Research Article

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Application of combined electrical resistivity tomography and seismic reflection method to explore hidden active faults in Pingwu, Sichuan, China

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Abstract: Pingwu County, which is located at the northern end of the Longmenshan fault structural belt, has an active regional geological structure. For a long time, the Longmenshan fault tectonic belt has become intensely active with frequent earthquakes. According to the existing geological data, the Pingwu–Qingchuan fault passes through the urban area of Pingwu. However, because of the great changes in the original landform of Pingwu caused by the construction activities in this urban area, a precise judgment of the location of the Pingwu–Qingchuan fault according to the new landform characteristics is difficult. Here, the seismic reflection method, electrical resistivity tomography (ERT), and drilling method were used to determine the accurate location of the buried active faults in Pingwu County. The seismic reflection method and ERT are used to determine the location of faults, the thickness of overlying strata of the fault, and the basic characteristics of faults. The drilling data can be used to divide the bedrock lithology and confirm the geophysical results. The geological model of the faults can be constructed by 3D inversion of ERT, and the structural characteristics of the faults can be viewed intuitively. The results of this study can provide a basis for earthquake prevention and construction work in Pingwu. The finding also shows that seismic reflection method and ERT can effectively explore buried active faults in urban areas, where many sources of interferences may exist.

Keyword: faults, seismic reflection method, electrical resistivity tomography, 3D

1 Introduction

Pingwu County is located at the northern end of the Longmenshan fault structural belt, in which intense regional geological tectonic activity has been reported [1–3] (Figure 1a). According to the geological survey and 1:2,00,000 scale geological map of China (<http://geodata.ngac.cn/>), we speculate that the Qingchuan–Pingwu fault passes through the urban area of Pingwu County. However, for the part where the fault enters the urban area of Pingwu, its distribution position cannot be judged according to the satellite images and geomorphological characteristics. Hidden active faults in cities are closely related to earthquakes and geological hazards, and they are important factors affecting urban safety [4,5]. Traditional methods of fault identification include geological mapping and interpretation of aerial photographs [6]. However, the engineering of buildings has greatly changed the original landforms of urban areas, and the traditional geologically based methods of fault identification may be insufficient. The geophysical exploration methods have become an effective solution for the identification of buried active faults in cities [7]. However, many sources of interference (electromagnetism and noise) are present in urban areas due to human activities, which implies that some conventional geophysical methods cannot be applied. A comparison of the application potential of urban geophysical methods with that of conventional geophysical methods is thus necessary. The particularity of applying urban geophysical prospecting methods lies in two aspects. (1) The sources of interference in urban areas are strong. Urban human activities, such as transportation, construction, machinery operation, and other sources of vibration, are complex and will interfere with seismic exploration methods. In addition, electromagnetic waves, such as from transmission lines and electromechanical equipment, generated by human activities will seriously interfere with the electromagnetic exploration methods (natural-source magnetotellurics, audio-frequency magnetotellurics, and controlled source audio-frequency magnetotellurics). (2) Urban hardened ground will

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Figure 1: (a) Tectonic background and topographic relief of the eastern Tibet. (b) The topographic map of Pingwu. Red dots represent historical earthquakes, historical earthquake data were obtained from China Earthquake Network (<http://www.ceic.ac.cn>). (c) The formation of Pingwu. The stratum in the urban area (white area) is the Quaternary alluvial deposits.

increase the difficulty of method application and the quality of data acquisition. Moreover, urban buildings and hardened ground will seriously affect the layout of

surveying lines, and uneven site conditions caused by ground excavation will reduce the data quality. At present, the geophysical prospecting methods of urban

buried active faults include seismic method [8–10], electromagnetic method [11–17], resistivity [18–22], magnetic method [23–25], and gravity method [26–29].

We intend to use the geophysical prospecting method to determine the basic distribution of the Pingwu–Qingchuan fault in the urban area of Pingwu. Considering that a geophysical method may have many interpretation results, we use two geophysical methods and drilling to explore the buried faults in the city. The seismic reflection method and electrical resistivity tomography (ERT) were used in the places with few buildings. Drilling was carried out in urban central areas with many buildings and hardened grounds.

2 Geophysical methods

Faults are geological structures that cause strata fragmentation and displacement due to the uneven stress of the rock strata. Fault fracture zones develop in the process of fault generation. Regardless of the type of fault, loose fracture zones and ductile shear zones will exist at the fault plane caused by the relative displacement of two plates [30–32]. Different physical properties (electrical conductivity, dielectricity, density, and magnetism) can be observed between the two pans of rock masses or soils, and these differences can provide the necessary geophysical basis for developing geophysical prospecting methods [33–35]. Geophysical exploration technology is one of the most effective methods for identifying the fault structure characteristics [36]. However, there are many explanations for one kind of geophysical exploration method, integrated geophysical method can greatly improve the accuracy of the exploration results. Many recent studies have explored the application potential of the comprehensive geophysical exploration technology for investigating the fault structure characteristics [37–42]. However, studies are rare regarding the active faults identified in urban areas, which are identified by using geophysical prospecting methods. In this study, seismic reflection method and ERT are used as comprehensive geophysical prospecting methods to carry out the exploration of the buried active faults in the urban area of Pingwu.

2.1 Seismic reflection method

Seismic reflection method focuses on the obvious elastic difference between two strata. The difference between seismic reflection method and other geophysical

exploration methods is that seismic reflection method has the characteristics of high exploration accuracy, high horizontal and vertical resolutions, and abundant acquisition information [43–48]. To find a fault by using seismic reflection method, the two sides of the fault in the same layer of reflection wave arrival time difference are used as the basis of judgment. With this feature, seismic reflection method can be used to detect the effects of tensile or compressive faults. There are many studies have proven that seismic reflection method is one of the most effective methods for exploring the active faults, especially when determining the structural characteristics of these fault types [49–54].

2.2 Electrical resistivity tomography

ERT has the advantages of low cost, high efficiency, and abundant information collection. As one of the important methods of shallow geophysical exploration, ERT has been widely used in environmental geological surveys [55–58], engineering geological surveys [59,60], water conservation and hydropower engineering [61,62], urban engineering, and archaeology [63,64]. The selection of comprehensive geophysical prospecting methods depends on the geological characteristics, exploration depth, and resolution of a study area [65]. However, the geographical location of a study area is also another important factor in the selection of geophysical prospecting methods. Many interference factors can be observed in urban areas, and they seriously interfere with the geophysical prospecting methods. ERT is not interfered by mechanical vibration and electromagnetic waves, and it can provide abundant fault information. ERT can determine the location of shallow faults and the composition of the Quaternary overburden layer [66,67].

3 Geological background

Pingwu is located at the junction of the Yangtze Platform, Qinling fold belt, and Songpan–Ganzi block. Since the late Cenozoic, along with the rapid uplift of the Qinghai fold belt and the eastward creep of the plateau crust, a series of large-scale arc strike-slip faults have been formed in the eastern part of the plateau, which indicate the dominance of the horizontal tectonic stress field [68–70] (Figure 1a). The horizontal shear movement

Figure 2: (a) Different geophysical methods and drilling survey location. The red line is the Qingchuan–Pingwu fault, and the data are from 1:2,00,000 scale geological maps of China (<http://geodata.ngac.cn/>). The red dashed line is the hypothetical track of the fault. (b) ERT 1–6 profiles and Seismic S1–S3 profiles. R1i is the beginning of the line and R1e is the end of the line, and so are other lines. (c) Broken bedrock. (d) Outcrop of the fault.

toward the crust has transformed into a brittle overthrust nappe movement away from the Minshan fault zone and the Longmenshan tectonic belt, resulting in a typical tectonic environment of reverse faults. The movement

has also formed geophysical distortion zones, such as the Bouguer gravity anomaly and the aeromagnetic anomaly, and caused crustal thickness [71–74]. Due to the uplift of the Qinghai–Tibet Plateau and the further

development of the original faults, some major faults, such as Minjiang fault, Beichuan–Yingxiu fault, and Pingwu–Qingchuan fault, have manifested strong tectonic activities [75,76]. The whole area can be divided into blocks of different sizes [77,78]. The Pingwu–Qingchuan fault zone, which belongs to the north-central part of the Longmenshan fault, is the boundary fault between the Motianling Massif and the Longmenshan tectonic belt. The Qingchuan fault is located in the northeastern part of the Longmenshan tectonic belt, extending for about 100 km. Seismic reflection data show that the Qingchuan fault is an active fault dominated by a right-lateral strike-slip in the late Quaternary [79,80]. The Pingwu–Qingchuan fault zone has formed gentle valleys and steep cliffs in some areas. The width of the fault fracture zone varies from 10 m to one that exceeds 100 m. The Pingwu–Qingchuan fault has been strongly active since the Middle Pleistocene and active since the Late Quaternary [81]. Some studies have shown that the Qingchuan–Pingwu fault is the most active fault in the northeastern part of the Longmenshan fault zone, which has the possibility of strong earthquakes [82]. A total of 201 earthquakes with $M_s (\geq 4.7)$ were recorded in the study area ($30^{\circ}00'–35^{\circ}00'N$, $102^{\circ}00'–108^{\circ}00'E$) [83–85]. Among them, the 2008 Wenchuan earthquake ($M_s = 8.0$) caused a great damage to Pingwu County. Some studies show that the Wenchuan earthquake caused a 60 km long surface rupture zone of the Qingchuan fault [86–88].

4 Data acquisition

4.1 Geological outcrop survey

We investigated along the fault zone and found that the fault outcropped on the west side of the city (Figure 2c). The fracture zone and the crushing zone are approximately 40 m in width by cross-section measurement. The fault overburden layer is a pebble layer. The strike of the fault is $N70^{\circ}E$. The fault is confined, and there is no obvious fault plane. Most fault planes are S-shaped folds formed by compression, in which several quartzites are filled. The hanging wall of the fault is Devonian limestone, and the occurrence of the strata is the strike $N70^{\circ}E$. The footwall of the fault is Silurian phyllite, and the occurrence of the strata is $N65^{\circ}E$. The fault passes through Fujiang River and enters the urban area. There are no signs of faults on satellite images and geomorphology, so we consider Pingwu fault as a hidden fault.

We continue to trace along the direction of the fault and find that there is a bedrock fracture at the passage of the fault (Figure 2d). Subsequently, seismic reflection method and ERT are used as comprehensive geophysical prospecting methods to explore the hidden faults and their locations in Pingwu.

4.2 Set lines

The locations and trends of faults in urban areas can be predicted on the basis of field exploration and existing geological survey data (1:2,00,000 scale Chinese geological map). We have laid out surveying lines along the predicted fault strike. Three seismic reflection lines (S1–S3) and six ERT lines (R1–R6) are laid out in the areas with few buildings (Figure 2b). Among them, S1 and R1 coincide partially with S2 and R6, and the distance between two adjacent ERT lines is 25 m. In addition, to determine the lithology of bedrock and the location of faults in urban areas, four boreholes (D1–D4) are arranged along the predicted fault strike as supplements to ERT and seismic reflection methods. The terrain of the study area is generally inclined from northwest to southeast, and the altitude is 810–1,200 m. The shallow surface layer of the site is the sand gravel layer of alluvial pile, and the exposed parts of bedrock are Devonian limestone and Silurian phyllite.

4.3 Data collection

Three seismic refraction profiles were obtained with a 64-channel 24 bits Geometrics StrataVisor NZXP seismograph, 40 Hz natural frequency vertical geophones with a 4 m separation array, and an impact source of 15-pound hammer (Table 1). The DUK-2A instrument system is used for the data acquisition of ERT (Table 2).

4.4 Data processing

Three sets of effective data are obtained by seismic reflection method. The data processing mainly includes preprocessing, filter, deconvolution, velocity analysis, static correction, stacking, and seismic profile output (Figure 3a). Geogiga Seismic is used to process seismic reflection data. 2D ERT can get the vertical electrical

Table 1: Seismic reflection method data acquisition parameters

Seismic line	Exploded mode	Geophone (HZ)	Group interval (m)	Offset (m)		Folds	Excitation number	Receiving channels
				Minimum	Maximum			
S1	Hammering	40	4	20	112	6	30	24
S2	Hammering	40	4	20	112	6	22	24
S3	Hammering	40	4	20	112	6	31	24

Table 2: ERT data acquisition parameters

ERT line	Config	Direction	Electrode spacing (m)	Electrode number	Voltage (v)	Depth (m)
R1	Winner	N30°W	5	60	360	45
R2	Winner	N30°W	5	60	360	45
R3	Winner	N30°W	5	60	360	45
R4	Winner	N30°W	5	60	360	45
R5	Winner	N30°W	5	60	360	45
R6	Winner	N30°W	5	60	360	45

profile of geological body, and 3D ERT inversion results can get the 3D electrical model and electrical slices of the whole geological body, which can be used as a supplement to the 2D inversion results [89]. Six sets of effective exploration data are obtained by ERT. The ERT data acquisition is a 2D configuration, and the 2D ERT data of six lines are converted into 3D ERT inversion format by RES3DINV software (Figure 3b). The processing of 2D inversion of ERT is completed by RES2DINV software, and RES3DINV software was used for 3D inversion. Then, we use SKUA-GOCAD software to build the 3D geological model of the data obtained from the 3D inversion. The 3D inversion results are sliced into x - and y -directions, and the 3D geological model of ERT is obtained. The processing flow of the inversion of the ERT data and seismic data is shown in Figure 3.

5 Results and interpretation

Seismic reflections from the Quaternary have well continual appearances, the reflection wave from the Quaternary can be traced and compared in the whole profile, and the reflection energy is strong and continuous. From the top of the seismic section (Figure 4b), we can see that the seismic wave (green lines) is strong and can be tracked in Quaternary, while the seismic wave (yellow lines) is broken at 84 m of the section. It can be inferred that the thickness of the Quaternary is about 12 m, and there are faults at 84 m of seismic profile (Figure 4b). In the electrical section, the depth of the

Quaternary covering is marked with red dotted lines, which is about 15 m. There is a low-resistivity area in the range of 150–180 m in the profile, which is supposed to be a fault. The two areas marked by A and B in Figure 4c have obviously low resistivity, while the bedrock in the bottom of A and B are complete (also in Figure 7b), so we do not think there are fractures in these two low-resistivity areas. And we speculate that these two low-resistivity areas are affected by the changes in geological structure caused by the fault at 170 m of the profile (Figure 4c). From the seismic reflection and ERT results of Figure 4, we can infer that the thickness of the Quaternary cover at the profiling is about 15 m and the width of the Qingchuan–Pingwu fault is about 30 m.

The reflection wave can be tracked continuously in the event (Figure 5b). As shown in Figure 5b, after time–depth conversion, the seismic event is leaped at 20 m of the profile. At the same time, seismic event is also leaped at 60 m of seismic profile. We presumed that the two disconnection of seismic event are performance of the Qingchuan–Pingwu fault on the seismic profile (Figure 5b, F1, F2). Figure 5c is resistivity inversion result of R1. The surface of resistivity profile is obviously low-resistivity within 15 m, and then, the depth of the Quaternary can be inferred to be about 15 m. The resistivity decreases with the increase in depth at 165 m of resistivity profile, which shows obvious low resistivity. We speculate that this low-resistivity area is caused by fracture zone, and we think that the low-resistivity zone is the appearance of the Qingchuan–Pingwu fault. Interestingly, the seismic wave energy has decreased significantly between F1 and F2 (Figure 5b), and we think that this is

Figure 3: (a) Seismic data processing. (b) ERT inversion processing.

due to the loosening of rocks and soils within the fault fracture zone and the seismic wave energy has serious loss in the process of propagation. The width of low-resistivity zone in electrical profile (Figure 5c) is the same as that of seismic energy weakening zone in seismic section. So we can speculate that there is a fault between P1 and P2, and the width of fault is about 40 m.

From the results of drilling (Figure 9), we know that the bedrock on both sides of the fault is Limestone and Phyllite. It can be inferred that the low resistivity at the top of the section (Figure 5c) is Quaternary, while the bottom of the profile is supposed to be bedrock. The bedrock on both sides of the fault is Limestone and Phyllite. Finally, combined with seismic and electrical results, we can conclude that the Qingchuan–Pingwu

fault passes here (Figure 2b). The Quaternary thickness of the fault is about 15 m, and the width of the fault is about 40 m (Figure 5d).

Figure 6(b–d) illustrates the 3D inversion result of the ERT data together with a 3D geoelectric model and slices of the model. To observe the distribution of faults more intuitively, we adjust the proportion of geoelectric model to $x:y:z = 2:1:1$, in which the minimum apparent resistivity of the geoelectric model is limited to 250 Ω m. The resistivity at the top of the geoelectric model is generally less than 250 Ω m. From the results of the 3D inversion, we can conclude that the low resistivity on the top of the geoelectric model is the electrical reflection of the Quaternary sand gravel deposit. The depth of Quaternary is uneven, ranging from 12 to 15 m. In the

Figure 4: (a) The location of survey line (S2, R6). (b) Seismic reflection profiling (S2). Green line is the boundary of Quaternary and bedrock. (c) 2D inversion result of ERT (R6). Red dotted line is the boundary of Quaternary and bedrock. (d) Comprehensive geologic interpretation map.

range of 125–175 m of the geoelectric model, the resistivity decreases with the increase in depth, which is obviously different from the resistivity of the bedrock at the bottom. We speculate that the Qingchuan–Pingwu fault is located in the low-resistivity area. Faults are the

result of the rock structures that have given away to tectonic compression, extension, or lateral tension [90]. The resistivity value of fault fracture is related to the water content and the water salinities of fracture. Some studies have shown that the resistivity of aquifer is

Figure 5: (a) The location of survey line (S1, R1). (b) Seismic reflection profiling (S1). Green line is the boundary of Quaternary and bedrock. (c) 2D inversion result of ERT (R1). Red dotted line is the boundary of Quaternary and bedrock. (d) Comprehensive geologic interpretation map.

smaller with the increase in the water salinities [91]. And the rock mass at the fracture zone is broken, and its water content will be higher than that of intact rock mass, so it can be inferred that the resistivity value of fracture zone is lower than that of intact rock mass, and the fracture zone will show low resistance. Figure 6b shows that the resistivity of bedrock increases with depth, and the bedrock is relatively complete. 3D inversion results of ERT are basically consistent with

2D inversion and seismic reflection results, but 3D inversion results can intuitively see the distribution of faults and bedrock. Of course, the resolution of 2D inversion is higher than that of 3D inversion. In summary, from the results of seismic refraction and ERT, we can confirm that the fault passes through the survey line layout area. With the strike in NE-SW, the width of the Qingchuan–Pingwu fault is about 30–40 m, and the thickness of Quaternary ranges from 12 to 15 m.

Figure 6: (a) Position of ERT lines, (b) 3D geological model of ERT, (c) x-direction slices by ERT, and (d) y-direction slices by ERT.

Seismic data of line S3 are collected on cement-hardened road along the river bank, with buildings and a river on both sides. And hardened ground seriously affects the use of ERT, so that ERT is not used. Geological interpretation map (Figure 7c) can be obtained from seismic reflection profile (Figure 7b). The reflection wave from the bedrock interface can be traced and compared in the whole profile, and the reflection energy is strong and continuous. The reflection wave can be tracked continuously in the event (Figure 7b).

Table 3: Drilling exploration parameters

Drilling	Coordinate		Altitude (m)	Depth (m)
	Longitude	Latitude		
D1	104.5318	32.4128932	838.819	21.4
D2	104.5317	32.4124914	835.674	19.3
D3	104.5317	32.412014	835.751	21.4
D4	104.5316	32.4115755	835.049	32.3

Figure 7b shows that seismic waves in Quaternary have well continuity. After time–depth conversion, it can be inferred that the burial depth of Quaternary is about 20 m according to the reflection wave characteristics of time profile. Within the range of surveying lines, the thickness variation range of Quaternary overburden is relatively small. It infers that the location of the event axis at 110 m of the survey line is the reflection of the Qingchuan–Pingwu fault on the seismic profile.

Seismic reflection and ERT data indicate that the Qingchuan–Pingwu fault is a hidden fault and passes through the urban area. At the same time, we have also made four drillings (D1, D2, D3, and D4) along the

Table 4: Resistivity of medium

Formation	Medium	$\rho/(\Omega\text{ m})$
Quaternary	Topsoil	53–80
	Sandy pebble	62–369
Devonian	Limestone	356–2,500
Silurian	Phyllite	452–3,677

predicted fault strike to determine the lithology of bedrock and the location of faults in urban areas.

Core data show that the main material on the surface is miscellaneous fill, with an average thickness of about 5.2 m (Tables 3 and 4). The underlying layer of

Figure 7: (a) The location of survey line (S3). (b) Seismic reflection profiling (S3). The green line is the boundary between Quaternary and bedrock. (c) Geologic interpretation map.

Figure 8: Drilling interpretation profile. Miscellaneous fill is mainly composed of pebbles and soil, which contains some bricks, cement, and construction waste.

miscellaneous fill is sandy pebble layer with a thickness ranging from 4.4 to 8.3 m, and the stratum distribution of sandy pebble is continuous and stable. Besides, the core data show that the overburden thickness of the fault is between 11.7 and 12.7 m. Drilling results show that the bedrocks of D1 and D2 are Devonian limestone, while those of D3 and D4 are Silurian phyllite. Cores of drilling D1 and D2 are composed of Devonian gray-brown limestone with a dense, partly weathered, and thick-layered structure, undeveloped joints and fissures, a clear structural plane, and a relatively complete core. Meanwhile, the cores of drilling D3 and D4 are composed of Silurian gray-black phyllite with soft rocks that are mostly layered, schistose, and a clear structural plane. As we know, at the passage of the faults, under high-temperature and high-pressure environments of tectonism, the hard upper rock wall undergoes intense metamorphism and crumpling [92]. The soft lower rock wall is extruded and deformed, resulting in an unclear structural plane of the original rock mass in the lower wall, with a fractured rock formation, which is consistent with the outcropped fault profile. The bottom part gradually changes from

Figure 9: Exploration results infer the location of the Pingwu-Qingchuan fault in Pingwu.

strong-weathered phyllite to medium-weathered phyllite. The degree of core metamorphism indicates the development of fault cataclastic rocks, in which the differences in thickness and height of the overburden layers on both sides of the fault are apparent. From the joint section of the boreholes, we can infer that the fault passes between D2 and D3 (Figure 8).

6 Discussions

Geophysical exploration of the buried faults in the urban areas should not only overcome noise interference in cities but also solve problems caused by buildings. There is an urgent need to assess the variety of geophysical techniques available in urban to address the problems of urban geology and engineering [93]. Seismic reflection method, ERT, and the drilling method are used to investigate the buried faults in Pingwu, particularly to determine the location of the Pingwu-Qingchuan fault in the city and some of its basic characteristics. The findings show that seismic reflection method and ERT can effectively explore the buried active faults in the urban area. However, some problems in the study need to be considered. (1) Ground hardening is common in urban areas, and the placement of electrode rods in ERT can be disturbed during their use; (2) the Quaternary covering of the shallow surface in the urban area of Pingwu has been seriously excavated, and this scenario can lead to the non-universal results of geophysical

prospecting and surface drilling; (3) the incident angle of seismic wave between strata will affect the characteristic change of reflected wave [94], and the structural difference between two fault plates can be the basis of seismic exploration. The composition and water content of rocks will also affect the interpretation of seismic reflection exploration results [95], and the change of water content caused by the structural change of fault location will become the difficulty of interpretation of the seismic exploration results. Because one kind of geophysical method may have many interpretations, we recommend to use the comprehensive geophysical prospecting and drilling to carry out the work.

7 Conclusions

We explored Pingwu County by combining geophysical prospecting method and drilling to determine the distribution of the buried faults in the study area. The exploration results confirm that the Pingwu–Qingchuan fault passes through Pingwu (Figure 9). The results of this study show that the bedrock on both sides of the Qingchuan–Pingwu fault is limestone and phyllite. With the strike in WS, the width of the fault is about 30–40 m, and the thickness of Quaternary ranges from 12 to 15 m. The results of the exploration can provide an important guide to both the architectural urban planning and the earthquake prevention work of Pingwu County.

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