Three-dimensional electromagnetic method in shallow surface exploration in complex piedmont belt

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Abstract. In the complex piedmont area, the quality of seismic data is generally poor, and it is difficult to build the shallow velocity model, which leads to the inaccurate determination of the stratigraphic and structural positions. The combination of seismic and non-seismic exploration is an effective way for oil and gas exploration in complex piedmont belt. In the northwest of Sichuan Province, the joint exploration of three-dimensional audio-magnetotelluric (AMT) and transient electromagnetic (TEM) is carried out. The transient electromagnetic data is used as static correction for audio-magnetotelluric data, and the AMT data is used to detect the shallow surface structure within 1.5km buried depth. The three-dimensional geoelectric model of the study area is obtained by using AMT three-dimensional inversion, and the geological structure interpretation is carried out by combining well logging with the statistical data of rock physical properties, which provides a basis for seismic building the shallow surface model.

1. Introduction
There are six sets of source rock series in Northwest Sichuan, and 14 gas fields have been found which shows great exploration potential and good prospect and is the key target of Sichuan basin exploration at present. However, due to the complexity of surface topography and underground geological structure in Northwest Sichuan, it is difficult to obtain high quality seismic data. It is difficult to accurately determine the formation development and structural details using only seismic method. We get a large difference of the strata depth between the actual and design drilling data from the data interpretation results. The combination of seismic and non-seismic exploration is an effective way to explore oil and gas in complex piedmont belt. In order to study the integrated building model idea of seismic and non-seismic method, three-dimensional audio-magnetotelluric (AMT) and transient electromagnetic (TEM) were deployed in this area to provide near surface structural information for seismic building velocity model.

Figure 1. Base map of the survey area
Blue dots are AMT station, red dots are TEM station.
There are 5 AMT lines with a distance of 500m and station spacing of 200m. TEM survey lines coincide with AMT with a spacing of 400m between most stations. TEM survey stations are not deployed in the northwest of the study area due to construction difficulties, as shown in Figure 1.

2. Electromagnetic data processing
AMT and TEM methods are adopted in this study. The purpose is to utilize their own advantages to solve geological problems. The advantage of AMT is that the data acquisition is flexible and the exploration depth is large, which make it quite suitable to explore the electrical structure characteristics of buried depth more than 1.5km. But this method can be effected by the static displacement. In comparison, TEM is not affected by static displacement. But the data acquisition is limited by the severe terrain and the exploration depth is small, which is mainly used to correct the apparent resistivity of AMT, so as to achieve the purpose of static correction.

2.1. Static correction
TEM only measures the induced voltage within the time interval after the current is turned off, that is to say, only the pure secondary field anomaly is observed, which is not interfered by the primary field. As only the magnetic field is observed and the electric field is not observed, there is no static effect caused by the boundary charge accumulation of the shallow inhomogeneous body, which provides the basis for AMT static correction.

There are two methods to do AMT static correction with TEM data. One is to directly use the method proposed by Sternberg et al., which converts the time domain EM data to frequency domain to carry out static correction. The other is to use the inversion results of TEM to carry out static correction for AMT data. However, the second method will bring new errors to AMT static correction due to the uncertainty of TEM data inversion. Therefore, the first method is selected for AMT static correction.

2.2. AMT 3D inversion
The 5 AMT lines are basically parallel, which can be regarded as a 3D data and can be processed by 3D inversion method to obtain the electrical structure. In this process, three-dimensional preconditioned conjugate gradient inversion method is used, and the forward modeling is based on integral equation method.

Figure 2. Resistivity data volume by 3D AMT inversion

YX mode data is selected to do 3D inversion. The mesh of 3D inversion is divided into $161 \times 11 \times 48$. Thirty frequencies ranges from 10400 to 0.43Hz are used for inversion. The error floor of impedance and phase is set to be 5%. After 29 iterations, the root mean square error decreased to 1.83%.

Figure 2 shows the resistivity data volume by 3D AMT inversion. The resistivity profile features of the 5 lines are similar. A low resistivity syncline is developed in the middle to left of each line, and a set of high resistivity bodies are developed under both sides of the syncline.

Figure 3 shows the comparison of the observed and 3D inversion predicted apparent resistivity plane for the data at two frequencies, and Figure 4 shows the comparison of the observed and 3D inversion predicted apparent resistivity plane for the data at corresponding frequency. It can be seen from the two
figures that the predicted apparent resistivity of three-dimensional inversion is consistent with the observed data very well, and the phase is fitting better at high frequency, slightly worse at low frequency. It means that the 3D inversion result is good.

Figure 3. Comparison of apparent resistivity plane between observed and predicted by 3D inversion

Figure 4. Comparison of phase plane between observation and predicted by 3D inversion

3. Integrated Geological Model

3.1. Electrical characteristics
Combined with the measured resistivity data of field outcrop, the resistivity data in the study area is obtained through comprehensive statistical analysis. There are 7 sets of main electrical layers.

1. The resistivity of Cretaceous to Triassic is the lowest; 2. the resistivity of T2l changes greatly, which is higher than that of upper and lower strata; 3. the resistivity of T1f is lower, which is characterized by low resistivity; 4. the resistivity of Permian and Devonian is characterized by high resistivity; 5. Silurian to lower Cambrian is characterized by low resistivity; 6. the Sinian system is characterized by sub-high resistivity; 7. the basement Proterozoic is characterized by high resistivity.

The statistical results show that the vertical variation regularity of the layer resistivity in the study area is good, which provides a basis for the geological interpretation.

3.2. Integrated structural model
Collecting the geological map, outcrop profile and other data in the study area, the exposed layer, lithology, stratigraphic occurrence, main faults and other information are known. Besides, the structural modeling and interpretation on the basis of 3D inversion resistivity result are carried out. Line01 to line05 are adjacent with similar structure. Here, we take line03 as an example to introduce the interpretation results.

The line03 is in the direction of NW-SE, crossing three structural units of Tangwangzhai nappe, forward thrust belt and concealed structural belt successively from north to south. From the inverted resistivity profile as shown in Figure 5, it has the characteristics of high resistivity layer and low
resistivity layer overlapping in the depth direction, and obvious segmentation characteristics in the transverse direction. There are great differences in the resistivity between different sections. The thickness of the corresponding electrical layer also has dislocation or thickness change, and the resistivity interface information is abnormal and discontinuous, which reflects the existence of the fault. According to the characteristics of inverted resistivity profile, stratigraphic occurrence and fault features, taking fault F1 and F2 as the boundary, the sections are divided into three parts: the western North segment, the interruption zone and the south eastern segment. The layers of J, T1f, P2, P1, D and S are interpret respectively. Based on the interpretation scheme of Line03, the other 4 lines are interpreted. They are basically same.

Figure 5. Interpretation of inverted resistivity profile and surface outcrop along line03

The quality of seismic data is poor in the northwest part of the study area and the left part of the survey line, especially for the bottom boundary of the shallow Triassic and Permian system. According to the results of AMT 3D inversion and interpretation scheme, the seismic processor adjusted the shallow velocity model and carried out the migration processing for the seismic line again and achieved good result.

4. Conclusions
The three-dimensional exploration of AMT and TEM is an effective way to solve the geological problems of shallow surface. The surface structure information of the study area is obtained by TEM static correction and AMT 3D inversion. Combined with logging data, geological outcrop and physical property data, the 3D inverted resistivity profile is interpreted, and the North-South segmentation of the profile is obvious. The geological model provides non-seismic information which supports the seismic data reprocessing and improves the imaging quality.

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