Communication

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Branch fault discovered in Tangshan fault zone on the Kaiping-Guye boundary, North China

Abstract: One outcrop of the NE–SW-trending fault with a steep occurrence and grown gouge was discovered in the north segment of the Tangshan fault zone during a field survey near Jujialing village on the Kaiping-Guye boundary of Hebei province, North China. This zone has received less attention in seismic geologic surveys. In addition, three neighboring and parallel NE trending scarps with heights in the range of 1–1.5 m were discovered on the generally flat terrain close to the fault outcrop. The geochemical and multi-electrode resistivity surveys revealed sudden huge fluctuations in the Hg concentration within short distances from the fault outcrop and the three surface scarps. The multi-electrode resistivity survey also revealed a resistivity structure with extreme horizontal discontinuity, indicating the presence of a subsurface fault zone with a width of 40–50 m and a SE dip. This finding confirmed that the three surface NE trending scarps were late Quaternary fault scarps. Following an examination of the focal mechanism solutions and survey findings, it is suggested that the newly detected fault trending toward the northeast could be an unexplored branch fault in the flower structure of the northern section of the Tangshan fault zone. It is marked by recent activity that is mainly controlled by the right-lateral strike-slip. The discovery of this active fault is critical for an accurate assessment of the seismic hazard of north segment of the Tangshan fault zone.

Keywords: north segment of Tangshan fault zone, newly discovered branch fault, fault scarp, multi-electrode resistivity, geochemistry

1 Introduction

Several years of research have revealed that the 7.8 magnitude earthquake that struck the city of Tangshan, Hebei Province, North China, on 28 July 1976, occurred along the NE trending in the Tangshan fault zone. The main surface fracture of this quake spreads along the Tangshan main fault (which corresponds to fault V of the Fengluan coalmine), generally oriented in the N30°E direction and extending continuously for 8–11 km from Shengli Road in Tangshan City in the north to an area near Anjizhai in the south. This region is distinguished by dextral strike-slip displacements of up to 2.3 m and vertical displacements ranging from 0.2 to 0.7 m [1–3]. According to some scholars, the main surface fracture extends intermittently for 90 km, while three roughly parallel surface fractures exist on its two sides with dextral displacements ranging from 1 to 3 cm (which correspond to faults I and III of the Fengluan coalmine and the Zhangdingzhuan fault to the east of fault V) [4]. Later, shallow artificial seismic prospecting of the region led to a few scholars inferring that the Tangshan main fault, a fault that is closely correlated with the 1976 Tangshan earthquake, is a dextral strike-slip fault with an NW steep dip. The four key beds of the Holocene-lower Pleistocene strata of the Quaternary period were revealed to have dislocations with vertical drops ranging from 2.4 to 21 m from the newest stratum to the oldest stratum, while the north segment of the Tangshan fault zone was revealed to have reverse fault characteristics [5,6]. Other researchers hypothesized that the Tangshan fault zone is a reverse strike-slip fault zone with an NW high-angle dip, with (visual) vertical displacement reaching 15 m since the late Pleistocene period [7]. Furthermore, from the earthquake damage and co-seismic and post-seismic ground deformations of the 1976 Tangshan earthquake and the subsequent artificial seismic prospecting results, Qiu et al. inferred that the main seismogenic fault was located in the NE trending Fuzhuang-Xihe fault zone approximately 13 km to the southeast of Tangshan City [8]. The fault is 90 km in length, and the fault dip is NW; there is a relative settlement at the hanging wall, and the vertical displacement...
during the earthquake was 3 m. Moreover, the main seismogenic fault was reported as a normal dip-slip fault, although this notion was questioned by a few scholars [9]. Meanwhile, Guo et al. conducted borehole prospecting and trial trench excavation on three prospecting lines in a region 31 km to the south of Tangshan City and reported that the Tangshan main fault (fault V) experienced several late Quaternary dislocation events, with the fractures in the 1976 Tangshan earthquake representing the most recent dislocation event [10].

A few scholars analyzed the surface fracture zone and the focal mechanism solutions of the 1976 Tangshan earthquake and inferred that the seismogenic structure (the NE trending Tangshan fault zone) is an active fault zone characterized by the dextral strike-slip, with the flower structure constituting one of the main structural characteristics of the strike-slip fault zone [11–14]. Later, Liu et al. conducted a reflection profile prospecting across the south segment of the Tangshan fault zone in Fengnan District, south of the urban area at the Tangshan fault zone is a large-scale inland strike-slip fault zone, with the typical flower structure shaped at the shallow part, and the lower crust and the rust-mantle transition zone cut and disturbed at the deep part [15]. Therefore, it was reasoned that during the Tangshan earthquake of 1976, fractures spread first from the deep part to the shallow part at a depth of 5–10 km and then further upward along the main fault and several branch faults in the flower-structure fault zone [16]. However, due to the co-seismic slip difference among the branch faults and the coverage difference among the loose strata at the shallow part, it was disputed whether the branch faults on the two sides were involved in the fracturing process besides the main fault.

The Tangshan fault zone and surface fractures of the 1976 M = 7.8 Tangshan earthquake have received the most attention in existing research on the Tangshan fault zone and surface fractures. However, no attention was paid to the Guye District, which is located to the north of Tangshan City’s urban region, in the now-completed research project titled Urban Active Fault Prospecting and Seismic Hazard Evaluation of Tangshan City. In the north segment of the Tangshan fault zone, no surface fracture zone has been revealed, and no research or report on new activity had been released after the 1976 Tangshan earthquake until the discovery of one outcrop of the NE–SW-trending fault in our field survey that was aimed to implement a scientific research task beginning in 2021 in a small gully to the south of the Jujiangping village at the Kaiping-Guye boundary in the north segment of the Tangshan fault zone. Field geological and geomorphic surveys, cross-fault multi-electrode resistivity prospecting, and geochemical measurements were then carried out to investigate the newly discovered fault and the north segment of the Tangshan fault zone. The investigation findings were then analyzed to reveal information such as the region’s geological structure and focal mechanism solutions. This study provides a scientific foundation for assessing future seismic hazards in the region and is critical for earthquake prevention and mitigation efforts. The present article was finally prepared as an interim report of the above-stated scientific research task.

2 Seismic geological background of the study region

From a large-scale spatial location, the study region is located in the eastern part of the North China Craton, a prehistoric continent that presently forms part of the Eurasian plate. The North China Craton records a comprehensive and intricate geological history involving igneous, sedimentary, and metamorphic processes that are unparalleled on Earth. It encompasses a vast area of 1.7 million km², including northern and northeastern China, most parts of the Korean Peninsula, and southern Mongolia (Figure 1a). The North China Craton is a very ancient landmass that has experienced prolonged stability, a characteristic trait of cratons. Nonetheless, the deeper parts of the North China Craton have undergone de-cratonization, resulting in the instability of this region.

The Tangshan fault zone is located on the south rim of the Yanshan fault block. It is part of the Tangshan-Hejian-Xingtai new seismotectonic belt, which arose during the Yanshan movement and has gradually grown since the late Tertiary period [17]. During the Mesozoic and early Cenozoic epochs, the region was an uplift area. The upper Paleozoic strata were directly overlaid by the Quaternary sedimentary strata, with the thickness ranging from several dozens of meters to over a hundred meters, without any sedimentation of the Paleogene and Neogene strata in the Mesozoic era and Cainozoic era [10]. Several strong neotectonic movements occurred then, one of which was the Yanshan movement, which began in the Mesozoic era. As substantial magmatic activities occurred in the regions in the east and north, extensive structural deformations occurred. The tectonic framework was then transformed in the Cainozoic era due to the subduction of the oceanic crust, with the NE trending structure transforming from sinistral to dextral while the stress state changed from extrusion to extension. Large-scale chasmic activities occurred as several thrust
faults with high-angle dips that emerged in the Late Jurassic epoch were transformed into extension faults due to the loosening effect following the squeezing effect (Figure 1b). This has resulted in a quite complex crustal structure [18–21]. In structural terms, the Tangshan fault zone is located in the diamond fault block bordered by the NE trending Fengtai-Yejituo fault and the Ninghe-Changli fault on one side and the NW trending Jiyunhe fault and the Luanxian-Leting fault on the other side. It is a regional active fault zone comprised of several parallel NNE-NE trending faults. The deep seismic reflection profile revealed that the flower structure was shaped at the shallow part. At the same time, the lower crust material and the crust-mantle transition zone were cut and disturbed at the deep part, influencing earthquake preparation and occurrence in the study region [22]. Furthermore, small earthquake fine positioning and focal mechanism solution analysis have revealed that the Tangshan fault zone has segmental characteristics, consisting of the north and south segments. The north segment includes, from the west to the east, the Douhe fault, the Weishan-Changshan south slope fault, and the Tangshan-Guye fault. The south segment includes, from west to east, the Wanglanzhuang fault, the Tangshan-Fengnan fault, and the Tangshan-Nanhu fault (Figure 1c). Therefore, the geological structure of the region is complex [23–25].
The Tangshan fault zone is located at the intersection of the Zhangjiakou-Bohai earthquake zone and the Hebei Plateau earthquake zone. Since 1970, $2M \geq 7.0$ earthquakes, $3M \geq 6.0$ earthquakes, and $21M \geq 5.0$ earthquakes have occurred close to the Tangshan fault zone, as reported in the earthquake catalog. One of them, the 1976 $M = 7.8$ Tangshan earthquake is a huge catastrophe to China in which over 200,000 people died. Geologically, it is of particular interest because it occurred on the North China craton; such cratons worldwide are stable, not liable to earthquakes. The eastern part of the North China craton has been thinned from Paleozoic-Triassic 250-km-thick cratonic lithosphere to the present ocean-like 70 km-thick lithosphere so that the earthquakes could occur so frequently [26,27]. The eastern part of the craton was also destructed by the collision of the South China during the Triassic [28,29]; it is liable to the far-reaching effect of penetration of the Indian continent into Asia, which likely is the fundamental mechanism for the earthquakes in North China. Following the 1976 $M = 7.8$ Tangshan earthquake, seismic activity in the Tangshan City region has generally remained attenuated, with spatially unevenly distributed aftershocks. Since 1996, few $M \geq 4.0$ earthquakes have been witnessed close to the epicenter of the $M = 7.8$ Tangshan earthquake, while an NW trending earthquake-intensive zone has emerged close to the north segment of the Tangshan fault zone, where moderate seismic activities continue in a fluctuation state. The current study area is located in an earthquake-intensive zone.

3 Field survey of the discovered fault

3.1 Tectonic setting of the discovered outcrop

Regarding the geographic location and structure, the discovered fault is located between the Weishan-Changshan south slope fault and the Tangshan-Guye fault in the north segment of the Tangshan fault zone, which is a previously known fault zone comprising several parallel NE trending branch faults. Previous research by scholars on the crustal structure and tectonics of the Tangshan Earthquake Zone showed that the deep seismic reflection profiles provided direct evidence of the flower-shaped structure of the Tangshan fault zone. It was evident that a group of branching faults were present between the Tangshan Fengnan Fault (F2) and the Tangshan Guye Fault (F6), indicating that the newly identified fault may be part of the branching fault network of the Tangshan fault zone (Figure 2) [15].

The fault outcrop is located in Tangshan City, near the Kaiping-Guye boundary, in a small NE trending gully about 1 km south of Jujiating village in the Kaiping District (Figure 3a). The trial trench tracking on the grown bedding fault plane in the bright-color Mesozoic shale revealed that the fault plane occurrence is steep, the fault trend is NE, the dip direction is SE, the dip angle is 80–90°, and the exposed gouge belt width is approximately 5 cm (Figure 3b–d). The discovered outcrop is covered by a modern soil layer with a thickness of 30–40 cm. This soil layer has not been dislocated upwardly by the fault plane.

3.2 Distribution state of the surrounding scarps

Extensive research has revealed that surface scarps that emerge and spread along faults are a significant geomorphic feature of late Quaternary fault activity. Therefore, these surface scarps serve as geomorphic markers for identifying active faults [30–32]. To verify the fault characteristics of the discovered outcrop depicted in Figure 3, a large-range and all-inclusive field survey was conducted in the present study. In the survey, a few senior villagers and retired coalmine workers from the study region were interviewed to discuss the geological and geomorphic issues probably associated with the fault activities. In the 1960s, springs appeared throughout the year at Mazhuangzi village, located to the east of the fault outcrop, but these springs vanished by the 1980s, reflecting the effects of the 1976 Tangshan earthquake on the study region. A further analysis was conducted, and a preliminary judgment of two segments of the neighboring and parallel NE–SW-trending fault scarps close to the fault outcrop was established. Finally, a field measurement was conducted on the scarp terrain. The survey locations are depicted in Figure 3a. Table 1 displays the measurement results.

The first scarp is located to the north of the west road of Shijiangying village. In relation to the surrounding terrain, the scarp is: high in the north, with a maximum height of 1.4 m and an average height of over 0.5 m; low in the south; and not evident to the southwest of Shijiangying village (numbers 1–13). According to the lithology of the exposed bedrock, it is Ordovician limestone, and the width...
of the fault mud is about 3 cm. The people interviewed in
the field survey informed that there was an easily obser-
vable bedrock at a depth of 40 cm along the east extension
line of the first scarp. This suggested the previous existence
of a scarp and its subsequent disappearance due to artificial
terrain modification. The second scarp is located to the
south of Jujialing village. This scarp has a maximum height
of 1.56 m and an average height of more than 0.9 m (num-
bers 14–28). The bedrock’s broken fault zone is exposed in a
small gully along the extension line of the scarp, as an
outcrop of fault gouge with a width of about 5 cm. The
lithology of Shihezi Fm is purplish red sandstone. The third

Figure 2: Results of the deep seismic reflection profile for the Tangshan Fault Zone (quoted from Crustal Structures and tectonics of Tangshan earthquake area: results from deep seismic reflection profiling [15]).
scarp is located to the north of Yangjiazhuang village and northeast of Gulouzhuang village. The maximum height of this scarp is 1.41 m, and an average height of over 0.9 m (numbers 29–36). The bedrock is exposed at the scarp’s base, and it is Carboniferous Permian sandstone (Table 1; Figure 4). According to the scarp location and height distribution and the exposed bedrock and broken fault zone state along the extension line of the three scarps, it was inferred that these scarps were closely associated with the discovered fault outcrop (Figure 3). Therefore, it was
reasoned that these scarps are fault scarps. Furthermore, the detection of three fault scarps, as evident from their disruption of the recent earth surface (Figures 3 and 4; Table 1), suggests that the NE-trending fault found in the northern section of the Tangshan fault zone could be a fault that originated in the late Quaternary period.

### Table 1: Parameter list of height measurement for the fault scarps

<table>
<thead>
<tr>
<th>Fault scarp grouping</th>
<th>Number</th>
<th>Longitude (°)</th>
<th>Latitude (°)</th>
<th>Scarp height (m)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group I</td>
<td>1</td>
<td>118.3131 E</td>
<td>39.7222 N</td>
<td>1.33</td>
<td>Outcropping of fault gouge in the northwest of Jujialing village and the width is approximately 3 cm</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>118.3128 E</td>
<td>39.7228 N</td>
<td>0.29</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>118.3128 E</td>
<td>39.7233 N</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>118.3128 E</td>
<td>39.7236 N</td>
<td>0.40</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>118.3264 E</td>
<td>39.7322 N</td>
<td>0.84</td>
<td>Northwest of Liujiawa village</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>118.3244 E</td>
<td>39.7322 N</td>
<td>1.20</td>
<td>Gully, depth of about 3 meters</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>118.3233 E</td>
<td>39.7311 N</td>
<td>1.40</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>118.3244 E</td>
<td>39.7300 N</td>
<td>-</td>
<td>Outcrop of basement rocks, the lithology is Ordovician limestone</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>118.3031 E</td>
<td>39.7153 N</td>
<td>-</td>
<td>Outcrop of basement rocks in the north of Yangjiazhuang village, the lithology is Ordovician limestone</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>118.3036 E</td>
<td>39.7150 N</td>
<td>-</td>
<td>Outcrop of basement rocks, the lithology is Ordovician limestone</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>118.3405 E</td>
<td>39.7407 N</td>
<td>0.65</td>
<td>North of west road of Shijiangying Village</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>118.3406 E</td>
<td>39.7409 N</td>
<td>1.30</td>
<td></td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>118.3406 E</td>
<td>39.7401 N</td>
<td>0.70</td>
<td></td>
</tr>
<tr>
<td>Group II</td>
<td>14</td>
<td>118.3197 E</td>
<td>39.7203 N</td>
<td>1.56</td>
<td>Newly discovered fault outcrop Outcropping of fault gouge and the width is approximately 5 cm</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>118.3211 E</td>
<td>39.7208 N</td>
<td>0.52</td>
<td></td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>118.3219 E</td>
<td>39.7211 N</td>
<td>1.28</td>
<td></td>
</tr>
<tr>
<td></td>
<td>17</td>
<td>118.3222 E</td>
<td>39.7217 N</td>
<td>-</td>
<td>There are signs, but man-made transformation</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>118.3261 E</td>
<td>39.7269 N</td>
<td>-</td>
<td>There is bedrock fracture zone in the trench; the lithology is purplish red sandstone of Shihezi Fm</td>
</tr>
<tr>
<td></td>
<td>19</td>
<td>118.3239 E</td>
<td>39.7256 N</td>
<td>0.56</td>
<td>Gully, depth of about 3 meters</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>118.3230 E</td>
<td>39.7240 N</td>
<td>-</td>
<td>West of Liujiawa village, the lithology is purplish red sandstone of Shihezi Fm</td>
</tr>
<tr>
<td></td>
<td>21</td>
<td>118.3314 E</td>
<td>39.7256 N</td>
<td>0.80</td>
<td>On the east of the road from Liujiawa village to Mazhuangzi village</td>
</tr>
<tr>
<td></td>
<td>22</td>
<td>118.3314 E</td>
<td>39.7253 N</td>
<td>0.53</td>
<td></td>
</tr>
<tr>
<td></td>
<td>23</td>
<td>118.3317 E</td>
<td>39.7258 N</td>
<td>0.40</td>
<td></td>
</tr>
<tr>
<td></td>
<td>24</td>
<td>118.3308 E</td>
<td>39.7247 N</td>
<td>0.77</td>
<td>Bedrock is exposed in the west of the point, the lithology is Carboniferous Permian sandstone, with loess covering 0.65M</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>118.3133 E</td>
<td>39.7181 N</td>
<td>1.26</td>
<td>Along the Northeast fault fracture zone outcrop of Yangjiazhuang village, the lithology is Carboniferous Permian sandstone</td>
</tr>
<tr>
<td></td>
<td>26</td>
<td>118.3142 E</td>
<td>39.7183 N</td>
<td>1.21</td>
<td></td>
</tr>
<tr>
<td></td>
<td>27</td>
<td>118.3144 E</td>
<td>39.7186 N</td>
<td>1.36</td>
<td></td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>118.3156 E</td>
<td>39.7194 N</td>
<td>0.95</td>
<td></td>
</tr>
<tr>
<td>Group III</td>
<td>29</td>
<td>118.3142 E</td>
<td>39.7128 N</td>
<td>1.00</td>
<td>West of Xiaogang village, East of Yangjiazhuang village</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>118.3147 E</td>
<td>39.7133 N</td>
<td>1.02</td>
<td></td>
</tr>
<tr>
<td></td>
<td>31</td>
<td>118.3042 E</td>
<td>39.7078 N</td>
<td>1.21</td>
<td>West of Yangjiazhuang village, Scarp strike N50E</td>
</tr>
<tr>
<td></td>
<td>32</td>
<td>118.3044 E</td>
<td>39.7078 N</td>
<td>1.41</td>
<td></td>
</tr>
<tr>
<td></td>
<td>33</td>
<td>118.3042 E</td>
<td>39.7075 N</td>
<td>0.67</td>
<td></td>
</tr>
<tr>
<td></td>
<td>34</td>
<td>118.2989 E</td>
<td>39.7039 N</td>
<td>0.90</td>
<td>East of Gulouzhuang village</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>118.2903 E</td>
<td>39.7050 N</td>
<td>0.74</td>
<td></td>
</tr>
<tr>
<td></td>
<td>36</td>
<td>118.2975 E</td>
<td>39.7031 N</td>
<td>-</td>
<td>Outcrop of basement rocks, the lithology is Carboniferous Permian sandstone</td>
</tr>
</tbody>
</table>
4 Evidence analysis of the discovered fault

4.1 Geophysical and geochemical prospecting survey and data analysis

Prospecting of the hidden faults and determination of the fault activity are conducted using various geophysical and geochemical prospecting methods that enable determining the specific location and the actual scale of active faults. Among these different methods, multi-electrode resistivity prospecting and gas geochemical measurement are the most widely used. The multi-electrode resistivity prospecting method is based on the conductivity difference between the subsurface rock and the soil masses. This method enables achieving geological structure inversion through current field observation and distribution law research on the artificially established stable underground current field [33]. This method ensures low cost, high efficiency, rich information, easy interpretation, and substantial improvement of the prospecting capability [34]. Therefore, this method is adopted in urban active fault prospecting and applied to hidden fault prospecting in several cases [35–38]. The geochemical characteristics of the fault zone gas are strongly correlated with fault structure and activity [39]. In addition, the concentration and the escaping rate of the soil gas (the gas escaping from the earth’s surface along the broken fault zone) are sensitive and objective indicators of the crustal stress–strain state [40,41]. The measurement of the soil gas close to the fault zone, while contributing to the determination of fault zone activity and regional earthquake hazard level, also provides geochemical evidence in the prospecting of concealed fractures [46]. In view of the above-stated facts and advantages, multi-electrode resistivity prospecting and geochemical measurement were conducted for the discovered fault in the present study.

4.1.1 Survey profile layout and methodology

To conduct multi-electrode resistivity prospecting, the resistivity data were obtained using the WGMD-4 multi-electrode resistivity survey system developed by Chongqing Benteng Digital Control Technical Institute. The electrode distance was 10 m, and the total length of the profile line at Jujialing village was 1790 m (Figure 5). There were a total of 180 physical points. The data sorting procedure was carried out with the aid of a Swedish-developed CRT multi-electrode resistivity imaging and viewing system. After that, the 2D RES inversion software was used, with 3–5 fitting iterations, and the error rate was around 5%. The field data were first sorted and then converted through inversion processing to obtain the depth-resistivity relationships and the underground geoelectric cross-section characteristics. The initial two-dimensional geoelectric model was established by the inversion process. The inversion parameters (damping coefficient, iteration coefficient, convergence limit, etc.) were selected based on the data obtained from the geological survey. The inversion calculations were performed using the least square method. In the geochemical measurements, the concentrations of Rn, CO₂, and Hg in the fault zone gas were measured at the profile of the multi-electrode resistivity survey, with intensive observation at the discovered fault outcrop. One guidance hole was drilled with a steel chisel at each measurement point to accommodate the sampler. The drilling depth was about 80 cm, and the hole size was about 30 mm. The sampler was linked to the pump via a rubber tube to discharge the residual gas in the rubber tube and sampler before collecting gas samples. The gas flow rate set using the pump was 1.0 L/min, the gas extraction duration

Figure 4: A field photograph capturing the fault scarps of the newly identified NE-trending fault.
was 2 min, and the sample volume was 2 L. The concentration of Rn was measured using Alpha Guard P2000 emanometer. The time interval between the measurement of two Rn samples was 1 min, and the number of data items was 15. The emanometer was cleaned after the measurement of each Rn sample. The concentration of CO₂ was measured using the GXH-3010 portable infrared CO₂ analyzer. The concentration of Hg was measured using the Aadtech mercury detector. For all devices used, calibration error was less than 10%. Before the measurement process, the concentrations of the atmospheric components at the measurement site were also measured to ensure the validity of the measurement results.

4.1.2 Survey result analysis

The findings of the multi-electrode resistivity survey line concur with the geological section of the area in regard to the location of the fault. The profile of the prospecting lines of the multi-electrode resistivity survey revealed an extreme horizontal discontinuity in the resistivity structure across the fault outcrop. The width of the resistivity structure’s horizontal discontinuity belt was 40–50 m, the dip direction was SE, and the dip angle was 70–80° (Figure 6), reflecting the width and occurrence of the fault zone at shallow depth and indicating that the fault zone has a relative rise (reverse) component motion at the SE rock mass (hanging wall). The existence of a thick close-to-surface low-resistivity (high-conductivity) layer at the NW rock mass (footwall) led to the inference that there exists a Kainozoic or Quaternary loose stratum.

According to the existing research, the underground elements Rn and Hg at a greater depth are transported easily to the earth’s surface across fractures and other channels, and the changes in the elemental concentrations in the soil close to the fault zone provide information, such as the fault activity situation and the crustal stress–strain state [47,48]. The geochemical measurements performed in this study revealed the following patterns for Rn, CO₂, and Hg concentrations: On the prospecting lines, Rn concentrations were high in the 950–1,200 m range (Figure 7). The concentrations of Rn and CO₂ gas show peaks in the fault scarp and fracture zones, and the measured values have some coincidence, which may be related to the fact that CO₂ is an Rn carrier. Because Rn transport rates are low and distances are short, corresponding gases are required as carriers during surface transport [49]. The concentrations of
soil gas released are influenced by tectonic activity, crustal thickness, seismic activity, and environmental and anthropogenic disturbances [50]. The measurement ensures that the soil type is essentially the same as are the instruments and parameters used, as well as the personnel and location, effectively reducing the influence of environmental

Figure 6: Multi-pole resistivity measurement results and distribution of geological profiles in the study area (a, result of the multi-electrode resistivity survey; b, sketch of geological section; changed from new evidence for the distribution of surface rupture zone of the 1976 Ms7.8 Tangshan earthquake [10]).

Figure 7: Result distribution of the gas geochemical survey.
and human factors on soil gas measurements. On the prospecting lines, the Hg concentration fluctuated dramatically between 950 and 1,150 m (Figure 7). Deep Hg elements have high penetration and can diffuse into the atmosphere, but they are susceptible to soil organic matter sorption during upward transport [51]. Therefore, the peak Hg concentration varies in relation to Rn and CO₂. Still, the location of the main peak distribution is relatively concentrated and does not affect the fault location determination. Previous gas geochemical field results show that the Rn anomaly threshold in Tangshan is 8294.1 Bq/m³, the CO₂ anomaly threshold is 0.23%, and the Hg anomaly threshold is 17 ng/m³ [52,53]. The measurements of the three gases conducted at a depth of 950–1,200 m along the profile, which represents the newly discovered fault outcrop, revealed concentrations exceeding the anomaly threshold for the Tangshan area. The anomalies of the gas measurements were also observed in close proximity to the known Weishan-Changshan fault (at a depth of 1,600–1,800 m along the measurement profile), implying that gas measurements can serve as an indicator of the fracture zone and the presence of a fault zone at a depth of 950–1,200 m in the survey profile. The concentrations of Rn, Hg, and CO₂ exhibited sharp fluctuations against a high-value background on both sides of the survey profile, implying the existence of a hidden broken fault zone beneath the two sides.

The results of both multi-electrode resistivity prospecting and geochemical measurement revealed abnormal changes in the range of 950–1,200 m (at the location of the discovered fault outcrop), which reflected the substantial scale and new activity of the discovered NE-SW-trending fault.

4.2 Movement pattern of the discovered fault

The tectonic settings of the relevant region and the tectonic conditions of the earthquake zone are strongly correlated with earthquake preparation and occurrence. Therefore, thoroughly examining the distribution characteristics of the relevant region’s geological structure is critical in assessing earthquake hazards and predicting seismic risk zones. After the major shock in 1976, several ML ≥4.0 earthquakes occurred in the old earthquake zone of Tangshan City, with evident regularity in space distribution. The seismic locations of these ML ≥4.0 earthquakes that occurred following the main shock were concentrated close to the epicenter. In comparison, the seismic locations of the ML ≥4.0 earthquakes after 1996 had evidently changed to the north segment of the Tangshan fault zone. The earthquakes in the north segment of the Tangshan fault zone were repositioned in this study, and the focal mechanism solutions for the ML ≥4.0 earthquakes that occurred after 1996 were obtained. The focal mechanism solution analysis of the zone with the discovered NE-SW-trending fault and its surrounding region revealed that the NE trending nodal plane of the focal mechanism solutions of several earthquakes (including the M5.1 earthquake that occurred on 12th July 2020) in the north segment of Tangshan fault zone and its surrounding region is the nodal plane characterized by the dextral strike-slip under the effect of the principal compressive stress in the SEE-NWW trending approximately horizontal zone (Figure 8).

The ground fluids are distributed widely in the pores of the crustal rock and are quite sensitive to the changes occurring in the regional tectonic activities and the crustal stress-strain field [54]. Therefore, several scholars in China and other countries consider these ground fluids the most effective means to determine fault activity [55,56]. The deep region’s fluids are important factors influencing earthquake preparation and occurrence, whereas the shallow region’s fluids are important carriers of precursor information sensitively reflecting earthquake preparation and occurrence [57]. The earthquake response characteristics of groundwater and surface water at various spatial scales revealed that the response range for surface water extended from several dozens of kilometers to several hundreds of kilometers.

**Figure 8:** Distribution of the epicenters (left) and the focal mechanism solutions of ML ≥ 4.0 earthquakes that struck the old earthquake zone of Tangshan City.
and for groundwater from several hundreds of kilometers to several thousands of kilometers, confirming the strong correlation between ground fluid anomaly and regional tectonic activity [58]. The field survey conducted in the present study revealed that the surface water on the second scarp disappeared after the 1976 Tangshan earthquake, which suggested an aquifer change due to fault activities. According to the existing research on groundwater before the $M = 7.8$ earthquake, there have been abnormal changes in the groundwater over a period prior to the earthquake [59]. This finding indicates the effects of the regional geological structure on the earthquake and reflects the movement of all branch faults in the large-scale flower structure of the strike-slip fault zone. According to the findings of the reported surveys, the NE trending Tangshan fault zone is a strike-slip fault zone with a large-scale flower structure, and fractures spread along two branch faults of the flower-structure fault zone in addition to the main fault during the $M = 7.8$ Tangshan earthquake of 1976 [15]. Thus, it was deduced that the identified fault might have played a role in the $M = 7.8$ Tangshan earthquake and could be one of the branch faults in the Tangshan fault zone with a significant flower structure.

It was inferred from the focal mechanism solutions and the resistivity profile that the discovered fault is a normal-dextral strike-slip fault characterized by a dextral strike-slip and a relative drop at the SE rock mass (hanging wall). In addition, from the existence of a thick close-to-surface low-resistivity (high-conductivity) layer at the SE rock mass (hanging wall), it was inferred that there was a high loose stratum. Accordingly, it was demonstrated through the two-field surveys that the discovered fault to the south of the Jujiaying village was a previously unknown branch fault in the flower-structure Tangshan fault zone. Tangshan Fault Zone flower structures are relatively complex, and under the influence of regional tectonic stress, the original negative flower structures change to positive flower structures [60,61]. Moreover, the profile of the multi-electrode resistivity survey revealed that the width of the horizontal discontinuity belt in the resistivity structure associated with the fault was 40–50 m, and the dip direction was SE. The dip angle was approximately 80°, which reflects the fault occurrence at the deep region and indicates that the fault has a relative drop (normal) component motion at the SE rock mass (hanging wall). When the current research findings on surface water changes in the region surrounding the discovered fault were combined with the findings of relevant existing research published in the literature, it was discovered that the discovered fault was involved in the $M = 7.8$ Tangshan earthquake.

5 Conclusion

The NE-trending fault identified in the northern section of the Tangshan fault zone, located near Jujiaying village, might be a previously unexplored branch fault in the fault zone’s flower structure. This fault’s discovery could be linked to the $M = 7.8$ Tangshan earthquake that occurred in 1976. A fault scarp belt with three scarps was discovered along the extension line of the fault outcrop, and the scarps dislocated the late Quaternary topographic surface. Furthermore, multi-electrode resistivity prospecting and geochemical measurements across the scarps revealed abrupt large fluctuations in Hg concentration over short distances and extreme horizontal discontinuity in the resistivity structure, indicating the presence of a fault zone with a width of 40–50 m. These findings suggested the substantial scale and new activity of the discovered NE–SW-trending fault. Furthermore, it was inferred from the focal mechanism solutions that the discovered NE–SW-trending fault is a strike-slip fault characterized by a dextral strike-slip and a relative rise (reverse) component motion at the SE rock mass (hanging wall).

The detection of the branch fault, as presented in this study, would provide valuable insights into the presence, size, and earthquake-triggering potential of active faults within the northern section of the Tangshan fault zone. The research findings are extremely important for earthquake prevention and mitigation in Tangshan’s old earthquake zone, as well as for major project planning and construction.

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References


