Evaluation of weathered crust reservoirs in buried hills in western uplift belt of JB block in Indonesia

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Abstract. After nearly 20 years of exploration, the western uplift belt of the JB block is now at a high exploration level, and the buried hill has become another new exploration area besides lithologic traps. On the basis of the results of well logging of 17 wells, core of 6 wells and logging interpretation of 17 wells, the differences in the vertical texture features of the basement reservoir are fully considered. According to the differences of logging and seismic response characteristics of 500 km\textsuperscript{2} between weathered zone and the fractured zone, the colored inversion technique and spectral imaging technique combined with seismic attribute technology are used to predict the plane distribution of porous reservoir in weathered crust. The pre-stack elastic wave impedance inversion technique is preferred for oil-gas-bearing detection evaluation. The results show that the lithology of the B paleo-uplift is granite, and that of the P paleo-uplift is phyllite. The vertical zoning of the buried hill reservoir is obvious, which can be divided into weathered crust zone, fractured zone and tight zone from top to bottom. From the top of the weatheredzone to the fractured zone, the porosity becomes smaller gradually, and distributes in the shape of the discontinuous strips laterally. The planar distribution of the pore-type reservoirs in the weathered zone is obviously controlled by the paleo-structure, and is in the shape of strips and flakiness with obvious zoning characteristics. The porous reservoir is relatively developed on the crest of the paleo-structure, and the weathered crust reservoir quality of B uplift is superior to that of the P uplifts. Hydrocarbon mainly distributes in the high parts of the two paleo-structures in the shape of strip and flakiness. The results provide a scientific basis for the follow-up drilling decision-making.

1. Introduction

After nearly 20 years of exploration and development, the western uplift belt of JB block in South Sumatra Basin is currently in the stage of high maturity. Buried hills have become the new exploration area besides lithologic traps. According to the international exploration experience of buried hills, weathered crust is the main place for oil and gas accumulation in the basement reservoir.

Weathered crust reservoir is mainly formed by weathering and leaching at the early stage of tectonics, while fractured reservoir is formed by multi-stage tectonic transformation and closely related to tectonic evolution. According to the drilling and testing results, weathered crust reservoirs are the main effective reservoir of buried hills in western uplift belt. But different weathered crust structures vary in reservoir rock type, thickness, porosity and fracture development degree. [1] Many geophysical experts and scholars have explored the technical methods for the prediction of basement reservoir [2]. The paper aims to predict the planar distribution of porous reservoir in weathered crust using the colored inversion and spectral imaging technology combined with seismic attribute in
accordance with the differences of logging and seismic response characteristics between weathered and fractured zone, evaluate the oil-gas-bearing by the pre-stack elastic wave impedance inversion technique. The results define the planar distribution, hydrocarbon-bearing properties and risk exploration potential area of the weathered crust porous reservoir, providing a scientific basis for the follow-up drilling decision-making.

2. Geological background
The tectonic evolution of the Sumatra Basin Group is directly related to the interaction between the Sunda Plate and the Indian-Australian Plate. The Sumatra Trench is its western boundary, which is cut by the Sumatra dextral strike-slip fault. The basement of the Sumatra Basin Group consists of three sequences, i.e. the Carboniferous-Lower Permian Tapanuli group, the Upper Permian-Lower Jurassic Pesangan group and the Upper Jurassic-Lower Cretaceous Woyla group [3]. During the Cenozoic period, the Sumatra Basin Group experienced four major tectonic evolutions, namely the strong extensional fault depression from Eocene to Oligocene, fault-depression transition in late Oligocene, depression in Miocene, and structural inversion from Pliocene to present. JB block is located in the South Sumatra Basin. The western uplift belt mainly refers to the west part of the Betara sag, and is separated from the Betara sag by a large reversed fault [4]. Three paleo-uplifts develop. Due to the limitations of the data, W paleo-uplift is not within the scope of this paper, focusing on the two other paleo-uplifts, P and B (Figure 1).

3. Data and methods

3.1. Data
3D seismic data of 500 km², core data of 6 wells and logging data of 17 wells are available.

3.2. Methods
The colored inversion and spectrum imaging technique supplemented by seismic attribute are applied to predict the planar distribution of weathered crust reservoirs. The pre-stack elastic wave impedance inversion technique is optimized to evaluate the oil-gas-bearing of weathered crust reservoirs.

Colored inversion technique (CI). Invented by Lancaster et al., CI is a kind of log-constrained impedance inversion technique in frequency domain, the core of which is to set a suitable operator to match the seismic spectrum with the well’s impedance spectrum, and then complete the inversion by convolution [5]. The wave impedance generated by CI has a spectrum following the exponential law and is limited by the seismic bandwidth, but the best resolution can be obtained by CI within a given bandwidth. CI only needs a filtering process to complete the inversion, no wavelet extraction is required, it is very fast and convenient from calibration to inversion [6]. As to CI, it uses the coincidence degree of the well-side inversion result and the actual logging curve as the basis for parameter optimization, without initial model constraint or obvious wavelet extraction, ensuring the credibility and interpretability of the inversion data and leaving the basic characteristics of seismic reflection relatively intact. Also, CI can clearly reflect the spatial change of lithofacies and lithology, and keep lateral variation of the amplitude which is conductive to the planar sedimentary imaging. Similar to the seismic data processing, CI is little affected by human interference and characterized by objective geological phenomena and fast calculation. It only needs to introduce a matching operator to complete the connection between logging and seismic data, avoiding excessive modelling in the sparse spike inversion. Although limited by seismic bandwidth, CI can achieve the best longitudinal resolution within a given bandwidth without sacrificing seismic lateral resolution. The basic process of CI is as follows. Firstly, analyse the wave impedance of the well and fit the well energy spectrum curve, then analyze seismic wave impedance and fit the seismic energy spectrum curve. Secondly, set a matching operator in the frequency domain to match the seismic spectrum with the well's wave impedance spectrum. Finally, apply the matching operator to the seismic data and then convert back to the time domain [7-8].
Figure 1. Regional location of the study area and structural division (from [4]).

Spectrum imaging technology (SI). SI is to perform time-frequency analysis on the 3D seismic data volume, and generate a plurality of narrow band time-frequency data bodies with different main frequencies, and then extract various attributes for the characterization of the geological body. The theoretical basis of SI is the tuning effect of thin-layer reflections, i.e. the reflection amplitude is maximized when the thickness of the thin layer is equal to 1/4 wavelength [9]. Based on this characteristic, one can perform spectral decomposition of seismic data volume, use the tuning frequency to calculate the formation thickness, and scan with the tuning frequency to obtain the spatial distribution of the geological body corresponding to the tuned thickness. Peyton Lynn (1998) successfully used spectral decomposition technique to describe the old stratigraphic features in the central United States [10]. Spectral imaging results not only described the boundaries, but also depicted the filling characteristics of different periods of the canyon. Burnett (2003) used wavelet transform spectral decomposition technique to characterize the gas-bearing reservoirs in northeastern Mexico [11]. Chakraborty et al. (1995) explained that time-frequency analysis using wavelet transform is a multi-scale method [12]. The wavelet spectrum imaging technique first uses wavelet to simulate Ricker wavelets of different frequencies, and then performs Marr wavelet frequency division processing on the seismic signals to obtain signals of three different frequency bands of low, medium and high, and then the three frequency division signals of each sampling point are represented by red (R), green (G), and blue (B) respectively, and finally the three primary colors of red (R), green (G), and blue (B) are combined into the color values of the sampling points[13].

Pre-stack elastic wave impedance inversion technique (EI). Based on the systematic analysis of the traditional AVO method, Connolly (1999) proposed a concept and calculation formula of the elastic wave impedance related to the incident angle [14]. In this method, the elastic wave impedance is a function of the angle of incidence, which preserves the characteristic that the amplitude of the seismic
reflection varies with the offset or angle of incidence. Whitcombe et al. (2002) normalized the Connolly’s formula and proposed the concept of extended elastic impedance and the elastic impedance calculation formula [15]. EI technical flow is as follows. Firstly, the S-wave velocity in the well is inverted by the P-wave time difference, density, mud content, porosity, water saturation and various elastic parameters of the skeleton and fluid, and then the elastic wave impedance at different incident angles of each well is inverted. Secondly, under the constraints of structural framework and reservoir sedimentary model, the elastic wave impedance model is established by seismic fractal interpolation technique, and then the seismic wavelets related to the incident angle are obtained by the generalized linear inversion technique. Finally, Vp, Vs,Vp/Vs, poisson's ratio, shear modulus and other elastic parameters are fitted by means of mathematical tools such as least square method[16-17].

4. Evaluation of weathered crust reservoir

4.1. Characteristics of weathered crust reservoir
In the study area, a total of 17 wells were drilled to basement, with general drilling thickness 20-30m. Only well NB-1 and NB-5 have a relatively large drilling thickness, up to 500-600 m (MD). A small amount of cores in the basement are available from 6 wells. Based on the core observation combining well logging and logging data, it is defined that the lithology of B paleo-high is granite and that of P paleo-high is phyllite by seismic attributes, waveform clustering analysis and Gamma inversion.

From the overlying strata to the weathered layer, the GR curve changes most obviously. It obviously jumps and forms a big step. It changes from less than 100 API to more than 200 API with a clear interface between overburden and weathering. The other logging curves also have different degrees of zigzag. Due to the development of the pores in the weathered zone, the density and acoustic waves are greatly jugged compared with the fractured zone. In addition, the resistivity of the fractured zone is significantly higher than that of the weathered zone, forming a clear interface. Core porosity, permeability test report and logging interpretation results show that the weathered crust has better reservoir properties. With the weathering weakened, the reservoir properties get worse and gradually become a tight layer from the top to the lower (figure 2).

On the seismic section, the top of the basement has the wave group characteristics of two troughs sandwiched with one peak. The weathered crust corresponds to the lower trough reflection with the characteristics of low frequency, high amplitude and high value anomalies (light colors) on RMS (Figure 3). The petrophysical analysis shows that the reservoir with good properties of the weathered crust has the characteristics of low P-wave impedance.

4.2. Plane distribution of weathered crust reservoir
On the basis of fine seismic calibration, the top and bottom surface of weathered crust are tracked and the fine structural interpretation is carried out. Then the CI and SI techniques combined with seismic attribute technology are applied to study the plane distribution of the weathered crust reservoir.

As can be seen from the CI and SI sections, the vertical zoning features are obvious. From the top of the weathered zone to the fractured zone, the porosity of reservoir gradually deteriorates. Better reservoir (light colors) distributes discontinuously in strips laterally, good matching with the wells (Figure 4).

The CI and SI plans of the weathered zone can be obtained under the constraints of the top and bottom of the weathered crust. As can be seen from the plans, the distribution of porous reservoirs in the weathered zone is obviously controlled by the paleo-highs with distinct zoning features, showing a strip-like and sheet-like distribution. The porous reservoirs are relatively developed and mainly distributed on the higher parts of the two paleo-uplifts (Figure 5). Also the quality of weathered crust reservoir in the B paleo-high is superior to that in P paleo-high (Figure 6). The reason is that the basement lithology of the P-uplift is phyllite, which is resulted from epimetamorphism, and the lithology is loose. It is not easy to be preserved in situ to form weathered crust after weathering and leaching.
Figure 2. Characteristics of logging curve of basement (left: Well NB-1; right: Well NB-5).

Figure 3. Seismic and RMS attribute profiles of buried hill.

Figure 4. Inversion section (upper: CI; lower: SI).
Figure 5. Plane distribution of reservoirs in weathering crust (left: CI; right: SI).

Figure 6. Minimum amplitude of P-wave impedance of the weathering crust.

Figure 7. Elastic parameters for shear modulus of the weathering belt.

4.3. Evaluation of oil-and-gas-bearing of weathered crust reservoir

The EI technique is chosen to evaluate the oil-and-gas-bearing of weathered crust reservoirs in the study area after comparison and analysis of AVO, pre-stack elastic impedance inversion and post-stack high-frequency attenuation oil and gas detection in combination with the actual data in the study area.

Using the interpretation horizon as the control layer, the plane property is extracted by the interlayer control method, and the map of the shear modulus of the weathered zone is obtained. Oil and gas mainly distribute in the higher parts of the two paleo-highs in strips and sheets (Figure 7).

5. Conclusions

The plane distribution of weathered crust reservoirs is studied using CI and SI techniques supported by seismic attribute technology and oil-and-gas-bearing is evaluated using EI technique. The preliminary results achieved are as follows.

(1) The basement lithology of B paleo-high is granite and that of P paleo-high is phyllite.

(2) The vertical zoning of the basement reservoir is obvious, divided into weathered crust zone, fractured zone and tight zone from top to bottom, and the porosity becomes smaller gradually distributing in the discontinuous strips laterally.
(3) The plane distribution of porous reservoir in the weathered zone is obviously controlled by the paleo-structures with zonal features. The porous reservoirs on the higher parts of the paleo-highs are relatively developed. Moreover, the weathered crust reservoir of B-uplift is superior to that of P-uplift.

(4) Oil and gas mainly distribute in the higher parts of the two paleo-highs, which are distributed in strips and sheets.

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