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Using 3D seismic exploration to detect ground fissure

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Abstract:
As a kind of supergene geological phenomenon, ground fissure has brought great inconvenience to human life. In addition, it also has a close relationship with earthquake. However, it is very difficult to ascertain the extension depth of ground fissure since its concealment and uncertainty. In this paper, 3D seismic exploration is used to detect ground fissure in Shanxi Province of China. Specific parameters for seismic data acquisition, processing and interpretation are analysed. Firstly, seismic data acquisition method and its corresponding parameters are discussed. Small dose explosive sources and high frequency geophones are used. Small trace interval and appropriate fold are also adopted. Secondly, seismic data processing is processed from shot record to seismic profile. Multi-domain loop iteration de-noising is used to get high signal-to-noise ratio data. Accurate near surface model, interactive iteration and residual static correction are used to eliminate the impact of low velocity zone and the static correction problem. Large common middle point bin and small velocity analysis interval are used for high accuracy velocity spectrum analysis. The mute parameter of stretching distortion and the migration aperture are researched for shallow ground fissure detection. Thirdly, seismic data interpretation is processed to get ground fissure distribution. Fault enhanced filter is used to improve the signal-to-noise ratio effectively and the chimney cube is used to identify ground fissure automatically. Thus, the specific 3D seismic exploration method used in this paper is suitable for ground fissure detection.

1. Introduction

Geothermal Ground fissure is a geological phenomenon where the surface of the rock and soil produce craze and form a certain length of cracks under the action of the natural factors (Yang et al., 2018; Howard et al., 2019; Li et al., 2019), such as tectonic movement, the action of water or human factors (irrigation, excavation, etc). As a kind of supergene geological disaster phenomenon, ground fissure is common in many countries in the world (Bankher and Al-Harthi, 1999; Ayalew et al., 2004; Eleni et al., 2014; Gaur et al., 2015; Wang et al., 2016). Ground fissure can lead the ground and underground buildings to crack, the road surface to damage (Zhao et al., 2015; Xiong et al., 2017; Liu et al., 2019) and bring a lot of inconvenience for residents (Peng et al., 2007; Huang et al., 2010). A large number of surveys show that the ground fissure is not only the source of the earthquake but also the place where suffers from most seriously damage when earthquake happens (Liu et al., 2009; Zhang et al., 2011; Peng et al., 2012; Liu et al., 2018). Therefore, it is of great significance to take effective detection methods to find out ground fissure distribution characteristic.

Since the ground fissure shows the characteristics of concealment and uncertainty, it is very difficult to detect it accurately (Xu et al., 2015; Wang et al., 2018). If the drilling method is merely used, the exploration period will be long and the costs will be high. In addition, the number of boreholes and the scope of exploration are limited. Thus, it is difficult to meet the purpose of finding out the space distribution characteristic of ground fissure. Seismic exploration method, as a way of area exploration, has the advantages of large coverage area, high resolution and accurate detection results. It takes an irreplaceable advantage in detecting the spatial distribution feature of faults, oil and coal in conventional energy exploration. Therefore, ground fissure that has the same features with fault could also be detected by seismic exploration method.

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However, there are also some differences between ground fissure seismic exploration and normal fault detection. The following problems are common in the process of detecting ground fissure: (a) The purpose exploration layer is shallow and suffers from strong disturbance by the source; (b) The exploration area is generally near the city and urban area, the human activity and the external interference is very serious; (c) The signal-to noise ratio of seismic data is generally low; (d) The fold number is low. Therefore, based on the particularity of ground fissure detection, special methods must take into consideration in seismic data acquisition, processing and interpretation. In order to acquire shallow signal, many important parameters such as seismic source, geophone, offset, receiver interval and fold need to be researched in the process of seismic data acquisition. Many processing methods for getting ground fissure seismic signal such as de-noising technology, static correction, velocity analysis, stretching distortion removal and migration aperture should be studied in the process of seismic data processing. At the time of seismic data interpretation, reasonable seismic attributes need to be adopted to help the explanation of ground fissure.

2. Experiments

The exploration area is about 3 km^2 which located in the northeast of Qi County, Shanxi Province, China. The ground fissures are very developed, so the 3D seismic exploration is used for ground fissure detecting. The main geological tasks are to find out: (a) the distribution and the strike of the ground fissure; (b) the profile structure and developmental state of the ground fissure; (c) the buried depth of the ground fissure and the stratum structure.

2.1 Selection of seismic acquisition parameters

Seismic acquisition has played a decisive role in the whole process of 3D seismic exploration. Therefore, many parameters involved in the process of collecting ground fissure data are tested many times to get the best reflection signal.

2.1.1 Seismic source parameters

Explosive source can acquire wide frequency and high energy signal. Therefore, using the explosive source is a kind of effective anti-disturbance and high-resolution method for shallow seismic exploration. By comparing the seismic spectrums under different explosive quantity, it shows that as the quantity increased, low frequency component increases faster than high frequency and the dominant frequency becomes lower. In the research area, the target layer is shallow, so the small quantity of explosive source is used. The final explosive quantity parameter is 1.5-2 kg.

2.1.2 Geophone parameter

The target layers are shallow because ground fissure usually develop near the surface. Therefore, the high resolution is required in order to obtain accurate image of ground fissure. Analog geophones generally work at a narrow frequency band and have phase distortion from low frequency to high frequency. In addition, they have a small dynamic range, low sensitivity and poor consistency when conducting geophones in the field. In corporation, digital detectors receive signal in the range of 0-800 Hz with good amplitude fidelity, no phase distortion and frequency attenuation. The digital detectors also can directly output digital signal, avoiding external electromagnetic interference and sound transmission. Therefore, the three-component digital geophone-DSU3-428 (Fig. 1) is used for ground fissure detection in this research area.

Fig. 1. DSU3-Sercel-5.

In addition, the coupling of geophone with the ground is the key to receive seismic wave. Special punching equipment is made for the geophone hole to make the geophone couples well with the ground and improve the consistency of geophone receiving. After the geophone is installed, the clay is placed around the geophone to make it more coupled.

2.1.3 Acquisition parameter

The choice of the observation system parameters is the key to get high signal-to-noise ratio and high-resolution seismic data for the detecting of ground fissure. Thus, the parameters of offset, trace interval and fold are carefully researched to get high signal-to-noise ratio data for the target layers.

(1) Offset

According to the law of seismic wave propagation, the maximum offset usually equal to or a little larger than the depth of target layer. The main factors for the minimum offset are to avoid interference caused by the source explosion and to obtain the reflected wave data of the shallow target as far as possible. In addition, the need of shallow refraction is also considered. In this study, considering the surface construction environment and the receiving channel distance, the minimum offset distance is generally selected as 2.5 m.

(2) Trace interval

Using small trace interval can reduce the influence radius of the noise and protect the high frequency of the seismic signal (Liu et al., 2012). It also can improve the spatial sampling density to get high lateral resolution. In addition, the spatial false frequency of low frequency interference wave is avoided, which is more conducive to the separation of signal and noise, therefore the suppression effect of interference wave

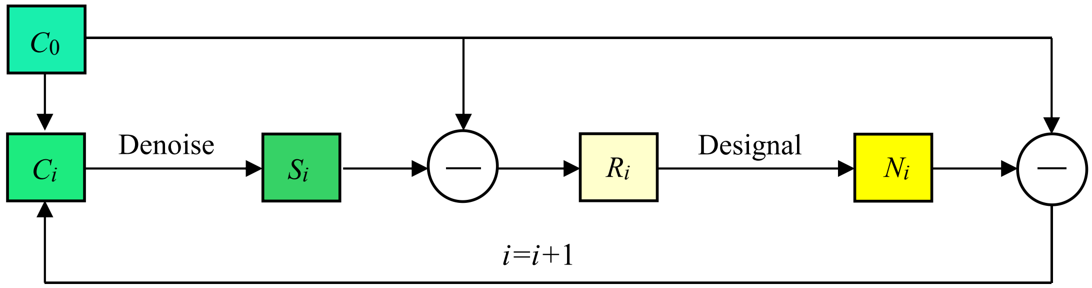


Fig. 2. The flow chart of multi-domain signal-to-noise separation loop iteration.

Table 1. Observation system parameters.

Parameters	value
Receiving line number/swath	4
Receiving number/line	140
Line interval	40 m
trace interval	5 m
Shot number/swath	2
shooting distance	20
maximum offset	699.3
Minimum offset	2.5
scroll distance for vertical	70
Scroll distance for horizontal	40
Folds for 10*5	20
Folds for 10*10	40
Exploration area	4
Full coverage area	4.701

is improved. In this area, the trace interval is 5 m.

(3) Fold

Fold of seismic data cannot be ignored for the shallow layer's high resolution seismic exploration. A higher coverage is required in shallow seismic exploration to suppress interference and improve the signal-to-noise ratio of seismic data. However, due to the low-pass filter characteristic of multiple coverages, excessive fold will reduce the resolution of seismic data, especially in the area of large fluctuation, subsurface with complex structure or great inhomogeneity changes. In addition, fold number is related to the detection costs and work efficiency, so appropriate fold is taken into account in the process of ground fissure detection (Pan et al., 2003). In this area, the fold for common middle point (CMP) bin 10 multiply 5 is 20 and CMP bin 10 multiply 10 is 40.

According to in-depth analysis for ground fissure detection above, the acquisition parameters are as Table 1.

2.2 Processing parameters

The difficulty of ground fissure seismic data processing is to extract weak reflection and image small structure in quaternary strata under the condition of strong interference background. In order to guarantee the effectiveness of the detection results, improving the signal-to-noise ratio of shallow seismic data is considered in the first place (Deng et al., 2003). Therefore, a unique way for processing is adopted.

2.2.1 De-noising technology

Through the investigation and analysis of original seismic data, the surface wave, acoustic and outliers are widespread in this project. The multi-domain loop iteration method is adopted to suppress noise. The basic principle is as follows:

As shown in Fig. 2, original signal data (S_0) and original noise data (R_0) are obtained after preliminary signal-to-noise isolation from original seismic data (C_0), that is $S_0 = C_0 - R_0$. The main ingredient of R_0 is noise, and some signal is also contained. After the de-signal processing, the N_0 is obtained from R_0. N_0 is the pure noise and no signal includes in. Thus, a new data C_1 is got by C_0 minus N_0. Because N_0 contains no signal, all the removal is noise and no signal is lost in the processing. Then, this processing can be circulated again. S_1 and R_1 can be obtained by signal-to-noise isolation from C_1, $S_1 = C_1 - R_1$ and then the de-signal is processed for R_1 and N_1 which contains pure noise is obtained. Another new data C_2 is got by C_1 minus N_1 and so on. As long as the data C_i contains noise, this process can be looped until the signal and noise are completely separated. Thus, the noise is suppressed effectively by the method of multi-domain signal-to-noise separation loop iteration.

2.2.2 Static correction

Static correction is the key step for shallow data processing. Due to the relatively low fold of shallow seismic data, the processing result is affected by the surface interference seriously. If the problem of static correction is not solved very well, the calculating precision of velocity field and profile quality will be affected seriously. Through the application of near surface model static correction, interactive iteration static correction and reflection wave residual static correction, the impact of low velocity zone in this area and the static problem are solved well. Then, the signal-to-noise ratio of seismic data is improved greatly.

2.2.3 Velocity analysis

Accurate velocity is another key factor for the shallow seismic data processing. Velocity analysis is to use a group of velocity values to flat the CMP gather and calculate the stacking amplitude, and then judge the optimal velocity at a certain time according to whether the event is leveled and the stacking amplitude is the maximum.

Suppose M seismic channels are set to receive signals, the offset is $x_1, x_2, x_3, \cdots, x_M$. Respectively, the vertical travel time of the CMP is t_0, when underlying medium is horizontal, the time correction formula for leveling the event is

$$\Delta t_m = t_m - t_0 = \sqrt{\frac{x_m^2}{v^2} + t_0^2} - t_0 \qquad m = 1, 2, 3 \cdots, M \quad (1)$$

where Δt_m is the move out correction value at point m (ms), t_m is the reflection time at point m (ms), t_0 is the vertical reflection time (ms), x_m is the offset at point m (m), v is the move out velocity (m/s).

According to the normal move out (NMO) correction formula, the seismic event is flattened when velocity v approaches the actual velocity; the Δt_m is high and the seismic event is corrected excess when velocity v is low; the Δt_m is low and the seismic event is under corrected when velocity v is high. However, the shallow layer seismic signal usually has less stacking times and much noise, it is difficult to obtain accurate dynamic correction velocity and flat the event, especially the data from the far offset. Therefore, large CMP bin is used when taking velocity spectrum analysis to reduce the influence of shallow interference and enhance the accuracy of velocity analysis. For the seismic data in this area, the CMP bin is 10 m multiply by 10 m. Concerning the shallow signal, the CMP bin increase to 20 m or more, but not too large, because too large CMP bin will put the signal from different reflect point together and reduce the accuracy of velocity analysis. In order to improve the velocity analysis accuracy further, the small velocity analysis interval of 10 m is taken to get a high precision velocity field. The velocity analysis is processed multiple times based on residual static correction.

2.2.4 The stretching distortion removal

Stretching distortion removal is a crucial step in shallow seismic data processing. In the shallow layer, the angle of incidence and reflection is greater than the data from deep and it is more easily affected by the seismic acquisition factors. Therefore, the reflection coefficient changes more dramatically and the stretching distortion becomes more seriously after NMO. In addition, the fold in the shallow layer is lower than the deep. Under so many unfavorable factors, the stretching distortion removal is carefully processed to protect the shallow seismic data. In theory, when the dynamic correction stretching distortion is more than a 1/3 wavelength, the stack result will be seriously affected. Therefore, how to deal with the stretch distortion for the far offset is a key issue in the shallow layer data processing. According to the scope of incident angle for the effective reflection, the approximate formula for the effective offset range in different depth is obtained: $X \leq 2/3\sqrt{3}H$ (X: offset, H: the depth of the aim strata), according to this formula, when the strata depth is 150 m, the maximum effective offset is 173 m, the offset greater than this will be cut.

2.2.5 Migration aperture

In prestack-time migration, the migration aperture will depend on the maximum offset, usually 2 times of the maximum offset is appropriate for migration aperture. Then, the aperture with 400, 600, 800, 1,200, 1,500, 2,000, 2,500 meters is tested, 1,500 meters which nearly equal to 2 times of maximum offset is the most clearly in seismic imaging results. Therefore, the migration aperture with 1,500 m is selected.

2.3 Seismic interpretation

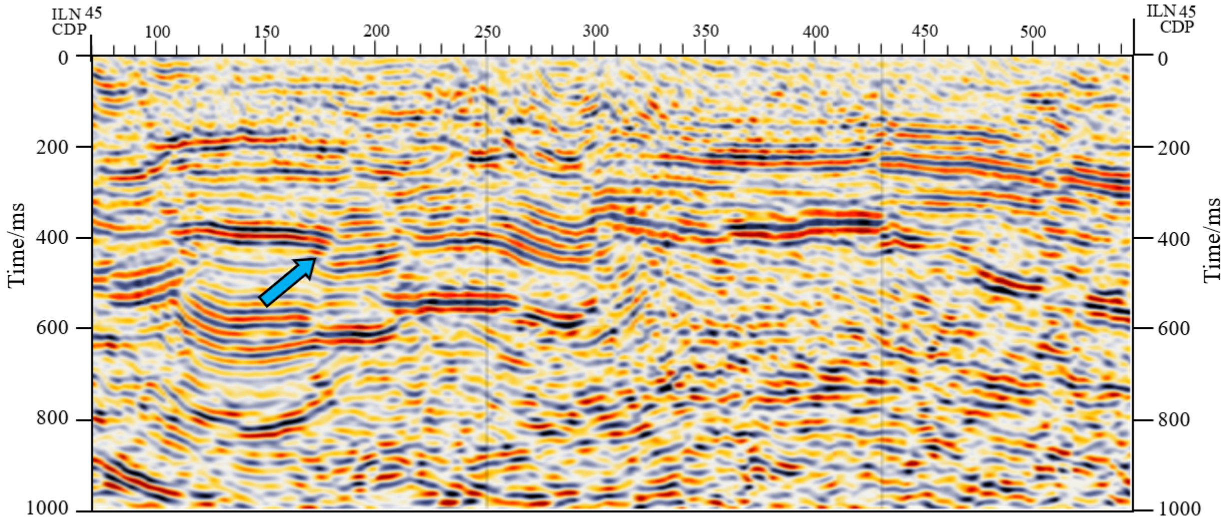
The existence of ground fissure will make the seismic reflection characteristic change, so the continuity of the event is destroyed and the seismic attribute is changed. The amplitude, frequency and phase transform differently according to the ground fissure size. Therefore, the seismic attribute is used to identify and predict the ground fissure.

Before interpretation, a fault enhanced filter is processed for the seismic data to make the ground fissure more clearly at the location of ground fissure and make the events more continuous at the location of no ground fissure. The principle of the fault enhanced filter is: the median filtering method is used at the location where the similarity value is high (no fault location) to improve data signal-to-noise ratio, the diffusion filter method is used to make the faults clearer where the similarity value is low (fault location). After several parameter test, the fault enhanced filter attribute is achieved for the interpretation of ground fissure (Fig. 3).

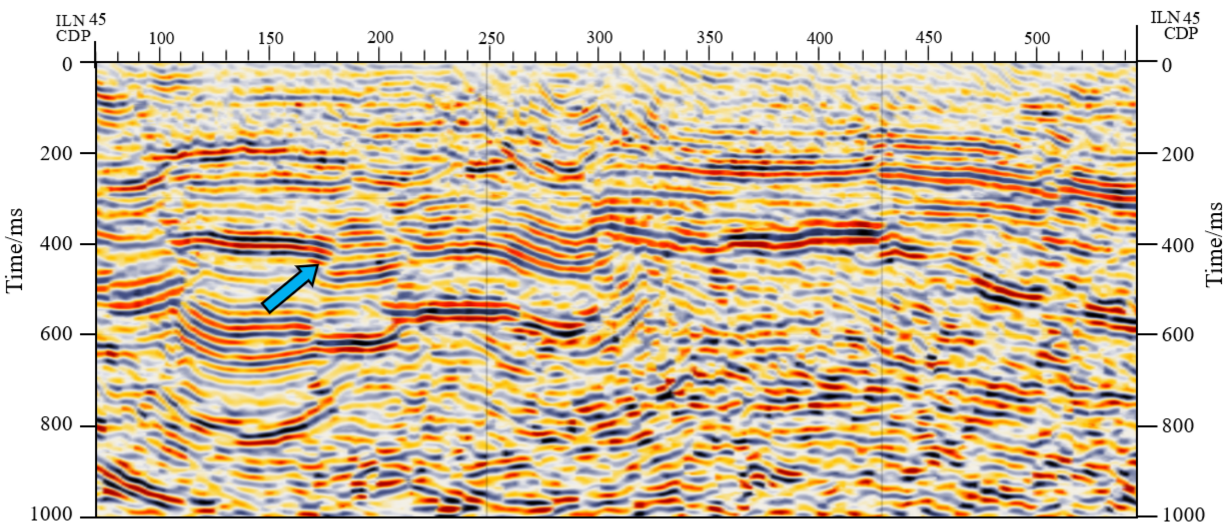
Based on the fault enhanced filter, the chimney cube is also used in the interpretation of ground fissure. The specific steps are as follows: (a) pick the samples at chimney development zone and normal formation zones respectively, (b) extract all kinds of seismic attribute and training neural network to get the distribution of chimney zone and normal area, (c) display the seismic data and chimney data together to test if the chimney cube is suitable for ground fissure detection. The parameter will be tested again and again until the satisfactory result is achieved. The overlapping display of the chimney cube and normal seismic is shown in Fig. 4, from this figure it is known that the gas chimney body attribute can be used to indicate ground fissure automatically. Thus, the chimney cube method improves the efficiency of ground fissure interpretation and reduces the multiplicity (Fig. 5).

3. Results

According to Automatic interpretation of layers, five horizons are interpreted in this area. From shallow to deep, these horizons are named for horizon 1, horizon 2, horizon 3, horizon 4 and horizon 5 in turns. The reflection characteristics of the five horizons are obvious and can be tracked obviously. They are almost parallel to each other and the topographies



(a)



(b)

Fig. 3. (a) The section before the fault enhanced filter. (b) The section after the fault enhanced filter.

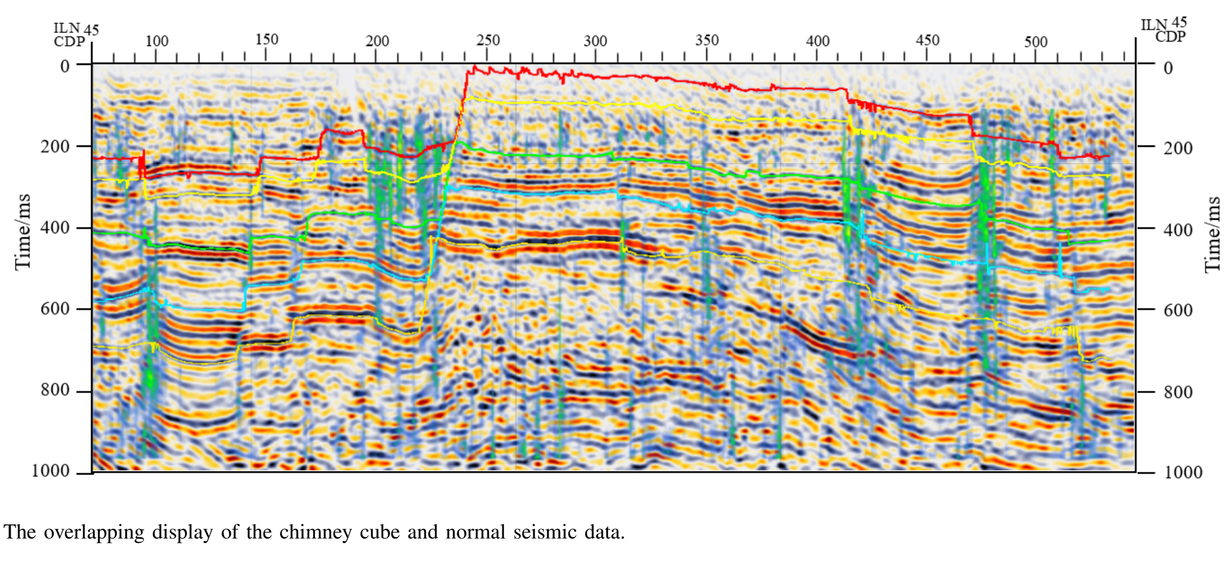


Fig. 4. The overlapping display of the chimney cube and normal seismic data.

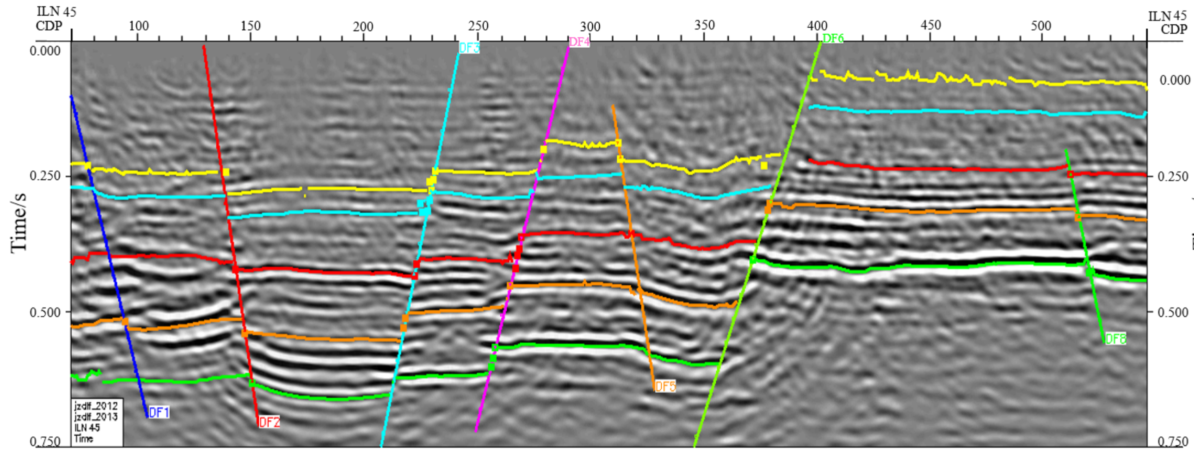


Fig. 5. Seismic interpretation profile.

are consistent. The buried depth is shallow in the north and large in the south. Horst and graben are very developed here. After the interpretation of the horizon, the ground fissures are obviously.

According to seismic attribute and manual interpretation, 11 ground fissures are interpreted in this area, from north to south they are DF1, DF2, DF3, DF4, DF5, DF6, DF7, DF8, DF9, DF10, DF11 in turns. If classified them in the view of fault, these are all normal fault, and the fault strike are almost NEE. The dip direction of the DF1, DF2, DF5, DF8, DF9, DF10, DF11 are SSE and DF3, DF4, DF6, DF7 are NNW. All the 11 ground fissures are across the area and extend outward. Thus the extending length of the ground fissure in this area is long and cutting depth is large. The fault throw of DF6 is the largest one and the fault throws decline gradually from DF4, DF5, DF3, DF2, DF1, DF9, DF10, DF11, DF7 to DF8. The horizons are divided into horst and graben structure by ground fissures. Therefore, ground fissure is closely related to modern tectonic activity in this area and it belongs to a kind of structural ground fissure, mining of groundwater and surface water infiltration make the ground fissures more developed (Zhang et al., 2012; Deng et al., 2013).

4. Conclusions

Through this research, many details of using 3D seismic data to detect ground fissure are discussed and some special methods for detecting ground fissure are acquired. The main conclusions are as follows:

1) Due to the shallow bury of the ground fissure, the seismic acquisition, processing and interpretation are different from conventional seismic exploration, so a series of specific methods are adopted in this paper to meet with the exploration of ground fissure.
2) In the process of seismic data acquisition, the quantity of explosives is tested according to the imagination of the target layer, this time 1.5-2 kg is used. In order to obtain high resolution seismic signal, three-component geophone-DSU3-428 is used. The offsets are selected to avoid the interference wave caused by source and to obtain the shallow reflection. The small receiver interval is adopted and appropriate fold is choosing.
3) In the course of processing, multi-domain loop iteration method is adopted to suppress noise. Through the application of near surface model static correction, interactive iteration static correction and reflection residual static correction, the impact of low velocity zone and the static problem can be solved well. Large CMP bin and small velocity analysis interval are used when taking velocity spectrum analysis. Multiple iterations between residual static correction and velocity analysis are needed. Stretching distortion removal parameter is selected according to the formula mentioned in the article. The migration aperture is choose depending on the maximum offset and some tests.
4) During the interpretation of ground fissure, fault enhanced filter is used to improve the signal-to-noise ratio effectively and the chimney cube is used to identify ground fissure automatically. The interpretation results are coincidence with the actual reveal data highly.
5) The ground fissures in this area is caused by tectonic action. Mining of groundwater and surface water infiltration make the ground fissures more developed.

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Conflict of interest

The authors declare no competing interest.

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