Application of 3D Seismic Exploration Technique in Evaluating and Optimizing Favorable Areas for Salt Cavern Gas Storages

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Abstract
With the significant increase of natural gas consumption in China, it is necessary to build underground gas storages to meet the demand of seasonal peaking and emergency backup gas supply. 3D seismic exploration technique plays a nonreplicable role in evaluating and optimizing salt cavern gas storages. Salt cavern gas storage exploration is characterized by its difficulties with superficial target layers and higher demand in identifying minor faults and salt bed thickness. By adopting the high-density spatial sampling 3D seismic acquisition technique, the high-accuracy imaging technique, the resolution-increasing processing technique and the comprehensive integration and interpretation technique, an effective guidance is made in evaluating and optimizing the favorable areas for salt cavern gas storages.
Keywords: salt cavern gas storage, 3D seismic survey, high-density spatial sampling, high-accuracy imaging technique, comprehensive evaluation technique

1. Introduction

Underground natural gas storage can properly solve the inhomogeneity problem for urban gas supply and plays a role in adjusting the peak season of gas; in the meantime, it may also act as emergency reserve gas facility when gas supply is interrupted temporarily due to accidents, such as the sudden occurrence of serious natural disaster to gas main or pipeline leakage, which has improved the reliability and security for gas supply greatly.

Typical underground gas storages can be classified into four types: exhausted oil and gas reservoirs, aquifers, salt caverns and abandoned mining pits. At the present the main gas storage form in China is salt cavern gas storage at present.

Southeast China is the major economic developing area and a densely populated region in China, but its major natural gas is sourced from West China; therefore, gas storage become a necessary measure to ensure the gas supply safety in this area. In recent years, precise 3D seismic surveys on salt cavern gas storages have been fconducted in Jintan, Huai'an and Yunying districts respectively. This paper describes that a good survey result is achieved after the tailor-made acquisition, processing and interpretation techniques are adopted aiming to the difficulties and characteristics of Huai'an salt cavern gas storages, which has provide an effective guidance for selecting and locating the favorable areas for Huai'an salt cavern gas storages.

2. Geological issues to be settled in evaluating and optimizing the salt hole gas storages

Huai'an gas storage is located within the Zhaoji secondary depression in Hongze rift of Honglianfu sag in North Jiangsu Basin. The internal of the sag is the Cenozoic sediments. Seismic survey and logging data show that the sag, upsetting from north to south, is a typical dustpan-type depression which is deeper in south and shallower in north and steeper in south and gentle in north with fault in south and overlap in north; and there is an obvious plane of unconformity between the substrate and the Mesozoic and Cenozoic stratum.

As a whole, the geological factors such as reservoir physical property, growth of structure traps, closeness of fault and closeness of cover stratum must be taken into account when to construct a salt cavern gas storage facility.

1) Growth of the structure trap
In general, gas storages should be constructed in a simple structure area with a large structure amplitude, a large trap closure area in shallower burial depth where no fault is developed or the fault has a good closeness.

2) Closeness of cover strata
The cover strata for gas storage shall be in tight lithology, large thickness and low permeability. In general, gypsum rock has best closeness, bauxitic mudstone is in the next place; and mudstone varies greatly in closeness. The research on regional cover strata needs to be made in combination with depositional facies.

3) Reservoirs occurrence modes
The rock salt stratum occurrence, thickness, the growth of insoluble intercalated beds and their spatial distributions are the key factors for the quality of the underground gas storage. Generally, the reservoir stratum suitable for developing gas storages should be characterized by a unitary lithological character, stable facies belt and a higher permeability performance.

4) Closeness of faults
Whether the construction of gas storage is successful or not usually relies upon the migration, accumulation and destructive effect of natural gas in the fault.

The geologic problems need to be solved for Huai'an salt cavern gas storage are mainly to identify the Palaeogene salt rock stratum and the adjoining rock strata, the distribution of sedimentary characteristics and structural forms, the distributional characteristics of faults in the salt rock stratum and adjoining rock strata and the distributional characteristics of the intercalated beds inside the salt rocks within the 3D survey area to provide a reliable geologic basis for the construction of gas storages.

3. Accurate 3D seismic exploration techniques for salt cavern gas storages

The elevation does not change much in the survey area, 13m-54m. Covered with dense rivers and channels, it is a typical water net surface in south China. It is involved with many villages and small towns.

The full-coverage 3D seismic area of Huai'an salt cavern gas storage is 34.61km^2; its maximum coverage area is 50 km^2.

1) 3D seismic acquisition techniques for salt cavern gas storages

Aiming at the characteristics of shallow target stratum, high requirement on resolution and high identification requirements on lithologic and thickness of strata, high-density wide-azimuth spatial acquisition technique is highlighted in the recording geometry to meet the requirements on data acquisition.

Bin size: Bin size should meet the lateral resolution and the maximum aliasing-free frequency, can ensure the homing and imaging of resolution and small tilt angle, improve the recognizing ability of thin layers and minor faults. Small bin is favorable to increase the recognizing ability. The bin adopted is 10m×10m.

Shot-trace density: Since shot-trace density is positively correlated with migration imaging and considering that the salt cavern gas storage exploration is mainly to identify fine structures, minor faults and thin salt beds, noise analysis, denoising, high frequency protection, the continuity of seismic wave field, even sampling and reducing the random noise produced during prestack migration processing should be taken into account when to design the trace density. In combination with the practical geological conditions in this area, the shot-trace density adopted has reached 640,000 traces/km^2.

Azimuth: Wide azimuth is quite favorable for increasing the imaging ability of subsurface geologic body; hence, the multi-line wide-azimuth recording geometry is adopted: 16 lines × 6 shots × 96 channels, the azimuth is up to 1.0.

2) Rock cavern 3D seismic data processing techniques

Considering that various noises are developed and the near-surface structure changes greatly in lithology and velocity in this area, following on-purpose processing techniques are emphasized.

HI-FI denoising technique: Appropriate denoising methods are selected aiming to the different types of noises to protect the effective information to the maximum degree and improve the S/N ratio of the data from the target area.

Resolution-increase processing technique: Deconvolution methods and parameters are fully tested and the frequency band for effective signals is widened reasonably to reasonably increase the resolution of the target layer data on the basis to ensure the S/N ratio and wave impedance characters.

High-accuracy imaging technique: A velocity analysis is made finely to establish a precise and reasonable migration velocity field. The prestack time migration processing is adopted to improve the imaging accuracy for small fault blocks and thin layers.

Through the on-purpose processing, a good imaging result for all the target strata are achieved. The bottom boundary for the gypsum subsection above the salt rock is the major indicator for the growth of salt rock section within the region of interest. With the phase of the target stratum as a mid-strong reflection through in good continuity, which is easy to be correlated and traced, it is an obvious lithology-varying interface. There is one set of Gypsic horizon or gypseous mudstone above it and a large set of salt rock sediments under it. It is show as an obvious lens and a distinct rock cavern stoping-out phenomenon can be seen in the 3D seismic processing section,(Fig. 1).

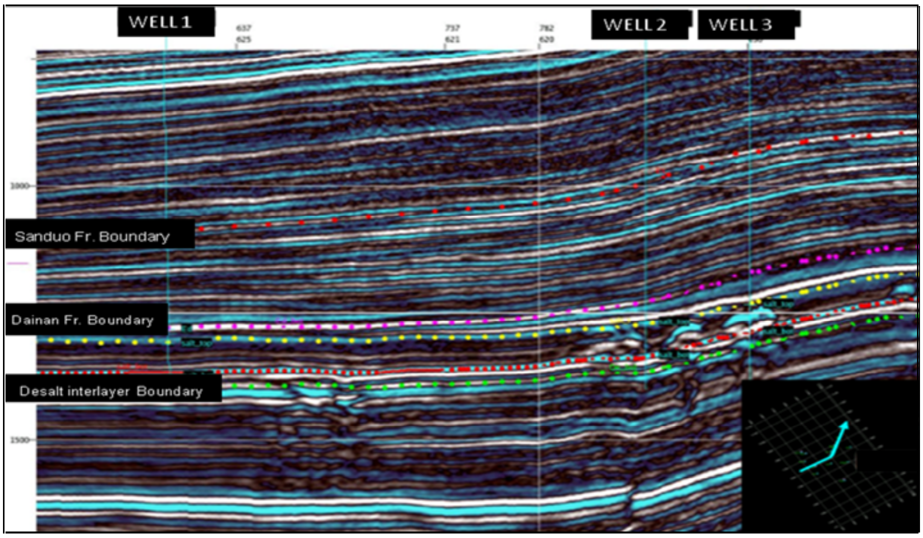

Fig. 1:3D migration section for the survey area

3) Comprehensive 3D seismic interpretation techniques for salt cavern gas storages
Aiming to the exploration characteristics and geologic objective requirements of salt cavern gas storages, the integrated interpretation techniques including the fine faults identification, salt bed spatial occurrence prediction and comprehensive geologic research are studied and applied, see(Fig. 2).

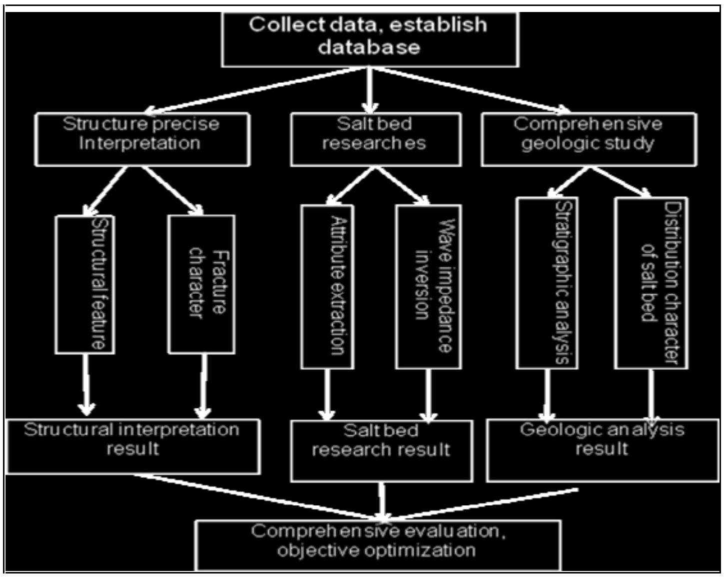

Fig. 2:Interpretation workflow and key technology diagram for salt cavern gas storage

Accuate fault interpretation technique: To make accurate demonstrations in the view of plane, section and multi-direction using the 3D inline, crossline, random line and time slice; and use the correlation body and 3D visualization techniques to verify the fracture arrays.

Use the VSP data for Well A in the area to precisely determine the relationship between the seismic reflecting horizon and the geologic horizon; and then, use the sonic logging data from Well A to create and calibrate the synthetic seismogram. Consequently, the VSP corridor stack section has a good coincidence relation with the wave impedance character of the seismic section, the salt rock characteristics are clear and the calibration result is reliable(Fig. 3).

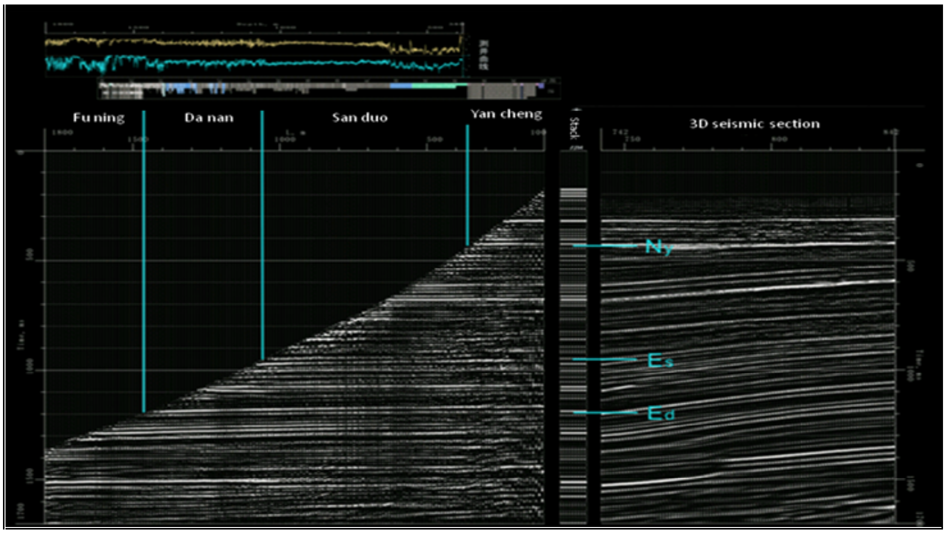

Fig. 3: VSP bridge-type precise calibration for Well A

Extract the curvature that reflects the torque of event and the edge detection attribute that reflects the gray scale variance ration of image to analyze the variation of lithology and subsurface structures and find out the macro distribution pattern of horizon and fault in solid space(Fig. 4).

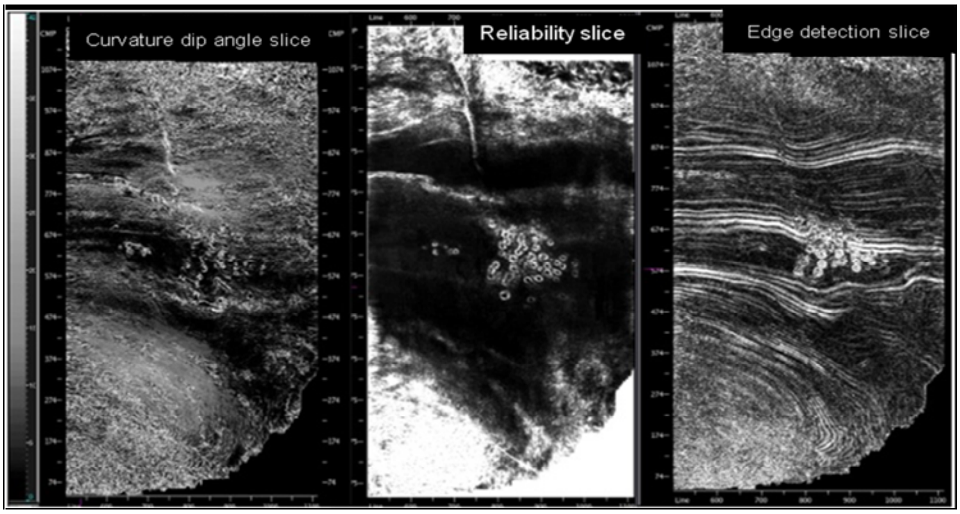

Fig. 4 :3D seismic data attribute time slice (1360ms)

Multi-attribute salt bed prediction technique: Extract multiple seismic attributes along the interpreted horizon, analyze these attributes comprehensively and make prediction on the lateral distribution of the salt bed, interlayer and interval layer in combination with the wave impedance inversion result.

Salt bed log interpretation technique: The salt beds (red areas) have a distinguishing characteristic in the log curve, i.e. the P-wave impedance is high, the P-wave time difference, the density and the gamma is small; there is a big gap between it with the range of the corresponding curve value(Fig. 5).

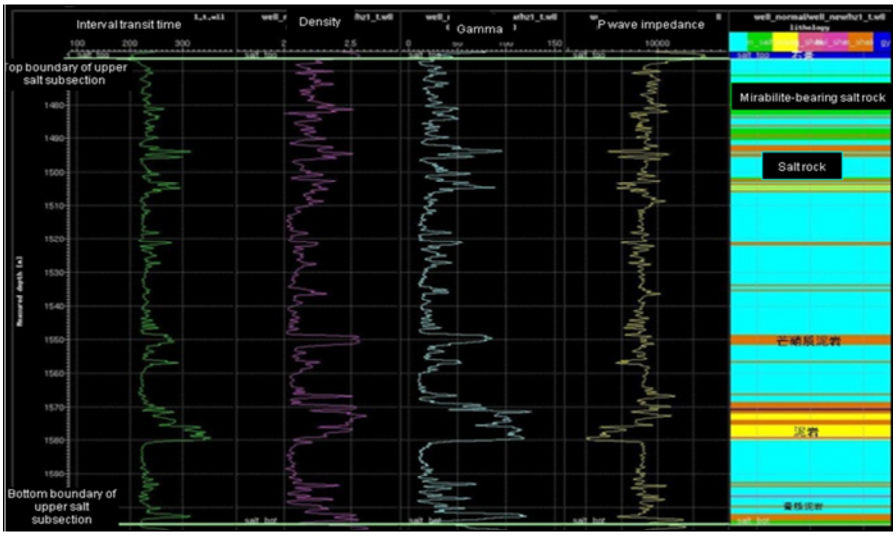

Fig. 5:Well A log curve and lithologic collum

The P-wave impedances for salt rock, argillaceous gypsum and saline mudstone are all distributed in the same range, but they have a great gap with the P-wave impedance for sandy mudstone. The wave impedance of saline mudstone is 8500-10000g/cc*m/s; while one mudstone is 6000-8000g/cc*m/s, In this case, most saline formation in the upper salt subsection, mudstone and limy mudstone can be identified using P-wave impedance attribute(Fig. 6).

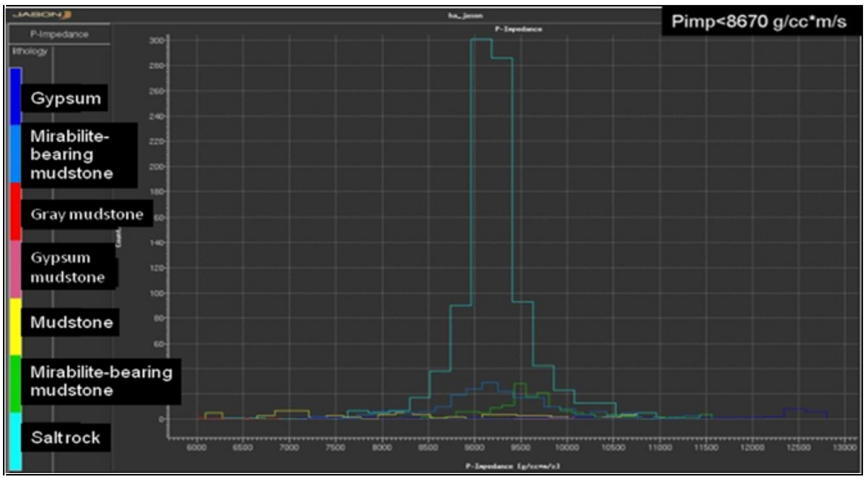

Fig. 6: P-wave impedance histogram for Well A

Since the restriction to sparse impulse inversion is dependent upon the resolution of seismic data, the inversion result reflects the comprehensive response of several sets of lithology and may predict the distribution pattern of salt rock in the whole area; however, it can hardly predict the thickness variation trend of thin interlayers.

In order to predict the muddy intercalation within the salt rock more accurated, the geologic statistics, which takes the well and sparse impulse inversion impedance data volumes as its input, is used to make the inversion.

It can be seen that the section obtained through geologic statistics inversion can distinguish several salt rock and mudstone formations; while the sparse impulse inversion section can only reflect large formations(Fig. 7).

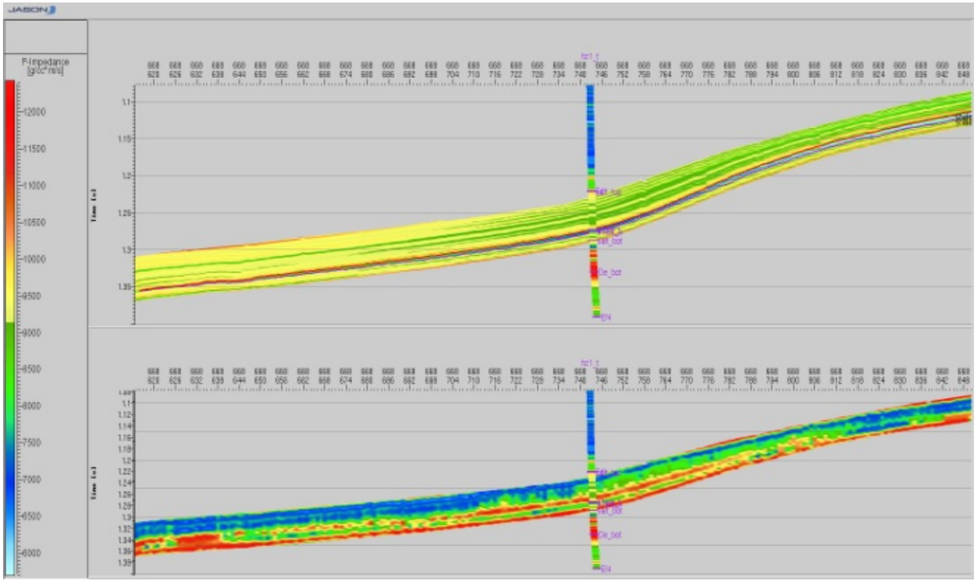

Fig. 7: Correlation of different inversion sections passing through Well A

Salt cavern gas storage comprehensive evaluation techniques: The favorable areas for salt cavern gas storages are the halite sedimentary zone with relatively weak tectonic movement where fault are undeveloped; in the meantime, it is required that the halite deposit must be in a certain area, large sedimentary thickness and good closeness.

According to the analysis on the upper salt subsection formation distribution characteristics, the salt rock sections of the major target intervals are developed in Section Fu IV of Paleogen, which is divided into 4 subsections: upper salt subsection, medium desalt intercalated bed, lower salt subsection and lower hard gypsum subsection. Among these subsections, the upper subsection is the major target interval for storage construction. It is more than 150m in thickness and it gets thinner toward both wings.

Analysis on the distribution pattern of mudstone intercalated bed shows that the No. 1-4 salt groups in upper salt subsection are mainly developed on both wings in the survey area with the regional accumulative thickness of mudstone exceeding 20m at maximum.

As for the salt rock distribution pattern of upper salt subsection, the P-wave impedance value for salt rock is 8670-11500g/cm^3*m/s according to the regional geologic statistics inversion and the log curve intersection analysis results. The salt rock thickness chart for upper salt subsection is achieved through calculation. Salt rocks are developed in all the groups of No.1-4 salt groups in the upper salt subsection in the whole area. The salt rock is thicker than 95m in the middle and the south central of the survey area. It gets thinner gradually toward the both wings.

According to the analysis on the top and bottom fracture characteristics of the major storage construction intervals, fault is developed neither in the roof nor in the floor of No. 1-4 salt groups in the upper salt subsection; and there are only four NWW extending normal faults in the northeast and southwest of the survey area. The stretching length of the longest fault in the south is 2.15km.

According to the evaluation on the roof and floor geologic conditions of storage construction interval, salt cavern gas storage facility requires that the adjoining rock distribution must be stable; have good physical and mechanical properties, and they should function as a good closure layer. Therefore, it is quite essential to select the adjoining rocks. The top of No. 1-4 salt groups in the upper salt subsection is a mudstone interval with mixed gypsum component, which is more than 50m in thickness, it can act as the roof of the salt cavern gas storage; and there is one set of mudstone interval (>7m) at the bottom of No. 1-4 salt groups in the upper salt subsection, its closure condition is quite good.

According to the analysis on the goal distribution range of upper salt subsection, it can be seen in the salt bed amplitude plane for the bottom boundary of No. 1-4 salt groups in the upper salt subsection that goaf is located in the east central of the survey area covering an area about 4.3km^2(Fig. 8).

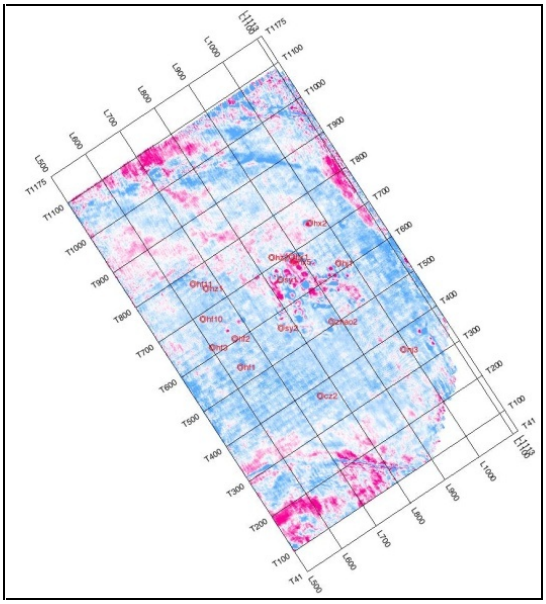

Fig. 8:Bottom boundary amplitude plane for No. 1-4 salt groups in the upper salt subsection

Through an evaluation on the separation fracture and salt bed features as well as the distribution of salt bed using the geologic, tectonic and salt bed comprehensively, the favorable areas and key targets for storage construction are proposed.

4. **Acquisition effect**

Through a comprehensive interpretation of the 3D seismic data, the thickness variation pattern of salt bed, the occurrence and distribution pattern of faults in this area are identified and a comprehensive evaluation are performed on the favorable blocks for subsurface gas storages in the survey area.

The geologic conditions of the upper salt subsection and the adjoining rocks are analyzed. Among them, Group A is higher in salt rock content; it is relatively thick and does not contain any large mudstone intercalated bed set; therefore, the favorable storage construction area is divided giving priority to No. 1-4 salt groups. On the principle that the salt rock thickness should be more than 80m and the burial depth of top surface should be less than 2000m, the boundary for the favorable storage construction area is drawn (the blue polygon), the total area of the favorable area is 14.5km^2. Fig. 8 is the an overlay of the burial depth for the bottom boundary of the gypsum subsection above the salt rock and the thickness of the salt rocks in No. 1-4 salt groups in the upper salt subsection (the isoline represents the burial depth; the color represents the thickness). Considering that the goaf has some influences on the closure condition of the storage area (According to the distributive range of the goaf described by the amplitude plane extracted along the gypsum subsection boundary above salt rock, it covers an area about 2.3km^2), the No. 1-4 salt group favorable area for storage construction is marked out keeping the goaf away (the green polygon). Its area is 12.2 km^2(Fig. 9) and (Fig. 10).

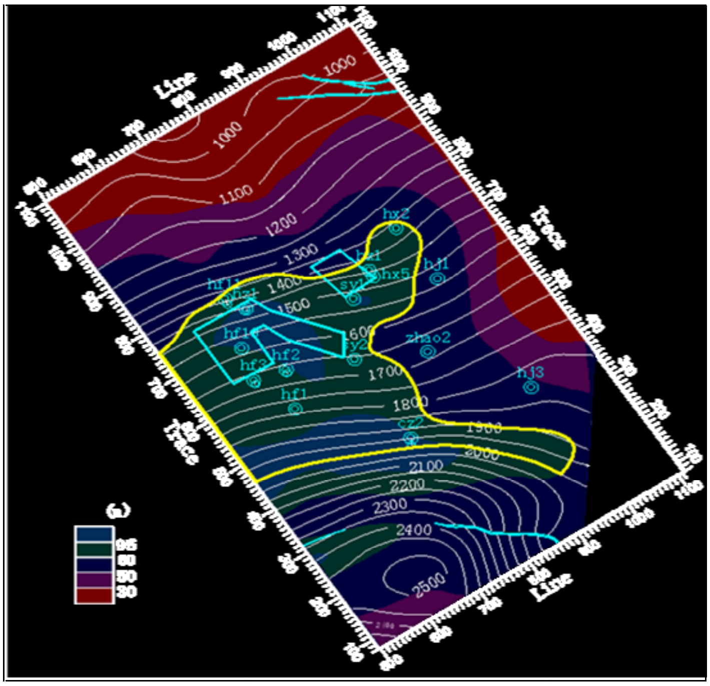

Fig. 9:Overall evaluation map for Salt Group A in the upper salt subsection in the 3D survey area

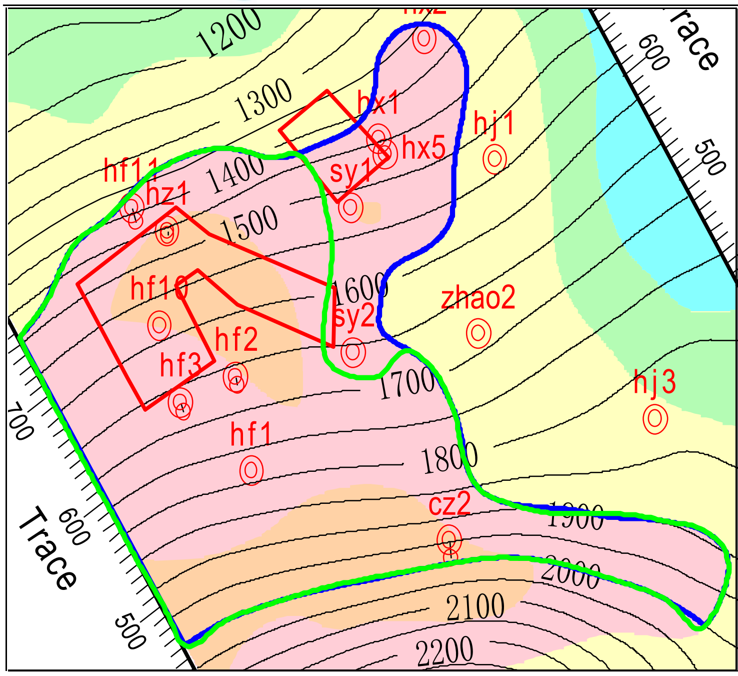

Fig.10:Overall evaluation map for the favorable area of Salt Group A in the upper salt subsection in the 3D survey area

Conclusions

High-density spatial sampling 3D recording geometry provides solid data foundation for the high-precise imaging, resolution improvement and overall evaluation of salt cavern gas storages;

HI-FI and high resolution data processing is the interpretation and inversion basis for seismic data;

VSP has guaranteed the establishment accuracy of velocity field and has provided a reliable basis for horizon calibration and inversion;

The geologic statistics inversion has increased the seismic inversion resolution so that it is an effective method to effectively identify the characters for intercalated layers;

The overall evaluation technique has proposed the favorable area and key objectives for storage construction;

3D seismic survey can effectively guide the optimization and selection of the favorable areas for subsurface salt cavern gas storages.