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Research article

Methods of phase division and distribution prediction of volcanic rocks in the Anda Sag, Xujiaweizi Fault Depression, Songliao Basin

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Abstract

The Anda Sag, the northern part of the Xujiaweizi Fault Depression in the Songliao Basin, contains high-quality source rocks and tight, lithologic gas deposit-dominated volcanic reservoirs of the Lower Cretaceous Yingcheng Formation. This area is known to have a variety of volcanic edifices that are characterized by multi-phase eruption and superimposed distribution. Currently, the sag has been highly explored, and drilling of targets in the critical crater areas with reservoirs relatively developed has basically finished. So, additional targets will be defined. Thus, a criterion for dividing the volcanic eruption phases was established based on core, well log and seismic response marks. Through a well-seismic skeleton section analysis, it was believed that three volcanic eruption phases (I, II and III) occurred in the Anda Sag. Finally, the volcanic edifice and facies belt distribution of each phase were predicted by using seismic coherence body and trend-surface analysis technologies, with over 30 new volcanic crater targets identified. The predicted results show that the distribution of lithofacies and lithologies determines the framework of better volcanic reservoirs in the west and south than that in the east and north respectively. Lithological-structural gas reservoirs are dominant in the west, while tight lithologic gas reservoirs are dominant in the east. Based on the study results, the favorable exploration area is finalized as 950 km^2, a potential of 100 billion m^3 gas resources has been implemented.

Keywords: Songliao Basin; Xujiaweizi Fault Depression; Anda Sag; Volcanic rock; Eruption phase; Lithofacies distribution; Volcanic crater province; Log response; Seismic reflection

The Anda Sag is located in the northern part of the Xujiaweizi Fault Depression in the Songliao Basin, where the Lower Cretaceous Yingcheng Formation and formations below it constitute a half graben-like fault depression controlled by the northern section of the Xuxi fault, with fault in the west and overlap in the east. The Yingcheng Formation top is a sag in near SN strike. The formations deposited during fault depression period include the Lower Cretaceous Huoshiling Formation, Shahezi Formation and Yingcheng Formation. The Shahezi Formation is mainly dark mudstone in deep lake to semi-deep lake facies, with well-developed source rocks. The Yingcheng Formation is mainly volcanic rock in its third member [1,2]. Developing in the whole area, the source rock in Shahezi Formation and reservoir rock in Yingcheng Formation form good vertical configuration favorable for gas accumulation.

By far, the Anda Sag has been highly explored, with 28 prospecting wells drilled, more than 1×10^8 m^3 gas in place and 603.24×10^8 m^3 predicted reserves in volcanic reservoir beds reported. Drilling results reveal that apparent crater targets with better reservoir beds have been basically drilled, thus, it is urgent to seek new subtle crater targets. Therefore, by combining geologic and geophysical data, and analysis of outcrop profiles of volcanic rocks in the Yingcheng Formation at the basin edge by former researchers, based on the actual data of 28 wells in the Anda Sag, we have found out geologic and seismic marks for identifying volcanic eruption phases; then, using high-resolution 3D seismic data, and on the basis

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of phase correlation by well-tie sections, we have constructed main sections for seismic interpretation in the whole sag, to facilitate tracing and correlation in the whole area; consequently, we have confirmed three major eruption phases in this area, and figured out volcanic features such as distribution scope, thickness and lithofacies etc. of various phases, identified over 30 new volcanic craters and proximal crater targets. By drilling the newly identified targets (Well Dashen 16 and Well Dashen 17) in phase II, two sets of good gas layers of 203 m and 99 m thick respectively have been revealed. These encouraging discoveries expand gas-bearing scope of the area, and show that the exploration potential of gas resources in Anda Sag may reach 1000×10^8 m^3. Volcanic phase division and correlation, phase seismic interpretation, and fine lithofacies delineation techniques developed in the course of the study have provided technical means for studying volcanic phase subdivision and predicting subtle targets, and strong support for exploration deployment.

1. Division method of volcanic eruption phases

A volcanic eruption phase usually refers to a relatively concentrated activity along volcanic eruption conduits or faults, during which a set of material combination with genetic relationship in lithology and lithofacies in vertical direction is formed with the regular changes of magmatic component, eruption mode and eruption scale [3]. Study results of former researchers show that the volcanic rocks in the Yingcheng Formation in the Anda Sag was formed 12 Ma ago in a very short period of eruption, and subjected to long reformation in late period. Hence, there are apparent phase interfaces on core, well log and seismic response features [4].

1.1. Geologic marks

Because of changes in structural environment and volcanic action, there are usually small discontinuous surfaces, weathered crusts, depositional interbeds and different rock assemblages etc. between different phases. These differences are usually regarded as interface basis for dividing phases.

1.1.1. Weathered crust

Weathered and eroded planes formed on lava surface after magmatic explosion usually have apparent differences in color and hardness. Statistics of drilled wells in the basin and outcrops at basin edge show that the weathered crust is usually dozens of centimeters to several meters thick.

1.1.2. Depositional interbed

The regional and local deposits formed during dormant period of volcanic eruption are generally less than 100 m thick (usually several meters to dozens of meters). The depositional interbed is usually regarded as the top of the lower phase.

1.1.3. Lithologic interface

It refers to the regular changes in material components and eruption mode of volcanoes. The lithological change belt of volcanic rocks (such as change from acidic volcanic rock to intermediate-mafic rock) is also interface of phase division.

1.1.4. Lithofacies sequence

A complete process of volcanic eruption is continuous or quasi-continuous in lithology and structural feature. One eruption phase usually has one or more phase sequence associations, its lithology association has certain regularity in space, namely, volcanic conduit facies → explosive facies → effusive facies → volcanic sediment facies.

1.2. Well log response marks

Well log curve features are important basis for dividing volcanic eruption phases. Volcanic rock identification in non coring sections is mainly based on log curve changes. GR, resistivity and density with high sensitivity, are generally used in lithology identification [5,6]. GR value from high to low reflects lithology changes from acidic to mafic. Resistivity curve, closely related to rock texture, can better distinguish lava and clastic rock. Density logs mainly reflect rock tightness and physical properties (Fig. 1).

Generally, rock associations with the same components have stable well log features, while phase interfaces usually have abrupt changes in well log features. Geologic marks (such as weathered crust, volcanic ash bed and depositional interbed, etc.) all have different well log response features: Weathered crusts have high GR, low resistivity and low density, and usually distorted caliper curve due to collapse. The depositional interbeds are generally higher in log amplitude than volcanic rocks, especially high in GR value. Volcanic ash beds have high GR, low resistivity and high density values, and high amplitude and serrated shape on GR log. The interfaces of abrupt change in lithologic associations (such as acidic-basic) show abrupt changes in GR, resistivity and density values.

1.3. Seismic reflection marks

With the continuous improvement in precision, seismic data has been widely used for fine division of volcanic rock phases. As volcanic rocks of different phases have different seismic reflection features [7], they can be finely interpreted on seismic sections. Firstly, volcanic eruption conduits should be found out on seismic sections, which usually show as streaky chaotic reflections from bottom to top, with width gradually increasing, and top seismic reflection of moundy or domal shape. Taking this as the center, tracing the reflection event to its two sides, to the intersections where the top event and bottom event cross, the top and bottom boundary lines defined this way are the interface of the volcanic rock in this phase, often in mushroom shape. If two volcanic eruption conduits are close, and rock bodies formed by their eruption overlap, the thinnest location is the boundary of single volcanic rock body [8,9].

Based on the criterion for phase division established for this area, we analyzed 28 drilled prospecting wells in the Anda