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Geophysical evaluation methods for buried hill reservoirs in the Jiyang superdepression of the Bohai Bay basin, eastern China

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Abstract
The Jiyang superdepression is one of the richest hydrocarbon accumulations in the Bohai Bay basin, eastern China. Comprehensive seismic methods have been used in buried hill exploration in Jiyang to describe these fractured reservoirs better. Accurate seismic stratigraphic demarcation and variable-velocity mapping were applied to reveal the inner structure of the buried hills and determine the nature of the structural traps more precisely. Based on the analysis of rock properties and the characteristics of well-developed buried hill reservoirs, we have successfully linked the geology and seismic response by applying seismic forward technology. Log-constrained inversion, absorption coefficient analysis and tectonic forward-inversion with FMI loggings were applied to analyse and evaluate the buried hill reservoirs and gave satisfying results. The reservoir prediction was successful, which confirmed that the comprehensive utilization of these methods can be helpful in the exploration of buried hill reservoirs.

Keywords: reservoir prediction, fracture reservoir, buried hill, Bohai Bay basin

1. Introduction
Bohai Bay basin, with an area of 200 000 km², is a rift basin of Mesozoic–Cenozoic age and an important petroliferous basin in eastern China (Tian et al 1992, Allen et al 1997, Jin and Peter 1998, He and Wang 2003, Hu et al 2001, Zhang 2004). The Jiyang superdepression lies in the southeast of the Bohai Bay basin, and the northeast of Shandong Province, China, which includes the Dongying, Huimin, Zhanhua and Chezhen depressions (figure 1). The superdepression is one of the most productive petroleum provinces in the Bohai Bay basin, which, since 1984, has maintained stable yearly production and gradually become the second largest oil producer in China (Zhang et al 2004). Almost one third of the total proven petroleum reserves in the Jiyang superdepression comes from Tertiary reservoirs (Guo 2001). However, abundant oil has also been found in pre-Tertiary reservoirs. With the increase in oil production, buried hill reservoirs have gradually become a major exploration target and important base for increasing reserves and production in the Jiyang superdepression.

A buried hill reservoir is defined as a hydrocarbon accumulation in younger sedimentary formations in buried hill traps. The quality of seismic data from a buried hill is typically very poor: seismic strength can be weak and discontinuous events in the seismic sections occur due to factors such as abnormal depth and variable lateral velocity. As a result, it is difficult to evaluate the reservoir in the buried hill from the seismic data directly (Du et al 2002, Li et al 2003). Buried hill reservoir evaluation is challenging, but it is necessary to find methods of determining the inner structure and geophysical
characteristics of these important hydrocarbon reservoirs (Li et al. 2003).

This paper takes the Jiyang superdepression as a study area and discusses geophysical evaluation methods for buried hill hydrocarbon reservoirs. In order to identify the complex structures of buried hills in detail, interval velocity analysis, accurate stratigraphic demarcation and the technique of variable-velocity mapping are adopted in our study. By studying the geophysical characteristics of buried hill reservoirs and linking the geology to the seismic response with forward calculation, we evaluate the buried hills in the Jiyang superdepression using seismic inversion methods combined with well information, such as well-log-constrained inversion, absorption coefficient analysis and FMI logging. Good results in the determination of the structural evolution and reservoir evaluation of these buried hills have been obtained.

2. Geomorphology and inner structure of the buried hills

2.1. Interval velocity analysis of the pre-Tertiary strata

Velocity analysis is the key to seismic depth imaging because it has a direct effect on the quality of seismic images (Behzad 2006). The buried hills in the Jiyang superdepression consist mainly of pre-Tertiary strata, so the accurate interval velocity analysis of the pre-Tertiary strata is crucial for the seismic imaging that will define the structure of the buried hills.

The pre-Tertiary tectonic evolution of the Jiyang superdepression is similar to that of the Bohai Bay basin (Tian et al. 1992, Wu et al. 2005). The pre-Tertiary buried hill can be divided into four tectonic layers. These are, from the base up, an Archean metamorphic basement, a Cambrian–Ordovician marine carbonate, a Carboniferous–Permian transitional carbonate with interbedded coal, and Jurassic–Cretaceous continental deposits with pyroclastics. The Middle Ordovician–Lower Carboniferous and Triassic are absent (Li et al. 2003). The density, porosity and acoustic velocity vary in the strata because of differences in lithology, compaction, growth thickness and denudation of the layers. We take the thickness of the lithostratigraphy as the weight coefficient to calculate the interval velocity. The weighted method is superior in calculating interval velocity in that it avoids cumulative human error and improves accuracy. We acquired four average interval velocities based on the statistical results of acoustic logging: 4200 m s$^{-1}$ for the Cretaceous, 4000 m s$^{-1}$ for the Jurassic, 4400 m s$^{-1}$ for the Upper Palaeozoic and 5759 m s$^{-1}$ for the Lower Palaeozoic. We make velocity overlays of different types of strata by analysis in order to obtain a structural definition.
2.2. Reflection characteristics and accurate seismic stratigraphic demarcation of the buried hill reservoirs

The inner reflectors of the pre-Tertiary strata are well known from 3D seismic surveys in the Chezhen and Zhanhua depressions (figure 1). Two important reflectors and nine reflection events are revealed in seismic sections across well CG 201 in the Futai oilfield of the Chezhen depression (figures 1 and 2). In this well, oil layers in a buried hill reservoir were encountered and an oil stream of 222.7 t/day was obtained. The accurate stratigraphic demarcation of the buried hill in well CG 201 provides basic data for buried hill structure and reservoir research, which may be applied to the identification and description of the internal reflection characters of lower Palaeozoic buried hills in the Chezhen depression or even other areas in the Jiyang superdepression.

Figure 2 shows nine seismic reflection events corresponding to different lower Palaeozoic strata in the seismic section. The lower Palaeozoic lithology consists mainly of limestone and dolomite. The top and the bottom of lower Palaeozoic strata display two series of strong reflectors, \( T_{g1} \) and \( T_{g2} \) respectively, with an interval time of 400 ms in the seismic section (figure 2). \( T_{g1} \) corresponds to the reflection above the second member of the Badou formation close to the top of the lower Palaeozoic, and \( T_{g2} \) the reflection of the top of the Mantou formation shale, just 120 m above the top of the Archean. Because there are only weak or even no reflections between the Cambrian and Archean strata in the seismic sections at all frequencies, \( T_{g2} \) is generally taken to reflect the structure of the top of the Archean, but it is necessary to make a depth correction to define the depth accurately.

2.3. The technique of variable-velocity mapping

Accurate determination of the velocity of subsurface media is an essential factor in seismic exploration because the depth of a reflection layer will be defined exactly only if the velocity is accurate. Interval velocity calculated from stack velocity using the Dix formula is widely used in seismic processing, assuming that the velocity field is laterally constant. In the Jiyang superdepression, a unified velocity field, called the Dongying velocity, is used for time–depth conversion for long times:

\[
V_{\text{ave}} = 942.76 \cdot e^{0.245 \cdot t_0}.
\]  

(1)

However, half-graben-like depressions, with faults in the north and overlap in the south, were widely developed in the Jiyang superdepression in the Palaeogene, forming a complicated structure of alternating sags and swells (Li et al 2003). The buried hills are usually deep and the lateral variation of velocity in overlying strata is too great for the unified Dongying velocity to be applied. In order to
ascertain the buried hill structure accurately, a variable-velocity mapping technique is applied instead.

Variable-velocity mapping can establish a one-to-one correspondence between geodesic coordinate, reflection travel time and average velocity by using interval velocity inversion for target layers. Therefore, the time–depth conversion could be made using the calculated average velocity for each CDP cell of the study area, instead of the unified Dongying velocity field. Figure 3 shows the difference between the Dongying velocity and variable velocity in one CDP cell. A flow diagram of the variable-velocity mapping technique is shown in figure 4.

The main steps of this technique are as follows.

1. Build an original database. The data consist of field measurements, primary stack velocity spectra, VSP logging data, the geologic zonation of the drilling, floating base level data, $T_0$ values of main target layers and well location information.

2. Preprocess stack velocities. A filter correction is made to primary stack velocities in order to remove accidental errors from field acquisition and processing.

3. Invert interval velocity from stack velocity. Forward iteration is applied to compute interval velocity. First, given a primary model from the Dix formula, we compute the synthetic response using a ray tracing scheme referring to field acquisition parameters. Then, the stack velocity spectra of the synthetic seismogram are picked by simulating the actual processing and compared with observed data to modify the model until the misfit is smaller than the given value.

4. Build the average velocity field. Once proven to meet the required resolution of the multi-supervision, the interval velocities are converted to average velocity.

5. Map with variable velocity. We establish the spatial velocity field by combining the stack velocity field and the iso-$T_0$ data of every seismic reflector. During the inversion of interval velocity, we obtain the average velocity, spatial displacement and strata dip of each reflector at the same time, and then extract the average velocity of each target layer from the spatial velocity field. After that, filter correction, misfit correction, trend surface analysis, borehole correction and time–depth conversion are run. Finally, spatial displacement migration and floating base level corrections are made.

Figure 3. Plot showing the difference between the shift velocity and unified Dongying field, $V_{ave}$. $T_{01}$–$T_{06}$ are the target horizons.

Figure 4. Flow diagram showing the procedures used to plot shift velocity.
Figure 5. Structural map of the buried hill surface in the Futai oil trap (a) before and (b) after application of the variable velocity field. The closure of the structural trap in the variable velocity map is 800 m, 300 m higher than in the unified velocity map.

Figure 5 shows two isobath maps of the buried hill surface in the Futai oilfield, before and after using the variable-velocity field. In the map obtained from the unified Dongying velocity field (figure 5(a)), the top of the buried hill displays a complex faulted block structure, and the closure is 500 m. However, in the map obtained by variable-velocity mapping (figure 5(b)), its structural shape changes to an anticline with faults, and the closure has increased to 800 m. By applying the variable-velocity mapping technique, the type of structural trap has changed from a faulted block to an anticline complicated by faults and with higher closure, and is closer to the real shape of the buried hill.

3. Seismic characteristics of buried hill reservoirs

3.1. Rock petrophysical parameter analysis and the identification of seismic characteristics

Rock petrophysical parameters of the buried hill reservoir, which are influenced by fractures and corrosion, can reflect the anisotropy of rock (Anselmetti et al. 1998). Because the stratigraphic structures and rock constituents vary in buried hill strata, their petrophysical parameters are different. Even if in the same formation, varying degrees of fracture development can give rise to discrepancies in petrophysical parameters. Using tested data from 115 wells in the Jiyang superdepression, we simulated the subsurface temperature and pressure and observed the following features of the fracture reservoir. (1) Fracture sections have undergone three successive periods: closure of original fractures, elastic deformation and breakup. In contrast, tight sections have only undergone the last two. (2) Fracture sections can grow easily just under low pressure. (3) The velocity of the compressive wave is 6200–6400 m s\(^{-1}\) in the non-reservoir section, and just 5500–5800 m s\(^{-1}\) in the reservoir section. This means that the velocity of the compressive wave decreases by 600–700 m s\(^{-1}\) (about 10%) when the reservoir gets developed. (4) The ratio \(V_p/V_s\) is equal to 1.9–2.0 in the non-reservoir section and 1.8 in the reservoir section, which shows that the decrease in velocity of the shear wave is less than that of the compressive wave in the reservoir dominated by vertical fractures. As a result, we can evaluate the development of reservoir beds using information extracted from the compressive wave.

Attributes of the compressive wave, such as quality factor, amplitude and dominant frequency, are related to the fracture aperture. A larger aperture indicates a greater intensity, better permeability and conductivity of fracture. The attributes mentioned above increase with a decrease in fracture openness, and therefore changes in these attributes can be used to detect and invert the fracture development degree.

3.2. Seismic forward simulation

Seismic forward simulation serves as a bridge between geological model and seismogram (John 2001, Anatoly et al. 1999) and provides us with an effective method to completely investigate the distribution of features in a reservoir. Based on the rock petrophysical parameters, we build an accurate geological model and then compute the seismogram by forward simulation, thereby defining the seismic characteristics of the reservoir.

3.2.1. Geological model of carbonate reservoirs and seismic response in real conditions. The carbonate reservoir strata in the buried hill have characteristic high velocity and density.
Figure 6. 6-1(a) to 6-5(a) represent geological models A1 to A5 respectively. 6-1(b) to 6-5(b) are their corresponding synthetic seismograms.
However, low-velocity layers, such as thin weathering beds, are present at the top of the buried hill surface. As a result, the surface is generally supposed to be a strong reflector in the seismic section. We designed five geologic models (A1, A2, A3, A4, and A5) and generated corresponding synthetic seismograms (figure 6). The velocities of the models are derived from statistics results of acoustic logging data in block CB 30 of the Zhanhua depression (figure 1).

Model A1 is a four-layered model with horizontal interfaces. The layers are all homogeneous isotropic media with seismic velocities of 4400 m s\(^{-1}\), 4000 m s\(^{-1}\), 5500 m s\(^{-1}\) and 5800 m s\(^{-1}\) respectively. The interface depths are 550 m, 580 m and 700 m respectively. The model has no fractures. Model A2 is a three-layered model with horizontal homogeneous isotropic strata with velocities of 4400 m s\(^{-1}\), 4000 m s\(^{-1}\) and 5800 m s\(^{-1}\) respectively. The interface depths are 550 m and 580 m respectively. There are 15 fractures with an interval of 20 m at the top of the third layer, 200 m horizontally from the source. The fractures are filled with an argillaceous medium of 2500 m s\(^{-1}\) velocity. Model A3 increases to 60 fractures with an interval of 4 m; all other conditions, compared with model A2, remain the same. In model A4, the depth of the second interface is 600 m, and the thickness of the low-velocity layer increases from 30 m to 50 m compared with model A3. In model A5, the fracture fill is a fluid, and the corresponding velocity decreases from 2500 m s\(^{-1}\) to 1600 m s\(^{-1}\) compared with model A3.

The difference equation (second order in time and fourth order in space) was applied to the numerical modelling as follows:

\[
p^n_{i,j} = 2p^n_{i,j} - p^{n-1}_{i,j} + e[a(p^n_{i+1,j} + p^n_{i-1,j}) + b(p^n_{i+1,j} + p^n_{i-1,j}) + c p^n_{i,j}] \\
+ f[a(p^n_{i,j+1} + p^n_{i,j-1}) + b(p^n_{i,j+1} + p^n_{i,j-1}) + c p^n_{i,j}] \\
(2)
\]

where \( p \) is the wavefield value, \( a = -1/12 \), \( b = 4/3 \) and \( c = -2.5 \). The parameters \( e \) and \( f \) are \( e = (c_{i,j}\Delta t/\Delta x)^2 \) and \( f = (c_{i,j}\Delta t/\Delta z)^2 \), where horizontal and vertical space step length, \( \Delta x \) and \( \Delta z \), are both 10 m, and the time step length, \( \Delta t \), is 1 ms.

In the modelling, a Ricker wavelet with a 35 Hz dominant frequency is chosen for the excitation wavelet of the source, which was located at (0, 0), and the horizontal distance between the source and the left edge of the fractures was 200 m. Wavefield changes with the time and space, and it is a function of \( x, z \) and \( t \). When \( z = 0 \), the wavefield value \( p(x, z = 0, t) \) is the surface seismogram. Figure 6 shows the processed single seismograms of the five geological models.

3.2.2. Geologic models with fractures (fractures and caves) and forward section. In order to make the model better accord with the real conditions, we designed another multi-layered model, model B, with fractures and caves which are generally common in the buried hill reservoirs of the Jiyang superdepression. Model B consists of multi-layered limestone media with bending interfaces. The interval velocities increase with depth so as to make the interface reflection strong and thus convenient for observation. In addition, we also designed five complexes of fractures and caves (represented by a velocity 500 m s\(^{-1}\) lower than the surrounding rocks) in several different layers. The model and corresponding seismogram were shown in figures 7(a) and (b) respectively. The red irregular blocks represent the five complexes of fractures and caves: one occurs just below the blue layer, Tg, the top of the Palaeozoic buried hill. To understand the seismic response anomaly around the fractures and caves, seismic attribute parameters, including instantaneous frequency and instantaneous amplitude, were analysed for the horizon Tg and the results shown in figure 7(c).

From the seismic forward simulation, we obtain the following information about the geophysical characteristics of the buried hill. (1) When no fractures exist at the top of the buried hill, even if there are reflectors, the reflection strength is weak (figure 6-1(b)). (2) In the medium with fractures, the scattering effect of the fractures (perturbation) complicates the seismic wavefield and its complexity scales to that of the fracture system. (3) At the top of the fracture zone, the reflection strength is weak with reverse polarity (figure 6-2(b)). The scattered wave is well developed in the

- Theoretical and applied aspects of geophysical exploration, focusing on seismic wave propagation and forward modelling in complex geological settings.
- Importance of fracture and cave structures in seismic wavefield complexity and reflectivity analysis.
- Use of synthetic seismograms for model validation and attribute analysis.
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Figure 8. Acoustic impedance section through wells CG 203, 20 and 201 using stochastic simulated inversion.

transition belt. (4) At the base of the fracture zone, although there is no interface, scattered waves interact and form a very continuous event, below which many bending scattered wave events appear (figure 6-3(b)). (5) Where the low-velocity weathering bed above the top of buried hill gets thicker, the number of seismic events at the top of buried hill increases (figure 6-4(b)). (6) The reflection strength of the buried hill top is stronger when the fractures are filled with fluid rather than the argillaceous medium (figure 6-5(b)). (7) The seismic strength of the fractures and caves obviously varies and is unstable relative to the surrounding reflection (figure 7(b)), and the corresponding instantaneous frequency and dominant amplitude decrease at the well-developed fracture zone (fractures and caves) (figure 7(c)).

4. Seismic reservoir prediction

Because of the deep burial depth and the complicated structures, the buried hill strata in the Jiyang superdepression display weak and discontinuous reflectors in the seismic sections. As a result, reservoir prediction using seismic sections directly is difficult. Some attributes of the strata, for instance, interval velocity and energy absorption character, provide information about fracture development in carbonate rock (Story et al 2000). In this study, we predict the fracture reservoirs of the buried hills starting from the wells and then achieve our aim using multi-information, generalized models.

4.1. Well-log-constrained inversion for fracture reservoirs of buried hills

Seismic inversion is a relatively effective technique for the quantitative study of reservoirs using velocity information (Martí et al 2006). 3D seismic inversion can provide the volume of wave impedance, which reflects the interval velocity variance. Moreover, with the constraint of well data, the inversion results will coincide with the subsurface structures more. Sparse spike inversion (SSI) is the dominant inversion method applied in oilfields, but in production practice, we have noted that the interval velocity contrast between the reservoir and non-reservoir is not obvious and reservoir prediction cannot be obtained with satisfactory resolution using SSI alone. In such a case, stochastic simulated inversion may be an alternative.

This method combines seismic reflection data, geological models and statistical information to give a combined seismic inversion and geological statistics simulation. It applies the seismic, geological and logging statistical data obtained from the well location, and extrapolates to the whole target space. The technique utilizes all the accessible data and makes the inversion results best fit the known information. The results are controlled by a geological framework model and previously known statistics from the well location. As a result, it has a relatively high resolution, thus providing clear prediction and interpretation of the reservoirs.

We made a successful reservoir prediction for buried hill CG 201, in the east of the northern buried hill zone of the west Chezhen depression, close to the source rocks. The reservoir contained mainly secondary fractures and dissolved pores, providing great accumulation space for the hydrocarbons. The fractures, with bead-like form, are highly conductive and partly open, giving rise to marked anisotropy in the reservoir. The faults and unconformity have controlled the development of the reservoirs.

According to the log data, log interpretation and well-testing data, four lower-Palaeozoic reservoir intervals exist in the buried hills of the Jiyang superdepression: the Badou formation–top of the upper Majiagou formation, the bottom
of the upper Majiagou formation, the bottom of the Yeli-Liangjiashan formation–top of the Fengshan formation, and the Mantou formation. The acoustic log data showed certain reservoir characteristics. The low-velocity layer corresponds to mudstone and high argillaceous limestone and dolostone, and the highest velocity layer corresponds to dense limestone and dolostone. Favourable reservoirs mainly lie in the medium high-velocity layers. We therefore conclude that inversion constrained by acoustic log data is a feasible technique.

The stochastic simulated inversion was run for the buried hill CG 201 in the Futai oilfield (figure 1). Figure 8 is an impedance inversion section through wells CG 203, CG 20 and CG 201. In the section, the upper reservoir of the Badou formation corresponds to a relatively low-impedance layer. The reservoirs from the lower Badou to Majiagou formation correspond to medium-high impedance layers, as do reservoirs from the Yeli-Liangjiashan–Fengshan formation. The low-impedance layer between the relatively high-impedance layers should reflect the high argillaceous strata. The bottom stratum of the Fengshan formation corresponds to the highest impedance layer, which is formed by dense carbonatite. The impedance below the Fengshan formation is mostly low. In general, stochastic simulated inversion has higher resolution for reservoirs. In the inversion, the spatial pattern of the reservoir is obvious and the near-well inversion results coincide well with the borehole log. The results are advantageous for further prediction of the reservoir, such as favourable reservoir thickness.

4.2. Buried hill fracture reservoir prediction with absorption coefficient analysis

For fracture reservoirs, absorption coefficient analysis is an important method of reservoir prediction (Best et al. 1994). When the seismic wave is propagating in the strata, the shape of the wavelet changes as a result of absorption. The higher the absorption coefficient is, the more rapidly the high-frequency signals attenuate compared to the low-frequency ones and the more frequently the shape of the wavelet changes. The absorption is generated by the inherent viscoelasticity of the rock matrix, which is related closely to lithology, porosity and pore fluid saturation. Many researchers have studied the absorption of seismic waves and given a quantitative definition (Kolsky 1953, 1956, Kjartansson 1979, Miklowitz 1978, Wang and Guo 2004). When the seismic wave is propagating in a viscoelastic medium, the absorption coefficient is given as follows:

$$\alpha(\omega) = \frac{|\omega|}{2\nu_r Q_r}, \quad (3.1)$$

or

$$\alpha^2 = \frac{\rho \eta^2 \omega^4}{4E(E^2 + \eta^2 \omega^2)}, \quad (3.2)$$

where \(\omega\) is circular frequency, \(\nu_r\) and \(Q_r\) are the phase velocity and Q value at a reference frequency, \(\eta\) is the viscosity coefficient, \(\rho\) is rock density, and \(E = \lambda + 2\mu\), where \(\lambda\) and \(\mu\) are Lame’s constants.

Since \(2\eta \omega\) is smaller than \(E\) within the frequency band of seismic exploration, we can simplify equation (3.2):

$$\alpha = \frac{\eta \omega^2 \sqrt{\rho}}{2(\lambda + 2\mu)^{3/2}}. \quad (4)$$

Substituting the equation \(V_p = \sqrt{(\lambda + 2\mu)/\rho}\) into equation (4), we obtain

$$\alpha = \frac{\eta \omega^2}{2\rho V_p^2}. \quad (5)$$

We note that the effective absorption coefficient is inversely proportional to the cube of the seismic wave velocity. Even if the velocity of the layer changes gently, absorption will change more obviously than velocity, indicating that the absorption coefficient is a sensitive parameter for reservoir prediction. For the Palaeozoic carbonate reservoir with relatively homogeneous lithology, the holes, caves and fractures, which control the reservoir physical properties, directly influence the seismic attenuation. In addition, hydrocarbon reservoirs attenuate the high frequency more strongly because of their inherent oil-bearing or gas-bearing properties, and the attenuation of gas-bearing horizons is higher than that of oil-bearing ones. We invert the absorption from the seismic data of buried hill CB 30 in the Zhanhua depression (figure 1) and further constrain the variable characteristics of the buried hill.

The results of absorption coefficient analysis can be taken as an important reference for predicting the favourable reservoir. From the prediction map of absorption coefficient for the Palaeozoic strata of buried hill CB 30 (figure 9), we find a NE trending high-value zone along the uplifted wall of the CB 30 normal fault. Wells CB 30, 301, 302 and 303 are all drilled in the high-value zone. In addition, a high-value zone exists
east of well CB 303. There may be two possible explanations of these high-value zones. One is that the fractures and caves are well developed; the other is that there is oil and gas in these zones. Referring to drilling wells, we find that the high values in these areas are due to the reservoirs here containing oil and gas.

4.3. FMI fracture prediction for buried hill reservoirs

Formation micro imager (FMI) logging is a newly developed technique in the recognition of underground structures (Osamu et al 1998, Abbaszadeh et al 2000, Yuan et al 2000, Qi et al 2000). In this study, it has been applied in wells CB 305 and CG 201. In well CB 305, reservoir attributes included high-conductivity fractures, fractures caused by drilling and a small quantity of high-resistivity fractures (figure 10). Fractures caused by drilling present a pinnate form, appear regularly in the same direction, but are quite heterogeneous from well to well. The strike of fractures caused by drilling can reveal the orientation of the present-day maximum horizontal principle stress, which is NWW-trending in the area of CB 305. A high-conductivity fracture (probable natural open fracture) will stand out as a dark sinuous line in the logging image, which is caused by drilling mud or other muddy fill. So, natural fractures can be identified in the FMI image; moreover, present-day horizontal stress can be also measured, which may provide important data for computing the local stress field by finite-element modelling.

A tectonic forward-inversion method has been developed for fracture prediction in order to solve the complex problem of characterizing buried hill reservoirs (Midland Valley Exploration 1999, Van de Sande 1996). The method can predict fractures by way of structure and cannot be constrained by seismic resolution and well number. Figure 11 shows the fracture distribution and the orientation of the reservoir of the Majiagou and Yeli-Liangjischan formations in a buried hill in the Zhuanghai region using this method. At the same time, we also analyse the openness of fractures from the direction of stress field, obtained by FMI logging and finite-element modelling. The fractures in the buried hill are very well developed and are distributed non-continuously according to the prediction results. So far, the most promising industrial wells in buried hills are all found to be located at the intersections of more than two sets of fractures with better openness. Well CB 30A-1 was tested between 3819 m and 4303 m and gave a production rate of 236 m³/day. A similar situation was found in the neighboring well CB 30A-2 where production between 3996.8–4630 m was tested, yielding a rate of 264 m³/day. The well also sits on an intersection where three fracture groups meet with good openness. Further drilling in the well confirmed the reliability of our predicted fracture distribution (Wu et al 2004).
5. Conclusions

The buried hills in the Jiyang superdepression were developed by multiple tectonic events. For this reason, the lateral variation of the reservoir characteristics is extremely great and the types of reservoir space are diverse, giving rise to difficulty in their evaluation. Fortunately, the application of accurate objective processing techniques, such as pre-stack depth migration, has mostly improved the quality of the seismic sections in the Jiyang superdepression and provided important basic data for the further reservoir research in this area.

Accurate seismic stratigraphic demarcation and variable-velocity mapping were applied to reveal the inner structure of the buried hills and determine the nature of the structural traps more exactly. Seismic forward technology has linked geology and seismic response based on the analysis of the rock properties and characteristics of well-developed buried hill reservoirs. We have applied multiple seismic methods to analyse and evaluate buried hill reservoirs in the Jiyang superdepression, such as log-constrained inversion, absorption coefficient and tectonic forward-inversion with FMI loggings. The results were satisfying and the fracture reservoir prediction successful, confirming that the comprehensive use of the methods mentioned above could be helpful in unravelling the complex character of buried hill reservoirs. Nevertheless, some problems were encountered in the reservoir study and need to be resolved for future exploration: for example, in the area with poor-quality seismic sections, gravity and magnetic joint inversion need to be made to define the seismic horizons accurately.

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