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Reservoir response analysis based on passive seismic tomography in CO2 injection: A case study of the Shizhuang CO2-ECBM Project

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ABSTRACT
CO2 injection into subsurface reservoirs for storage engineering is the most important means to reduce greenhouse gases. To satisfy the huge carbon-neutral target, injection and storage engineering exploration is needed for tight reservoirs beyond aquifers or abandoned reservoirs. Later, China carried out an exploration and research project on CO2-ECBM and CO2-EOR demonstration projects in tight reservoirs for the applicability, reliability and coordination of different monitoring technologies. This paper relies on the CO2-ECBM project for a passive monitoring technique of the TS634 well in ShiZhuang City, Shanxi Province, China. The monitoring adopted the three-component grid monitor system with the long-time continuous acquisition, and applied the passive seismic tomography algorithm, and obtained the energy perturbation during reservoir injection. The results integrated the target coal seam configuration, porosity, and permeability distribution of the layer before injection, which well represents the energy distribution and fractures probability distribution caused by fluid perturbation during the injection process. After that, comparing the results of the multi-period processing can illustrate the fluid transport trend and inter-well interconnection direction, and it is consistent with the production well verification. For the first CO2-ECBM demonstration project in China, the passive seismic monitoring technology is used to complete the fluid transport trend analysis with the passive seismic tomography technology as the core, and better presentation results are obtained at a certain scale, which initially verifies the effectiveness of the passive seismic monitoring technology for the ECBM carbon storage project. This study lays a foundation for the development of domestic carbon storage geophysical monitoring technology, and is more likely to improve the accuracy of comprehensive research on multi-dimensional and multi-domain monitoring technology.

Keywords: CO2-ECBM Project, Passive seismic tomography, Fluid migration trend, Fractures probability density

NONMENCLATURE

Abbreviations	
CCUS	Carbon Capture Utilization and Storage
ECBM	Enhanced Coal Bed Methane Recovery
EOR	enhanced oil recovery
SDI	Streaming Depth Imaging
LPLD	Long Period and Long Duration
Symbols	
MPa	Pressure

1. INTRODUCTION

In recent years, CO2 emissions are increasing, there is necessary to reduce the greenhouse gas emissions is the key for the process of modern human civilization. Countries have stepped up efforts to deploy clean and efficient energy policies and measures. The main solutions and technologies to achieve the goal including: CO2 is collected from combustion exhaust gases and the atmosphere, and then injected into deep abandoned or non-commercial deep reservoirs for isolation and determination of safe and permanent storage. Due to the need to achieve the goal of storing approximately 1 billion tons of CO2, this is a very difficult task if only high-porosity, high-permeability and weakly cemented formations are used [1]. Last years, the selection and

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monitoring of injected reservoirs have gradually expanded to tight reservoirs.

The Earth's brittle crust is a self-organized critical system [2]. Because the general fracture is in friction equilibrium state [3]. A stress or pressure change of less than 0.01 atmospheric pressure is sufficient to stimulate seismic activity. The distribution of earthquake magnitude and frequency is linear logarithmic, so small earthquakes are many orders of magnitude more than large earthquakes, and this distribution seems to have no lower magnitude limit [4]. In the case of artificial stimulation, seismic energy is continuously emitted at a lower level inside the fragile reservoir.

Before the injection project, the tight coal-bed methane reservoir will carry out a certain scale of fracturing project in this area in advance. Then, the well group is plugged to facilitate more coalbed methane replacement space for CO2 injection. The pore elastic stress wave caused by hydraulic fracturing will be more active [5]. Therefore, the reservoir is unstable, and more energy will be released after injection.

The passive seismic imaging method is very sensitive to this because it stacks the energy of multiple gathers rather than simply looking for large discrete events. Stacking the total energy can capture a large amount of microseismic energy. Because these microseismic are not clear, they cannot be distinguished as a single event, or cannot separate P-wave and S-wave arrivals. Lacazette et al and Sicking et al have applied passive seismic imaging methods in different work areas and developed a streaming depth imaging (SDI) workflow [5-10].

In this paper, passive seismic monitoring and imaging research are carried out in TS634 coalbed methane development well group, and the results of this method in tight coalbed methane reservoir are discussed and analyzed. The energy release and disturbance caused by diffusion after CO2 injection is presented by performing iso-depth domain imaging on the monitoring data at the same time interval before and during injection. Finally, by comparing with the production information at the same time, we illustrate the effectiveness of passive seismic monitoring and imaging technology in TS634 CBM development well group, and discuss the uncertainty.

2. GEOLOGICAL CONDITIONS IN TS634 WORK AREA

The TS634 coal-bed methane development well group is located in the southeast of Shizhuang Town, Qinshui County, Shanxi Province. The structural position is on the northwest-dipping slope zone in the south of Qinshui Basin, and the NE-trending Sitou fault is developed in the west(Fig. 1.).

A series of fold structures are developed in the southeast of TS634 well group, and no structures affecting storage are found in the reservoir. The hills on both sides of the TS634 well area are developed and located at the bottom of the valley. The altitude is about 900 m. The terrain is relatively gentle, and the depth of the target layer is about 600 m. TS634 is an injection well adjacent to the TS634J monitoring well, which is equipped with optical fiber sensors to monitor the temperature and pressure.

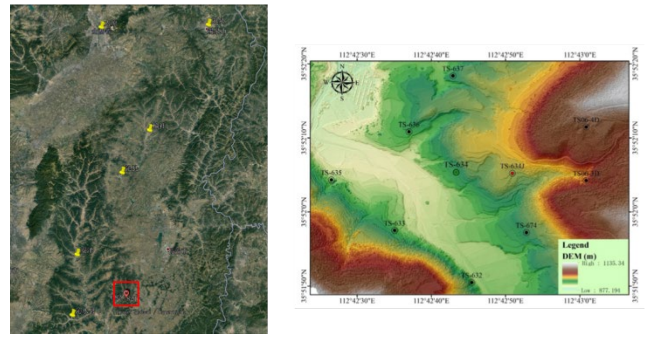

Fig. 1. Work area (the right image is a digital elevation model in the left image red frame)

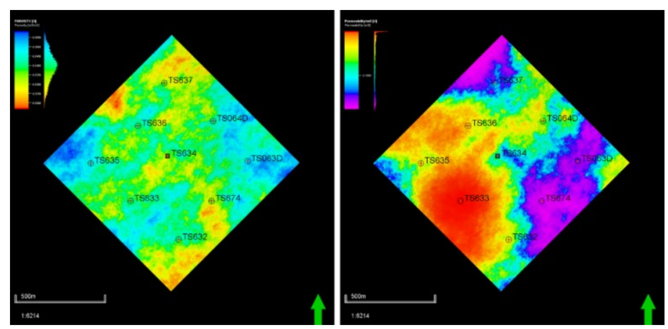

Fig. 2. The porosity and permeability of TS634 well group in the work area (the left figure is porosity, the right figure is permeability)

The target layer of the work area is developed from the bottom to the top of the Ordovician, the middle Carboniferous Benxi Formation, Taiyuan Formation, the lower Permian Shanxi Formation, the lower Shihezi Formation, the upper Permian upper Shihezi Formation, Shiqianfeng Formation and Quaternary strata. The drilling data show that the buried depth of the coal seam in the study area is less than 2000 m, which contains 20 coal seams. The total thickness of the coal-bearing strata is 193 m, of which the total thickness of the coal seam is 9.34 m, and the coal-bearing coefficient is 4.8 %. The metamorphic degree of coal and rock is relatively high, and the content of coal-bed methane is high. The target coal seam is 3 # coal seam of Shanxi Formation. Reservoir pressure is between 1.6-3.5 MPa and the porosity is about 4 %(Fig. 2.).

3. MATERIAL AND METHODS

3.1 CO2 injection passive seismic imaging technology

When CO2 is injected into the reservoir, the coal matrix will release methane and free out of the coal seam for CO2 storage, which is beneficial to improve the exploitation rate of coal-bed methane. In order to explore the dynamic migration and distribution of fluid in the reservoir, a series of multi-space and physical field monitoring systems were designed in the project, including ground geophones. The target depth of the monitored coal seam is about 600 m. Due to the active and abundant main signal sources inside the reservoir, the subsurface passive tomography method is worth trying.

Passive seismic tomography (PST) is a geophysical exploration technology that uses natural microseismic activity as the source (microseismic events with magnitude ranging from-1 to 2.0 Richter scale, almost everywhere) [11]. A portable and specially designed seismic monitoring network deployed on the ground and continuously recording for several months in order to detect the spatial distribution of local microseismicity [12,13].

The seismic signal collected by geophone is caused by underground passive seismic events. The source signal will be affected by many interference noises in the process of underground propagation. However, due to the factors such as seismic wave propagation path and underground medium difference, the frequency of noise and source signal is usually different, and the correlation between gathers is very small. The passive seismic imaging method does not need to accurately pick up the first arrival of microseismic events, so the imaging calculation efficiency is improved. And after multi-channel superposition, it can strengthen the original very weak passive seismic events and improve the reliability of imaging results. In the passive seismic observation, the data acquisition network can record the passive seismic signal in a time window, and the source location and time of the passive seismic event are unknown [6].

The monitoring target area where passive seismic events may occur is divided into multiple small voxels according to the positioning accuracy requirements. Each voxel is considered to be a potential source point of passive seismic events. The passive seismic source point is regarded as a diffraction point in the exploration seismic. According to the principle of reverse time migration, the signals received on all data traces are propagated in the time direction, which will inevitably converge at the passive seismic source point (Fig. 3.).

Therefore, it is necessary to traverse all the voxels in the monitoring area, and find the position of the maximum energy after stacking as the source point of the passive seismic event by the method of amplitude stacks.

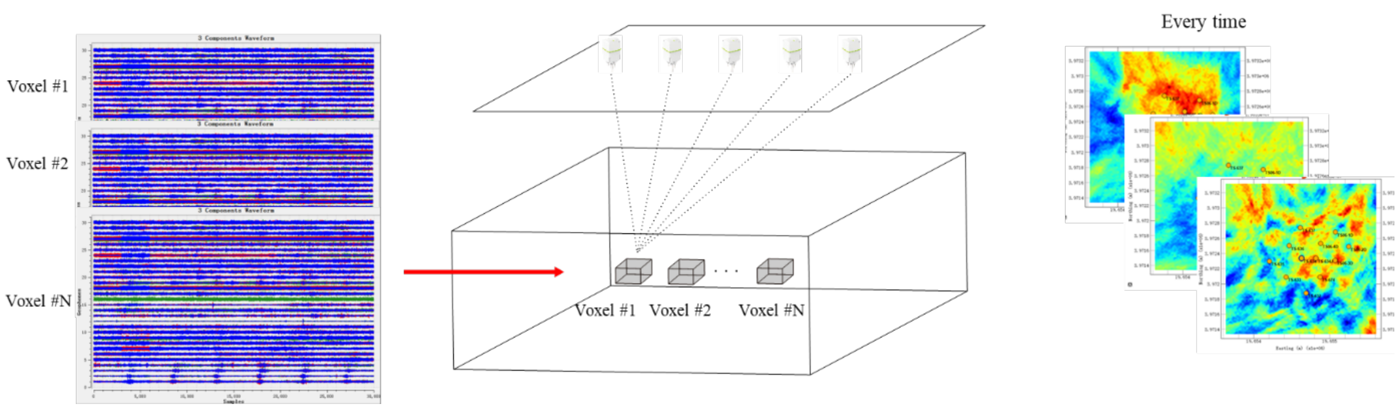

Fig. 3. The principle of passive seismic imaging(modified by Sicking and Malin, 2019)

3.2 Injection monitoring scheme and data workflow in TS634 well

The TS634 well group includes eight production wells distributed in and around the injection well (TS634). Before CO2 injection, 30 broadband three-component stations were deployed around the well group (Fig. 4.), and passive seismic data acquisition and imaging studies were conducted on the data before and after injection. In order to ensure consistency, the station does not move, and the environmental impact factors around the station are monitored daily. Data preprocessing needs to eliminate large interference and ensure sufficient data to avoid destructive factors that make monitoring data unavailable.

Passive seismic imaging of CO_2 injection is mainly based on the geometry and topology of the stack results, and the energy change of the fractures in the reservoir during injection is extracted as the result of passive imaging. The specific process is [14,15]:

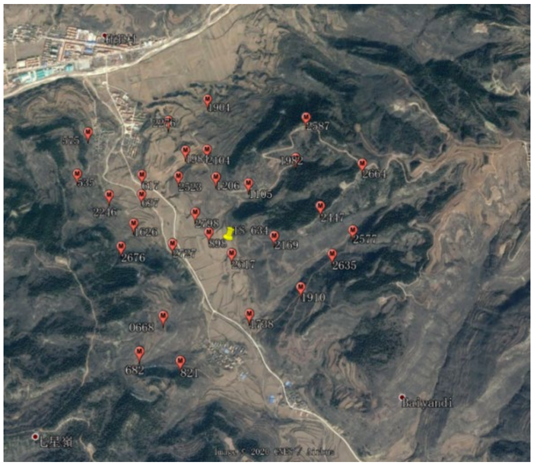

Fig. 4. Monitoring system in TS634 (red dots are the sensor positions, and yellow one is the injection well position)

(1)Data acquisition is performed in two cycles (before and after injection), and reliable data is selected for processing and analysis.

(2)The data is filtered to remove noise, static correction, etc., similar to the standard reflection seismic processing method, retaining highly correlated gather data (Fig. 5.).

(3)Using any available data, such as acoustic logging, stacking velocity of seismic data or VSP survey, a velocity model of the target layer is established. The velocity model needs to be as fine as possible. If there is enough data, an anisotropic velocity model with three-dimensional spatial variation can be established. If perforation can be obtained, these data can be used to fine-tune the initial model.

(4)The target layer is divided into voxels. Using the ray tracing algorithm, the one-way travel timetable from each voxel to each receiver is calculated. This step requires a fine speed model.

(5)Appling amplitude stack algorithm. According to the amplitude information selected in the time window, the amplitude of all traces corresponding to the same number of rows and columns. To calculate the similarity coefficient, and the results are stored in the corresponding position in the two-dimensional L_2 array of $i \times j$. Its specific form is[12]:

$$S_{ij} = \frac{\left(\sum_{n=1}^{N}\sum_{m=1}^{M} X_m\left(t_n - t_{ij}^{(m)}\right)\right)^2}{M \times \sum_{n=1}^{N}\sum_{m=1}^{M}\left(X_m\left(t_n - t_{ij}^{(m)}\right)\right)^2} \quad (1)$$

Where, S_{ij} is the similarity coefficient of the grid points corresponding to the i row and j column in the two-dimensional array L_2. N is the length of the time window. M are the number of geophones. $X_m(t_n - t_{ij}^{(m)})$ is the data of the m seismic trace, and seismic data amplitude of the first point in the time window after the length $t_{ij}^{(m)}$ of the time window is moved.

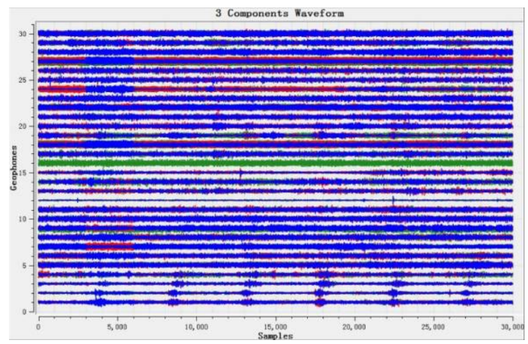

Fig. 5. The collected passive seismic data (one minute)

4. *RESULTS*

Through consistency analysis and correlation analysis of gathering data, the data volume of one month before injection and one month during injection is obtained by applying passive seismic data processing flow. After removing the interference of the background energy value, the reservoir energy disturbance result within one month during the injection period is obtained (Fig. 6.). The final results are mostly from CO_2 injection into the reservoir, and the energy release generated by fluid migration in the fracture network (Fig. 6., right).

The left diagram of Fig.6. shows the background value energy distribution. The depth range is structural position of 3 # coal roof and floor. It can be seen from the figure that the energy disturbance is large at the TS637 and TS632 positions, and the energy disturbance is low near the injection well, which is because the injection well did not perform any construction work at that time. The right figure is the result of energy disturbance in the reservoir after removing the background value at the same depth. It is not difficult to find that after a period of CO_2 injection, a high-energy band appears from the vicinity of TS634 to the northwest, passing through TS06-4D to TS06-1D and has a tendency to diffuse from TS06-

1D to TS637. The bottom hole energy value of the three production wells is small in the southwest direction, and the energy connection with other wells is poor.

Fig.7.left shows the distribution of gas moving dominant direction in TS634 well group during injection. The darker the color in the figure, the greater the gas channeling pressure received by the production well pointed at the end of the arrow, and the possible advantage trend of gas displacement is given according to the corresponding pressure gradient. There are four core directions: TS634-TS637; TS634-TS064D-TS061D; TS634-TS063D-TS061D; TS634-TS674-TS632.

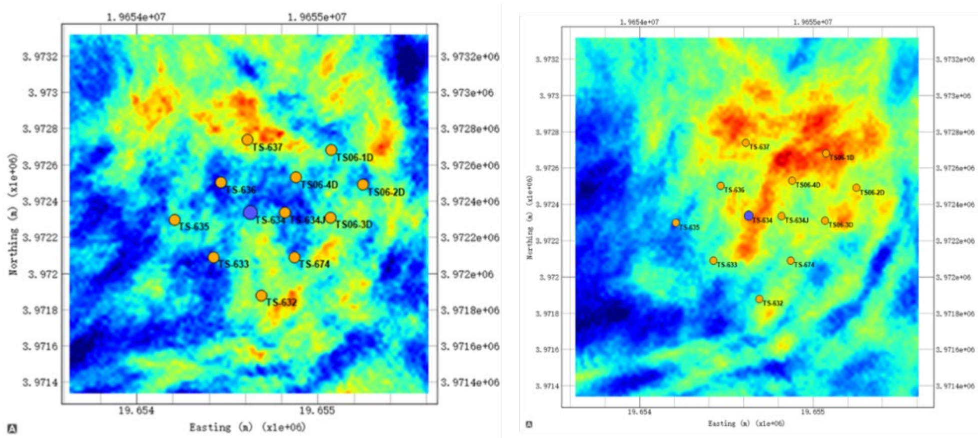

Fig. 6. The background value before CO2 injection and the energy disturbance in the reservoir after CO2 injection (TS634 well group,where blue dot is injection well, orange dots are production wells)

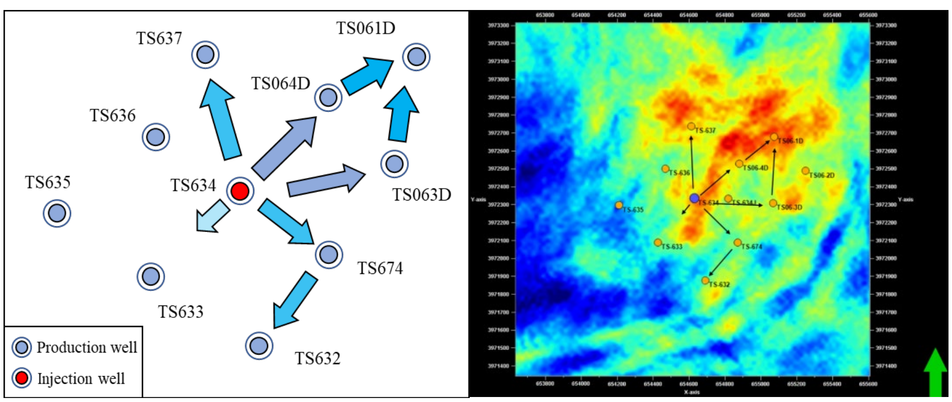

Fig. 7. Gas channeling advantageous distribution of TS634 well group (left,modified according to production data) and the final result and gas trend stack diagram(right)

Fig.7.right is the stack of energy and trend. The high energy area in the figure is roughly consistent with the gas channeling trend, and the whole is in a passive direction and has an aggregation trend in the northeast. Firstly, the consequences of passive seismic monitoring and imaging during CO2 injection in TS634 well group can show the energy release of fluid in reservoir fractures. Through the injection-production relationship between wells, the trend of CO2 fluid migration and diffusion can be described. The energy difference of the results represents different fluid injection-production activities during the injection period. Because of its intensive microseismic activity, it is inferred that the place with high energy is the main migration channel.

5. DISCUSSION

Hydraulic fracturing stimulates activity by reducing the normal stress of existing natural fractures, breaking new rocks, and changing the current stress state. It should be pointed out that the pressure pulse can be transmitted through the fracture network without transmitting the fluid [13]. Rock mechanics theory, field research and experiments show that fractures are intertwined in microseismic event clouds. Therefore, the central plane of high-density cloud is the location of large fracture [16,17].

The pressure of injection displacement process is much lower than that of hydraulic fracturing, and there are few microseismic events that can be identified. The passive seismic imaging method is very sensitive to this, and the total trace energy can also capture the energy of the long period and long duration (LPLD) events [18], and there may be other unclassified types of seismic activity.

The data set eliminates random noise and superimposes spatial stable signals over a long period of time. Because the activity in the fracture network is intermittent, it takes a long time window to full image it. Weak signals can be expressed in space by this method. After consistency analysis, the filtering of various noises in the collected data is suppressed, and the waveforms generated by internal disturbance, displacement and fracture of the reservoir are retained, which can reflect the activity behavior of CO_2 in the injection process, and then serve as the current production effective fluid space migration trend. It is worth mentioning that if the results of 3D seismic and pre-injection hydraulic fracturing stress analysis are combined, the fracture network of CO_2 injection displacement can be more accurately characterized, which has a positive guiding significance for injection and production engineering.

6. CONCLUSIONS

(1)The passive seismic imaging process is implemented to the data for a period of time before and after injection, and the energy disturbance results in the reservoir before and after injection are obtained. By removing the influence of background energy before injection, the energy disturbance result of CO_2 injection is obtained at a certain depth of the reservoir during this period. The high-energy bands are in the northeast direction and have an aggregation trend in the northeast.

(2)The consequence of passive seismic imaging is compared with the results of the dominant gas channeling between the TS634 well groups during the injection period. The gas channeling direction in the high-energy area is mostly coherent, and the overall direction is northeast.

(3)The result of passive seismic imaging are stacked by long-term invisible events, which can be used as the trend of fluid migration in the reservoir, and the high-energy area can be used as the high-density fracture distribution area of injection-production activities. According to the strength of the energy release, it can be used as a reference to fracture density and permeability distribution in this area.

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DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the manuscript.

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