and SLZ is about 22 km, and the minor difference in coseismic slips and magnitudes obtained from the two study sites may reflect
are estimated to be 3.06-3.53, 5.32-6.14, and 8.36-8.56 kyr, with corresponding earthquake ages determined by radiocarbon dating [58] and the ages derived from thermoluminescence dating [61], indicating that the northern and middle segments are characterized by Holocene seismic activity. Following event window analysis [83, 84] of the above dates, the ages of three paleoearthquakes are corrected to 8.36-8.56 kyr, 5.32-6.14 kyr, and 3.06-3.53 kyr, with a recurrence interval of ~2.6 kyr and an elapsed time (since the last earthquake) of ~3 kyr (Figure 9(b)).

Although the paleoearthquake history of the JCF has been well-established in terms of ages of the seismic events by previous studies [58, 61], the accurate coseismic slip of each seismic event is still unclear. The coseismic slip based on the traditional trenching method is 1.5-4.7 m, showing a large uncertainty range [58]. Due to lack of stratigraphic markers, this value is mainly estimated by the strata depth of the hanging wall and therefore has a large error range. The coseismic slips of the 3 seismic events estimated from the average height of each level knickpoint are 2.8 m, 3 m, and 2.6 m, respectively [60]. It should be noted that these values are not directly measured on the fault, which was severely destroyed by strong erosion. The coseismic slips in this study are directly obtained from the two bedrock fault surfaces, which are more accurate and reliable.

The previous trench and knickpoint studies indicate that the northern and middle segments experienced 3 ruptured events (8.36-8.56 kyr, 5.32-6.14 kyr, and 3.06-3.53 kyr) and have the characteristics of synchronous seismic activity since the beginning of the Holocene [58, 61, 64]. This study also reveals 3 ruptured events and their corresponding coseismic slips. In the absence of measured age constraints on the fault scarps studied here, it is necessary to make a good agreement in the amplitude of the fault along the strike during an earthquake event. Based on the comprehensive results of the above two study sites, the vertical coseismic slips of the three paleoearthquakes in the northern segment of the JCF are 1.32-1.74 m, 1.65-2.35 m, and 1.88-1.99 m, and the corresponding magnitudes are $M_s$7.4-$M_s$7.8, $M_s$7.5-$M_s$7.9, and $M_s$7.5-$M_s$7.9.

### 4.3. Paleoearthquake History and Slip Rate of the JCF

Due to the lack of direct dating (e.g., exposure ages) of the fault surfaces studied here, we compared the results of this study with previous research to establish a more complete paleoearthquake history of the JCF (Figure 9). The northern and middle segments of the JCF were active in the Holocene, while the southern segment remained inactive since the late Pleistocene [64]. Previous studies have determined ages for paleoearthquakes recorded in the JCF. Xie et al. [61] defined three paleoearthquakes on the northern and middle segments through the excavation of four trenches in 2008 (XZ, ZY, SGY, and XM1 in Figure 9(a)). According to thermoluminescence dating, the corresponding earthquake ages are estimated to be 3.06-3.53, 5.32-6.14, and ~8.36 kyr (Figure 9(b)). A similar study carried out by Guo et al. in 2012 [58] also revealed three paleoearthquakes on the northern and middle segments through the excavation of three trenches (LWG, XM2, and WY in Figure 9(a)). The corresponding earthquake ages determined by radiocarbon dating are 3.06-3.74, ~5.91, and 8.53-8.56 kyr (Figure 9(b)). Regarding the number of paleoearthquakes, both the studies conducted by Xie et al. in 2008 [61] and Guo et al. in 2012 [58] suggest that the northern and middle segments of the fault experienced three paleoearthquakes, which is in good agreement with the morphologic results of the bedrock fault scarps in this study. In terms of the activity time, the paleoearthquake ages obtained by radiocarbon dating [58] are highly consistent with the ages derived from thermoluminescence dating [61], indicating that the northern and middle segments are characterized by Holocene seismic activity. Following event window analysis [83, 84] of the above dates, the ages of three paleoearthquakes are corrected to 8.36-8.56 kyr, 5.32-6.14 kyr, and 3.06-3.53 kyr, with a recurrence interval of ~2.6 kyr and an elapsed time (since the last earthquake) of ~3 kyr (Figure 9(b)).

Although the paleoearthquake history of the JCF has been well-established in terms of ages of the seismic events by previous studies [58, 61], the accurate coseismic slip of each seismic event is still unclear. The coseismic slip based on the traditional trenching method is 1.5-4.7 m, showing a large uncertainty range [58]. Due to lack of stratigraphic markers, this value is mainly estimated by the strata depth of the hanging wall and therefore has a large error range. The coseismic slips of the 3 seismic events estimated from the average height of each level knickpoint are 2.8 m, 3 m, and 2.6 m, respectively [60]. It should be noted that these values are not directly measured on the fault, which was severely destroyed by strong erosion. The coseismic slips in this study are directly obtained from the two bedrock fault surfaces, which are more accurate and reliable.
The fault slip rate is another key parameter concerning fault activity. Based on the cumulative slip of 6.2 m from the SXC fault surface and a corresponding age of 8.36-8.56 kyr, the dip slip rate is estimated to be 0.72-0.74 mm/yr. A dip angle of 60° for the SXC fault surface leads to a vertical slip rate of 0.63-0.64 mm/yr on the northern segment of the JCF. Similarly, for the SLZ fault surface, based on the cumulative slip of 5.9 m and a corresponding age of 8.36-8.56 kyr, a dip slip rate of 0.69-0.71 mm/yr is estimated. Again, considering there is a dip angle of 70°, the corresponding vertical slip rate becomes 0.64-0.67 mm/yr. We provided a systematic summary about the slip rate of the JCF, which can be used as a reference frame (Figure S5). Previous studies show that the slip rate of the JCF is 0.58-0.86 mm/yr in the northern segment [64], which is in good agreement with the above two survey sites. It indirectly reflects the accuracy of the coseismic slip we obtained and the rationality of event matching.

It should be pointed out however that the prerequisite for the event match and the slip rate estimate is that the two bedrock fault scarps are produced by the 3 Holocene seismic events identified in previous research. Although we have provided more evidence and conducted further discussion to support seismic event match, it still lacks the absolute age constraints. Ideally, an absolute dating would be robust evidence to constrain the age of the bedrock fault outcrop, which has been applied to a number of case studies of bedrock normal faults [16, 27, 31, 34]. However, it needs a large amount of time and labor. As a result, we are unable to carry out this work soon. In the future, it is better to be supported by this robust method. Zou et al. in 2020 recovered the seismic history of Luoyunshan bedrock fault in southern Shanxi correlation between the seismic event sequence obtained in this study and previous studies. Besides the same number of seismic events found in this study and previous research, there are other three important pieces of evidence to support a correlation. The first is the scale of displacement for each event. Previous trench studies reveal that the magnitudes of the 3 earthquake events are greater than 7 [58], which is consistent with the results of this study (Figure 8). This indicates that 3 seismic events of similar magnitude are recorded both in trenches and on bedrock scarps. The second is that for each of the two bedrock fault outcrops, there is an excavated trench nearby, and the bedrock fault site and corresponding trench are close to each other (within 2 km) (Figures 1(b) and 9(a) and Figure S4). More importantly, the two bedrock fault sites and the excavated trenches nearby are on the same fault segment while there is no evidence of branch faults nearby (Figure 1(b) and Figure S4). The conditions above ensure that the latest three seismic events (in the Holocene) can be recorded both in the trenches and on the bedrock scarps. As for the seismic information prior to the Holocene, it may remain in certain study sites such as SLZ fault scarp (Figure 8(b)), but it is difficult to recognize and analyze. Thus, it is feasible to combine this study result with previous researches to obtain more complete paleoearthquake information of the JCF in the Holocene and make a more reasonable seismic risk assessment. Considering a recurrence interval of \(2.6 \text{ kyr}\), an elapsed time of more than 3 kyr, and the capacity of producing earthquakes with a coseismic slip greater than 2 m and magnitude greater than 7.5, the seismic hazard on the northern and middle segments of the JCF requires immediate attention.

Figure 9: Schematic map and paleoearthquake information of the JCF since the Holocene. (a) The schematic map of JCF. The red, green, and blue lines represent the north, middle, and south segments of the JCF, respectively. The yellow rectangles indicate the locations of the bedrock fault planes in this study, while the black and blue rectangles represent the locations of the trenches excavated by two previous researchers. The paleoearthquake information is shown in (b). The black and blue shaded bars represent three paleoearthquake events obtained by Xie et al. [61] in 2008 and Guo et al. [58] in 2012 through the trenching technique. The trench names are listed to the left, and the corresponding locations are marked by the black and blue rectangles. The numbers in the dashed ellipses indicate the coseismic slips obtained in this study. The numbers in the black and blue rectangles indicate the ages of the three paleoearthquake events obtained by Xie et al. [61] in 2008 and Guo et al. [58] in 2012, respectively.
Rift by combining the morphology results with the absolute ages [33], providing a feasible workflow. In future work, a series of $^{36}$Cl rock samples should be collected from the bedrock fault surfaces of the JCF and measured by Accelerator Mass Spectrometry (AMS) to determine the ages of each event interpreted from the morphology analysis.

4.4. Significance of Paleoearthquake Studies within the Bedrock Area. Typically, the normal faults at a basin-mountain boundary zone spatially separate two areas along a strike: the bedrock areas and the sedimentary areas (Figure 10(a)). The traditional method to study an active fault is based on analyzing displaced Quaternary deposits via the trenching technique [5–8, 10]. Therefore, its focused objects are the fault segments spreading into sedimentary areas with attention paid to Quaternary stratigraphic markers. The paleoearthquake study of bedrock fault surfaces focuses on fault scarps spreading into bedrock areas, increasing the number of sites available for study both spatially and temporally, providing a more complete understanding of the fault behavior. Trenching in sedimentary areas is an effective method for extracting the number and ages of earthquakes and establishing a paleoearthquake history. In comparison, the advantages of bedrock fault surface morphology analysis lie in the ability to rapidly identify seismic events and accurately measure coseismic slips. This helps to obtain the frequency of seismic events and evaluate the seismic capacity of a fault, as shown in this study. The combination of these two methods allows for the extraction of more faulting information, the synthesis of a more complete paleoearthquake reconstruction, and a better assessment of seismic hazards (Figure 10(b)).

5. Conclusions

The study of bedrock fault surfaces using a combination of aerial survey, field identification of weathering bands, and quantitative high-resolution morphology analysis can provide theoretical and methodological support for the research of active faults in bedrock areas. It is an effective method for efficiently identifying the number of paleoearthquakes, accurately obtaining the coseismic slip of individual paleoearthquakes, reasonably evaluating the seismic capacity of faulting in bedrock areas, and greatly expanding the number of study sites, thereby broadening the spatial and temporal understanding of events. Fractal analyses of the SXC and SLZ bedrock fault surfaces on the JCF show that both surfaces have the characteristics of vertical segmentation. This kind of segmentation feature indicates that the fault surfaces are exposed intermittently, likely due to periodic earthquakes. Thus, earthquake events can be identified by determining morphological segments, and the corresponding coseismic slip can be determined by the height of the identified segments. These kinds of studies complement the traditional trenching method in sedimentary areas, allowing for the extraction of more paleoseismic information and a fuller understanding of the activity behavior of the whole fault.

Figure 10: Normal fault distribution model at the basin-mountain boundary zone and combination significance of the two paleoearthquake study methods. (a) Model of a normal fault at the basin-mountain boundary zone. One fault is spreading along the strike in the bedrock and sedimentary areas. (b) The significance of combining the traditional trenching method, suitable for sedimentary areas, and quantitative morphology analysis, suitable for bedrock areas.
This study is also meaningful for seismic hazard assessment in the densely populated Taiyuan Basin. Based on high-precision quantitative morphology analysis of the bedrock fault surface, three paleoearthquake events are identified on both the SXC and SLZ bedrock fault scarps, which is consistent with the previous trenching results in sedimentary areas. The results suggest that the JCF is dominated by stick slip behavior and has the ability to produce earthquakes with magnitudes greater than 7.5. Considering the high slip rate, the capacity of producing $M > 7.5$ earthquakes, a recurrence interval of $>2.6$ kyr, and an elapsed time of more than 3 kyr since the last earthquake, full attention needs to be paid to potential seismic hazards on the northern and middle segments of the JCF. Since the absolute dating work has not been carried out on the bedrock fault outcrops, the lack of chronological evidence is the limitation of this study. In situ cosmogenic nuclide dating such as $^{36}$Cl should be carried out on the bedrock fault outcrops to provide a robust age constraint, which is also the focus of our future work.

Data Availability
The authors confirm that the data supporting the findings of this study are available within the article.

Conflicts of Interest
We declare that we have no financial and personal relationships with other people or organizations that can appropriately influence our work.

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Supplementary Materials
Figure S1: morphologic segment and segment height determination for the SXC bedrock fault surface by Student’s $t$-test. Figure S2: morphologic segment and segment height determination for the SLZ bedrock fault surface by Student’s $t$-test. Figure S3: schematic diagram of the bedrock fault scarp exhumation and the corresponding fractal curve. Figure S4: locations of the bedrock fault surfaces and nearby trenches. Figure S5: summary of the vertical slip rates for the JCF [64, 65, 85, 86]. (Supplementary Materials)

References
[1] Q. Deng, L. Chen, and Y. Ran, “Quantitative studies and applications of active tectonics,” *Earth Science Frontiers*, vol. 11, no. 4, pp. 383–392, 2004.
[2] T. Parsons, S. Toda, R. S. Stein, A. Barka, and J. H. Dieterich, “Heightened odds of large earthquakes near Istanbul: an interaction-based probability calculation,” *Science*, vol. 288, no. 5466, pp. 661–665, 2000.
[3] R. E. Wallace, “Active faults, paleoseismology, and earthquake hazards in the western United States,” *Earthquake Prediction*, vol. 4, pp. 209–216, 2013.
[4] J. Mccalpin, *Paleoseismology*, Academic Press, 2nd edition, 1996.
[5] K. E. Sieh, “Prehistoric large earthquakes produced by slip on the San Andreas Fault at Pallet Creek, California,” *Journal of Geophysical Research*, vol. 83, no. B8, pp. 3907–3939, 1978.
[6] K. E. Sieh, “Lateral offsets and revised dates of large earthquakes at Pallet Creek, California,” *Journal of Geophysical Research*, vol. 89, no. B9, pp. 7641–7670, 1980.
[7] P. Galli, F. Galadini, and D. Pantosti, “Twenty years of paleoseismology in Italy,” *Earth-Science Reviews*, vol. 88, no. 1–2, pp. 89–117, 2008.
[8] J. J. Young, J. R. Arrowsmith, L. Colini, L. B. Grant, and B. Gootee, “Three-dimensional excavation and recent rupture history along the Cholame segment of the San Andreas fault,” *Bulletin of the Seismological Society of America*, vol. 92, no. 7, pp. 2670–2688, 2002.
[9] G. E. Hilley and J. J. Young, “Deducing paleoearthquake timing and recurrence from paleoseismic data, part I: evaluation of new Bayesian Markov-chain Monte Carlo simulation methods applied to excavations with continuous peat growth,” *Bulletin of the Seismological Society of America*, vol. 98, no. 1, pp. 383–406, 2008.
[10] Y. Ran, L. Chen, J. Chen et al., “Paleoseismic evidence and repeat time of large earthquakes at three sites along the Longmenshan fault zone,” *Tectonophysics*, vol. 491, no. 1–4, pp. 141–153, 2010.
[11] P. Galli and V. Bosi, “Catastrophic 1638 earthquakes in Calabria (southern Italy): new insights from paleoseismological investigation,” *Journal of Geophysical Research*, vol. 108, no. B1, pp. ETG 1-1–ETG 120, 2003.
[12] P. Galli and E. Peronace, “New paleoseismic data from the Irpinia Fault. A different seismogenic perspective for southern Apennines (Italy),” *Earth-Science Reviews*, vol. 136, pp. 175–201, 2014.
[13] L. Mayer, “Dating Quaternary fault scarps formed in alluvium using morphologic parameters,” *Quaternary Research*, vol. 22, no. 3, pp. 300–313, 1984.
[14] I. S. Stewart, *Sensitivity of Fault-Generated Scarps as Indicators of Active Tectonism: Some Constrains from the Aegean Region*, John Wiley, Chichester, UK, 1993.
[15] I. S. Stewart, “A rough guide to limestone fault scarps,” *Journal of Structural Geology*, vol. 18, no. 10, pp. 1259–1264, 1996.
[16] M. Zreda and J. S. Noller, “Ages of prehistoric earthquakes revealed by cosmogenic chlorine-36 in a bedrock fault scarp at Hebgen Lake,” *Science*, vol. 282, no. 5391, pp. 1097–1099, 1998.
[17] L. Benedetti, R. Finkel, D. Papanastassiou et al., “Post-glacial slip history of the Sparta Fault (Greece) determined by $^{36}$Cl cosmogenic dating: evidence for non-periodic earthquakes,” *Geophysical Research Letters*, vol. 29, no. 8, pp. 87–1–87–4, 2002.
[18] A. Schlagenhauf, Y. Gaudemer, L. Benedetti et al., “Using in situ chlorine-36 cosmoneucleid to recover past earthquake histories on limestone normal fault scarps: a reappraisal of
methodology and interpretations," Geophysical Journal International, vol. 182, no. 1, pp. 36–72, 2010.

[19] A. Schlagenhaufer, I. Manighetti, L. Benedetti et al., “Earthquake supercycles in Central Italy, inferred from 36Cl exposure dating,” Earth and Planetary Science Letters, vol. 307, no. 3-4, pp. 487–500, 2011.

[20] P. A. Cowie, R. J. Phillips, G. P. Roberts et al., “Orogen-scale uplift in the central Italian Apennines drives episodic behaviour of earthquake faults,” Scientific Reports, vol. 7, no. 1, article 44858, 2017.

[21] S. Mechernich, S. Schneiderwind, J. Mason et al., “The seismic history of the Pisia fault (eastern Corinth rift, Greece) from fault plane weathering features and Cosmogenic36Cl dating,” Journal of Geophysical Research: Solid Earth, vol. 123, no. 5, pp. 4266–4284, 2018.

[22] A. Tye and T. Stahl, “Field estimate of paleoearthquake slip on a normal fault using the Schmidt hammer and terrestrial LiDAR: methods and application to the Hebgen fault (Montana, USA),” Earth Surface Processes and Landforms, vol. 43, no. 11, pp. 2397–2408, 2018.

[23] T. Stahl and A. Tye, “Schmidt hammer and terrestrial laser scanning (TLS) used to detect single event displacements on the Pleasant Valley fault (Nevada, USA),” Earth Surface Processes and Landforms, vol. 45, no. 2, pp. 473–483, 2020.

[24] S. G. Mitchell, Measuring fault displacement rates using in-situ cosmogenic 36Cl: the displacement of the Nahef East bedrock fault scarp in northern Israel, The Faculty of Geology Department, the University of Vermont, 1998.

[25] S. G. Mitchell, A. Matmon, P. R. Bierman, Y. Enzel, M. Cafée, and D. Rizzo, “Displacement history of a limestone normal fault scarp, northern Israel, from cosmogenic36Cl,” Journal of Geophysical Research: Solid Earth, vol. 106, no. B3, pp. 4247–4264, 2001.

[26] L. Benedetti, R. Finkel, G. King et al., “Motion on the Kaparelli Fault (Greece) prior to the 1981 earthquake sequence determined from 36Cl cosmogenic dating.” Terra Nova, vol. 15, no. 2, pp. 118–124, 2003.

[27] L. Benedetti, I. Manighetti, Y. Gaudemer et al., “Earthquake synchrony and clustering on Fucino faults (Central Italy) as revealed from in situ36Cl exposure dating,” Journal of Geophysical Research: Solid Earth, vol. 118, no. 9, pp. 4948–4974, 2013.

[28] V. Mouslopoulou, D. Moraets, and C. Fassoulas, “Identifying past earthquakes on carbonate faults: Advances and limitations of the ‘Rare Earth Element’ method based on analysis of the Spili Fault, Crete, Greece,” Earth and Planetary Science Letters, vol. 309, no. 1-2, pp. 45–55, 2011.

[29] B. Giaccio, F. Galadini, A. Sposato et al., “Image processing and roughness analysis of exposed bedrock fault planes as a tool for paleoseismological analysis: results from the Campo Felice fault (central Apennines, Italy),” Geomorphology, vol. 49, no. 3-4, pp. 281–301, 2003.

[30] H. J. Goodall, L. C. Gregory, L. N. J. Wedmore et al., “Determining histories of slip on normal faults with bedrock scarps using cosmogenic nuclide exposure data,” Tectonics, vol. 40, no. 3, 2021.

[31] L. Palumbo, L. Benedetti, D. Bourlés, A. Cinque, and R. Finkel, “Slip history of the Magnola fault (Apennines, Central Italy) from 36Cl surface exposure dating: evidence for strong earthquakes over the Holocene,” Earth and Planetary Science Letters, vol. 225, no. 1–2, pp. 163–176, 2004.

[32] H. He, Z. Wei, and A. Densmore, “Quantitative morphology of bedrock fault surfaces and identification of paleo-earthquakes,” Tectonophysics, vol. 693, pp. 22–31, 2016.

[33] J. J. Zou, H. L. He, Y. Yokoyama et al., “Seismic history of a bedrock fault scarp using qualitative morphology together with multiple dating methods: a case study of the Luoyunshan piedmont fault, southwestern Shanxi Rift, China,” Tectonophysics, vol. 788, p. 228473, 2020.

[34] L. Benedetti and J. van der Woerd, “Cosmogenic nuclide dating of earthquakes, faults, and toppled blocks,” Elements, vol. 10, no. 5, pp. 357–361, 2014.

[35] J. Carcaillot, I. Manighetti, C. Chauvel, A. Schlagenhaufer, and J. M. Nicole, “Identifying past earthquakes on an active normal fault (Magnola, Italy) from the chemical analysis of its exhumed carbonate fault plane,” Earth and Planetary Science Letters, vol. 271, no. 1–4, pp. 145–158, 2008.

[36] J. C. Hippolyte, G. Brocard, M. Tardy et al., “The recent fault scarps of the Western Alps (France): tectonic surface ruptures or gravitational sackung scarps? A combined mapping, geomorphic, levelling, and 26Al dating approach,” Tectonophysics, vol. 418, no. 3–4, pp. 255–276, 2006.

[37] P. Kong, D. Fink, C. G. Na, and W. Xiao, “Dip-slip rate determined by cosmogenic surface dating on a Holocene scarp of the Daju fault, Yunnan, China,” Tectonophysics, vol. 493, no. 1-2, pp. 106–112, 2010.

[38] X. Shen, D. Li, Y. Tian, Y. W. Lv, D. W. Li, and Y. F. Li, “Late Pleistocene - Holocene slip history of the Langshan-Seertengshan piedmont fault (Inner Mongolia, northern China) from cosmogenic 10Be dating on a bedrock fault scarp,” Journal of Mountain Science, vol. 13, no. 5, pp. 882–890, 2016.

[39] J. Tesson and L. Benedetti, “Seismic history from in situ 36Cl cosmogenic nuclide data on limestone fault scarps using Bayesian reversible jump Markov chain Monte Carlo,” Quaternary Geochronology, vol. 52, pp. 1–20, 2019.

[40] J. Tesson, B. Pace, L. Benedetti et al., “Seismic slip history of the Pizzalto fault (central Apennines, Italy) using in situ-produced36Cl cosmic ray exposure dating and rare earth element concentrations,” Journal of Geophysical Research: Solid Earth, vol. 121, no. 3, pp. 1983–2003, 2016.

[41] J. Tesson, L. Benedetti, V. Godard, C. Novaes, J. Fleury, and the ASTER Team, “Slip rate determined from cosmogenic nuclides on normal-fault facets,” Geology, vol. 49, no. 1, pp. 66–70, 2021.

[42] R. E. Wallace, “Fault scarps formed during the earthquake of October 2, 1915, Pleasant Valley, Nevada and some tectonic implications,” in Faulting Related to the 1915 Earthquakes in Pleasant Valley, Nevada, vol. 1274-A, pp. 1–33, United States Geological Survey Professional Paper, Alexandria, VA, USA, 1984.

[43] G. E. Tucker, S. W. McCoy, A. C. Whittaker, G. P. Roberts, S. T. Lancaster, and R. Phillips, “Geomorphic significance of postglacial bedrock scarps on normal-fault foothills,” Journal of Geophysical Research, vol. 116, no. F1, 2011.

[44] G. de Guidi, F. Brighenti, F. Carnemolla, D. Cataldo, and A. G. Piro, “New dating of rapid vertical deformation of Santa Tecla Fault scarps (Mt. Etna volcano, Sicily) by lichenometry method,” Quaternary International, vol. 525, pp. 78–88, 2019.

[45] I. Manighetti, E. Boucher, C. Chauvel, A. Schlagenhaufer, and L. Benedetti, “Rare earth elements record past earthquakes on exhumed limestone fault planes,” Terra Nova, vol. 22, no. 6, pp. 477–482, 2010.
[46] M. Luo, *Optical Stimulated Luminescence Dating of Rock Surfaces*, Institute of Geology, China Earthquake Administration, 2016.

[47] R. R. Jones, S. Kokkalas, and K. J. W. McCaffrey, "Quantitative analysis and visualization of nonplanar fault surfaces using terrestrial laser scanning (LiDAR)—the Arkitsa fault, Central Greece, as a case study," *Geosphere*, vol. 5, no. 6, pp. 465–482, 2009.

[48] Z. Y. Wei, H. L. He, and F. Shi, "Weathering history of an exposed bedrock fault surface interpreted from its topography," *Journal of Structural Geology*, vol. 56, pp. 34–44, 2013.

[49] E. E. Brodsky, J. J. Gilchrist, A. Sagy, and C. Collettini, "Faults smooth gradually as a function of slip," *Earth and Planetary Science Letters*, vol. 302, no. 1–2, pp. 185–193, 2011.

[50] T. Candela, F. Renard, J. Schmittbuhl, M. Bouchon, and E. E. Brodsky, "Fault slip distribution and fault roughness," *Geophysical Journal International*, vol. 187, no. 2, pp. 959–968, 2011.

[51] J. Mason, S. Schneiderwind, A. Pallikarakis et al., "Fault structure and deformation rates at the Lastros-Sfaka Graben, Crete," *Tectonophysics*, vol. 683, pp. 216–232, 2016.

[52] F. Renard, K. Mair, and O. Gundersen, "Surface roughness evolution on experimentally simulated faults," *Journal of Structural Geology*, vol. 45, pp. 101–112, 2012.

[53] A. Sagy and E. E. Brodsky, "Geometric and rheological asperities in an exposed fault zone," *Geophysical Research*, vol. 114, no. B2, pp. 2301, 2009.

[54] S. Schneiderwind, J. Mason, T. Wiatr, I. Papanikolaou, and K. Reicherter, "3-D visualisation of palaeoseismic trench stratigraphy and trench logging using terrestrial remote sensing and GPR – a multiparametric interpretation," *Solid Earth*, vol. 7, no. 2, pp. 323–340, 2016.

[55] S. Schneiderwind, S. J. Boulton, I. Papanikolaou, and K. Reicherter, "Innovative tidal notch detection using TLS and fuzzy logic: implications for palaeo-shorelines from compressional (Crete) and extensional (Gulf of Corinth) tectonic settings," *Geomorphology*, vol. 283, pp. 189–200, 2017.

[56] M. Wilkinson, G. P. Roberts, K. McCaffrey et al., "Slip distributions on active normal faults measured from LiDAR and field mapping of geomorphic offsets: an example from L’Aquila, Italy, and implications for modelling seismic moment release," *Geomorphology*, vol. 237, pp. 130–141, 2015.

[57] T. Wiatr, I. Papanikolaou, T. Fernández-Steeger, and K. Reicherter, "Bedrock fault scarp history: insight from LiDAR backscatter behaviour and analysis of structure changes," *Geomorphology*, vol. 228, pp. 421–431, 2015.

[58] H. Guo, W. L. Jiang, and X. S. Xie, "Analysis of Holocene faulting phenomena revealed in the three trenches along the Jiaocheng Fault, Shanxi," *Seismology and Geology*, vol. 34, no. 1, pp. 76–92, 2012.

[59] Working Group on Historical Earthquake Compilation of Shanxi Province Earthquake Administration (WGHECSPA), *Compilation of historical earthquake literature in Shanxi Province*, Seismological Publishing House, Beijing, 1991.

[60] C. B. Sun, X. S. Xie, and W. L. Jiang, "Distribution of the knipoints in fluvial gullies in response to the events of Holocene fault activity: a case study of the Jiaocheng Fault in Shanxi," *Seismology and Geology*, vol. 34, no. 2, pp. 254–267, 2012.

[61] X. S. Xie, W. L. Jiang, and C. B. Sun, "Comparison study on Holocene palaeoseismic activities among multi- trenches along the Jiaocheng Fault zone, Shanxi," *Seismology and Geology*, vol. 30, no. 2, pp. 412–430, 2008.

[62] Z. H. Li, J. Y. Zeng, and H. L. Ran, "Evaluation of the maximum potential earthquake probability in the northern section of Jiaocheng Fault zone," *Technology for Earthquake Disaster Prevention*, vol. 9, no. 4, pp. 770–781, 2014.

[63] Active Fault System around Ordos Massif, *The Research Group on Active Fault System around Ordos Massif*, State Seismological Bureau, Beijing, 1988.

[64] B. Q. Ma, G. L. Xu, X. Q. Sheng, D. Y. Cao, S. R. Zhang, and X. S. Mu, A Study on Tectonogeomorphology along the Jiaocheng Fault, Shanxi Province, Institute of Crustal Dynamics, China Earthquake Administration, 1999.

[65] G. L. Xu, B. Q. Ma, and W. L. Jiang, The behavior and segmentation of the Shanxi Jiaocheng active fault, Institute of Crustal Dynamics, China Seismological Bureau, 1998.

[66] H. Y. Bi, W. J. Zheng, J. Y. Zeng, J. X. Yu, and Z. K. Ren, "Application of SM photogrammetry method to the quantitative study of active tectonics," *Seismology and Geology (in Chinese)*, vol. 39, no. 4, pp. 656–674, 2017.

[67] Z. K. Ren, Z. W. Zhang, T. Chen et al., "Clustering of offsets on the Haiyuan Fault and their relationship to paleoearthquakes," *Geological Society of America Bulletin*, vol. 128, no. 1–2, pp. B31155.1–B3115518, 2015.

[68] O. Zielke, J. R. Arrowsmith, L. Grant Ludwig, and S. O. Akciz, "High-Resolution Topography-Derived Offsets along the 1857 Fort Tejon earthquake rupture trace, San Andreas Fault," *Bulletin of the Seismological Society of America*, vol. 102, no. 3, pp. 1135–1154, 2012.

[69] A. Sagy, E. E. Brodsky, and G. J. Axen, "Evolution of fault-surface roughness with slip," *Geology*, vol. 35, no. 3, pp. 283–286, 2007.

[70] W. L. Power and T. E. Tullis, "Euclidean and fractal models for the description of rock surface-roughness," *Journal of Geophysical Research*, vol. 96, no. B1, pp. 415–424, 1991.

[71] C. G. Chase, "Fluvial land sculpturing and the fractal dimension of topography," *Geomorphology*, vol. 5, no. 1–2, pp. 39–57, 1992.

[72] S. Davies and P. Hall, "Fractal analysis of surface roughness by using spatial data," *Journal of the Royal Statistical Society: Series B (Statistical Methodology)*, vol. 61, no. 1, pp. 3–37, 1999.

[73] L. Bi, H. He, Z. Wei, and F. Shi, "Fractal properties of landforms in the Ordos block and surrounding areas, China," *Geomorphology*, vol. 175-176, pp. 151–162, 2012.

[74] B. Klinkenberg, "Fractals and morphometric measures: is there a relationship?" *Geomorphology*, vol. 5, no. 1–2, pp. 5–20, 1992.

[75] Q.-C. Sung and Y.-C. Chen, "Self-affinity dimensions of topography and its implications in morphotectonics: an example from Taiwan," *Earthquake Geology*, vol. 62, no. 3–4, pp. 181–198, 2004.

[76] J. K. Elliott, "An investigation of the change in surface roughness through time on the foreland of Austre Okstindbreen, North Norway," *Computational Geosciences*, vol. 15, no. 2, pp. 209–217, 1989.

[77] B. B. Mandelbrot, "How long is the coast of Britain? Statistical self-similarity and fractional dimension," *Science*, vol. 156, no. 3775, pp. 636–638, 1967.

[78] T. Xu, I. D. Moore, and J. C. Gallant, "Fractals, fractal dimensions and landscapes – a review," *Geomorphology*, vol. 8, no. 4, pp. 245–262, 1993.
[79] Q. Sung, Y. Chen, and P. Chao, "Spatial variation of fractal parameters and its geological implications," *Terrestrial, Atmospheric and Oceanic Sciences*, vol. 9, no. 4, pp. 655–672, 1998.

[80] J. Z. Sun and H. H. Li, "Depositional rate of the Malan loess and its geological significance," *Acta Sedimentological Sinica*, vol. 7, no. 1, pp. 109–116, 1989.

[81] D. L. Wells and K. J. Coppersmith, "New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement," *Bulletin of the Seismological Society of America*, vol. 84, no. 4, pp. 974–1002, 1994.

[82] J. Liu and L. Wang, "Discussion on coefficients of statistical regressions between magnitude and earthquake rupture parameters," *Seismology and Geology*, vol. 18, no. 3, pp. 225–236, 1996.

[83] F. Y. Mao and P. Z. Zhang, *Progressive constraining method in paleoseismic study and paleoearthquakes along the major active faults in northern Xinjiang*, Institute of Geology, China Earthquake Administration, 1995.

[84] M. W. West, "Neotectonics of the Bear River fault zone," Colorado School of Mines, Uinta County, Wyoming and Summit County, Utah, 1986.

[85] X. Y. Cheng and T. A. Hou, "Active characteristics of the central segment of Jiaocheng Fault and its seismic risk," *Earthquake Research in Shanxi*, vol. 3, pp. 28–32, 1996.

[86] X. W. Wang, Y. H. Guo, and X. F. Fan, "Analysis of recent vertical deformation in Shanxi area," *Crustal Deformation and Earthquake*, vol. 21, no. 2, pp. 64–69, 2001.