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 km², a potential of 100 billion m³ 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 × 10⁸ m³ gas in place and 603.24 × 10⁸ m³ 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
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 $1000 \times 10^3 \text{m}^3$. 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 $\rightarrow$ explosive facies $\rightarrow$ effusive facies $\rightarrow$ 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.
Sag, and selected typical well (Well Dashen 1) as the marker well. From this well, the volcanic rock section can be divided into three phases (I, II and III) in vertical direction. The phase I rock is mainly acidic volcanic clastic rock interbedded with lava, with GR value between 120 and 180 API. The phase II is mainly thick mafic basalt, with GR value between 30 and 60 API. The phase III rock, mainly acidic rock interbedded with thin mafic basalt, takes on serration shape on GR, indicating relatively complex changes of lithology. Volcanic rocks in phase I and phase II are eruption products from different magmatic chambers of different natures. Thus, there is an eruption interface between phase I and phase II; a thin mud layer is held between phase II and phase III, meaning that there was a depositional break between phase II and phase III eruptions (Fig. 2).

2. Seismic interpretation methods for volcanic rock distribution in different phases

By calibrating eruption interfaces of all phases in a single well, starting from the marker well, we carried out division and lateral correlation of phases on well-tie sections, and fine seismic interpretation of the whole area. Our study indicates that the volcanic rocks in the Anda Sag were the products of three volcanic eruption phases (I, II and III). Seismic reflection features of each phase of eruption are: phase I is a set of medium amplitude and relatively continuous reflections; phase II is a set of high amplitude and continuous reflections; phase III is a set of weak amplitude, chaotic or discontinuous reflections (Fig. 3).

Seismic tracing and correlation show that phase I encountered in five wells is mainly acidic volcanic debris rock interbedded with lava, early in eruption time and subjected to strong erosion in later period, its internal seismic reflections show features of low frequency and weak reflection. The volcanic edifice mainly distributes in a band of SN strike along the Xuxi basement fault, limited in scope, continuous and uneven in thickness (80—130 m), and 405 km² in area. Found in 22 wells, phase II is mainly intermediate-mafic rocks of effusive facies, and is shown as continuous and strong reflections on seismic sections. Controlled by two basement faults (Xuxi and Xudong faults), this phase of eruption gave birth to two near SN strike volcanic belts in the east and west of the sag. Widely spread in the whole area, the eruption of this phase is relatively even in thickness (100—200 m), and 818 km² in area. Intersected in 23 wells, phase III is made of intermediate-acidic rock interbedded with minor intermediate-mafic rock of explosive facies and effusive facies. The volcanic rock of this phase usually melted through intermediate-mafic rock of phase II, with disturbance near the crater. The formation created by this eruption only limitedly distributes in the south part of the sag. Controlled by faults, the formation is absent in the east part, and thickens from north to south (100—400 m), with an area of 307 km² (Fig. 4 and Table 1).

3. Exploration potential of volcanic rocks

3.1. Prediction of favorable reservoir beds

3.1.1. Controlling factors of reservoir physical properties

A lot of research indicates that volcanic rocks, higher in matrix density, formed right after eruption to the surface, are less affected by compaction than sedimentary rocks. Therefore, the volcanic reservoir beds are mainly influenced by volcanic rock lithology and facies belt, reservoir beds in crater regions (explosive facies) and proximal crater regions

<table>
<thead>
<tr>
<th>Interface type</th>
<th>Lithology profile</th>
<th>Lithology description</th>
<th>GR / API</th>
<th>Resistivity/(Ω-m)</th>
<th>Compressional density/(g/cm³)</th>
<th>Phase interface</th>
<th>Data source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weathered crust</td>
<td></td>
<td>Rhylolitic crystal tuff</td>
<td>120-150</td>
<td>200</td>
<td>2.5</td>
<td>Depth of Well Xushen 1; 1-560-3-590 m</td>
<td>Map scale : 1:1 000</td>
</tr>
<tr>
<td>Depositional interbed</td>
<td></td>
<td>Rhylolitic sediment tuff</td>
<td>150-200</td>
<td>200</td>
<td>2.5</td>
<td>Depth of Well Dashen 1; 1-600-3-710 m</td>
<td>Map scale : 1:1 000</td>
</tr>
<tr>
<td>Volcanic ash bed</td>
<td></td>
<td>Basalt</td>
<td>30-60</td>
<td>300</td>
<td>2.5</td>
<td>Depth of Well Dashen 2; 1-600-3-710 m</td>
<td>Map scale : 1:1 000</td>
</tr>
<tr>
<td>Lithologic interface</td>
<td></td>
<td>Tuff</td>
<td>200</td>
<td>300</td>
<td>2.5</td>
<td>Depth of Well Wang 905; 3-269-3-340 m</td>
<td>Map scale : 1:1 000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Andesite</td>
<td>200</td>
<td>300</td>
<td>2.5</td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td>Basalt</td>
<td>300</td>
<td>300</td>
<td>2.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rheylolitic crystal tuff</td>
<td>300</td>
<td>300</td>
<td>2.5</td>
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<td></td>
<td></td>
<td>Rheylolitic</td>
<td>300</td>
<td>300</td>
<td>2.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 1. Well log response marks of volcanic eruption phase interfaces in the Anda Sag.
overlapped explosive-effusive facies) are better in physical properties than those in distal crater regions (volcanic deposit facies), and acidic reservoir beds have better physical properties than intermediate-mafic rocks. Lithology is a basic factor influencing physical properties of volcanic reservoir beds. Volcanic rocks of different lithologies have different hardness, density, component and texture, thus different porosity and permeability. The volcanic rocks in Anda Sag mainly include acidic rhyolite, rhyolitic crystal tuff, and intermediate-mafic andesite and basalt. Thin slice analysis results show that reservoir beds of rhyolitic rocks, generally vesicular texture, rich in primary pores, and experiencing strong later dissolution, have higher porosity and permeability, and higher productivity proved by drilling. The reservoir space in intermediate-mafic rocks are mainly secondary pores (such as dissolution pores in gravels) [10,11], but as the intermediate-mafic rocks have strong alteration, the pores are often filled by calcite and chlorite etc., leading to lower permeability and pore connectivity, so they often have lower porosity and permeability, and lower productivity in drilled wells.

Developed in various locations of volcanic edifices, volcanic facies are generally classified into 5 facies and 15 sub-facies by previous researchers. Affected by eruption mode, various locations usually developed multiple volcanic facies. The most developed facies in crater regions are explosive facies and volcanic conduit facies. The major facies in proximal crater regions is effusive facies, followed by explosive facies. The major facies in distal crater regions is volcanic deposit facies. The rocks in crater region mainly include volcanic breccia, agglomerate rock, cryptoexplosive breccia and rhyolite etc, and reservoir beds are between 1.7% and 15.6% in porosity, and between 0.1 and 2.5 mD in permeability; while in proximal crater regions with mostly rhyolite, andesite and basalt etc, reservoir beds have porosity between 0.2% and 10.4%, and permeability between 0.1 and 1.5 mD.
Volcanic deposit facies, dominated by sediment tuff, is generally poor in reservoir quality with porosity of less than 3% and permeability of less than 0.05 mD [12–14].

Furthermore, physical properties of reservoir beds are also influenced by structure locations of volcanic rocks. Rocks at the top of each eruption phase are higher in porosity. In the last stage of volcanic eruption, volcanic activity entered a dormant period. Especially, after the last stage of one eruption, the volcano would be inactive for a period, during which the volcanic rocks would generally suffer weathering and denudation, forming storage space and seepage paths such as secondary dissolution pores, and weathering and denudation fissures, etc [15]. Denudation mainly occurs at the unconformity surface formed by volcanic rocks between different eruption phases. The unconformity surfaces usually interconnect with tectonic fissures and joints etc., cutting rocks into fragments of different sizes, and forming good volcanic reservoir beds [16,17]. According to productivity tests and comprehensive well log interpretations in drilled wells, more than 60% gas layers are at the upper part of volcanic phases, for instance, phase II in Well Dashen X7 is thick basalt, according to a comprehensive interpretation, its top has a 38 m thick gas layer, with porosity of 18%, permeability of 1.8 mD, the commercial gas flow of $4.0414 \times 10^4$ m$^3$/d was tested after fracturing. Its lower part is dry layer. Similarly, the reservoir and gas layer in Well Dashen2 are also in the upper part of phase III eruption, and the lower part is dry layer, so it can be seen that volcanic phases play an important role in controlling the vertical distribution of volcanic gas reservoirs.

3.1.2. Prediction of volcanic facies distribution

Directed by volcanic eruption modes, using seismic coherence body, seismic attribute analysis and trend-surface analysis techniques, on the basis of well-seismic calibration, we established identification models of volcanic facies by seismic reflection features, and predicted the distribution of volcanic mass and facies belts in each eruption phase. Our study indicates that the distribution of volcanic rocks in Anda Sag is controlled by the basement faults and secondary faults; volcanic activity was stronger in the west, but apparently weaker in the east part of the sag; so volcanic rocks are thicker in the west and thinner in the east. Volcanic rocks, thicker (around 500 m) in the middle and west part of the Anda Sag, are usually in moundy or lenticular shape, middle-weak amplitude, chaotic reflection and weak coherence in seismic facies, showing features of crater explosive facies on conventional seismic sections. In the east part, volcanic rocks, continuous in distribution, have reflection features of sheetlike middle-strong amplitude, better-good continuity and strong coherence, showing the features of proximal crater effusive facies. The volcanic rocks, 200 m thick on average, are mainly intermediate-mafic rocks in wide and sheetlike distribution. Because of small magma viscosity and weak explosive energy, and scattered craters, the volcanic rocks are thinner in proximal crater areas, and reservoir beds overlap into big pieces across the whole area [18] (Fig. 5a–c). Through fine structure interpretation of volcanic rock tops and prediction of volcanic facies distribution in various phases, we identified over 30 new subtle volcanic crater targets at volcanic rock tops in various phases.

3.2. Exploration potentials

The prediction results of volcanic facies show that volcanic rocks in the Anda Sag are thicker in the west part and thinner in the east part. The west part is dominated by overlapped explosive facies and volcanic conduit facies, etc. in crater and proximal crater regions. In the east part, blanket effusive facies is widely spread, explosive facies is limited in proximal crater areas and smaller in thickness. The volcanic deposit facies in distal crater areas distribute on east and west sides and north part of this sag (Fig. 5-b). From lithology distribution, the south part of the sag is mainly acidic volcanic rocks, and the north part is mainly intermediate-mafic volcanic rocks. The distribution of lithofacies and lithologies determines the reservoir set-up of better quality in the west and south and poorer in the east and north, and control the gas-water distribution relationship and gas pool types. Prospecting wells drilled show that the volcanic reservoirs in explosive facies in the west part of this area have strong heterogeneity, quick
lateral changes, but poorer connectivity, good physical properties and gas-bearing properties; with water below gas, the gas pools are generally under strong control of structures (gas columns are bigger at high positions but smaller at low positions), representing lithological-structural gas pools. The blanket intermediate-mafic volcanic rocks in the east part have low porosity and low permeability; the reservoir beds stable in distribution on plane, generally produce gas regardless of structural locations, representing lithological gas pools. Six wells have been drilled and tested in volcanic reservoir beds in explosive facies in the western Anda Sag. Their daily production after fracturing was between $4.1044 \times 10^4$ and $20.2190 \times 10^4$ m$^3$, all obtaining commercial gas flow. Five wells have been drilled and tested in volcanic reservoir beds in explosive facies in the eastern Anda Sag. Their daily production after fracturing was between $0.1310 \times 10^4$ and $2.3233 \times 10^4$ m$^3$, all belonging to low production wells. The western Anda Sag has obtained proved gas reserves, the exploration degree of volcanic rocks in effusive facies in the eastern Anda Sag is relatively lower, the craters developed in local regions of the southeastern sag are important exploration targets for near term exploration. Drilling practices show that the volcanic reservoir beds in explosive facies in the west part of the sag have good physical properties and high productivity; commercial gas flows can be obtained by vertical wells; while the tight volcanic reservoir beds in effusive facies in proximal crater areas in the eastern sag have poorer physical properties, and vertical wells can only obtain low gas production, so currently, we are trying to improve production by horizontal wells. In 2010, Well Songshen102 was sidetracked in andesite interval with good gas test shows and widely distributed reservoir beds on plane. This well only obtained low gas production ($2.3233 \times 10^4$ m$^3$/day) after fracturing in the vertical interval of 3183–3259 m; but it produced $7.3856 \times 10^4$ m$^3$/d gas (three times more than that of the vertical section) after three-stage open hole fracturing in the sidetracked horizontal section of 611 m. The success of Well Songshen102 sidetracking brings hope for liberating gas in blanket reservoir beds of effusive facies. On the basis of lithofacies prediction of various phases, we have outlined 950 km$^2$ favorable exploration area of volcanic reservoir beds in effusive facies, and confirmed $1000 \times 10^8$ m$^3$ gas resources in the Anda Sag.

### Table 1

<table>
<thead>
<tr>
<th>Phase</th>
<th>Major lithology</th>
<th>Distribution scope</th>
<th>Area/km$^2$</th>
<th>Thickness/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>III</td>
<td>Intermediate-acidic rock interbedded with minor intermediate-mafic rock</td>
<td>South part of the sag</td>
<td>307</td>
<td>100–400</td>
</tr>
<tr>
<td>II</td>
<td>Intermediate-mafic rock</td>
<td>The whole area</td>
<td>818</td>
<td>100–200</td>
</tr>
<tr>
<td>I</td>
<td>Mainly acidic rock, with intermediate-mafic rock in local areas</td>
<td>Band distribution along the Xuxi fault</td>
<td>405</td>
<td>80–130</td>
</tr>
</tbody>
</table>

### 4. Conclusions

1) According to the identification marks of weathered crust, deposit interbed, abrupt change plane of lithologic association, response changes in GR and resistivity, etc. in volcanic rocks in single drilled wells, combining with seismic reflection features, we have confirmed three eruption phases of volcanic rocks in the Anda Sag.

2) By well-seismic lateral correlation and tracing, we have interpreted the plane distribution features of volcanic rocks in the three phases. Phase II, widely spread in the whole area, distributes in two near SN strike bands in the east and west of the sag, thicker in the west and thinner in the east. Phase I and phase III are limited in distribution, only found in the south part of the sag and along the Xuxi Fault.

3) Physical properties of volcanic reservoir beds are mainly related to volcanic rock lithologies, lithofacies and the distances away from the crater. Physical properties of volcanic reservoir beds in crater and proximal crater areas are better than those in distal crater areas. Physical properties of acidic rocks are better than those of

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Fig. 5. Distribution of volcanic lithofacies in the Yingcheng Fm in the Anda Sag.
intermediate-mafic rocks. Drilled wells reveal that reservoir beds at the top of each eruption phase are relatively developed. By using coherent body and seismic attribute analysis techniques etc., combining conventional seismic reflection features in volcanic rock, we predicted the distribution of volcanic edifice and facies belts in each eruption phase. Volcanic rocks of explosive facies proximal to craters with good physical properties were developed in the middle and western regions of the Anda Sag. Volcanic rocks of effusive facies with poorer physical properties were developed in eastern region of the Anda Sag. Besides, we have identified over 30 new volcanic exploration targets at the volcanic rock tops of various phases.

4) The distribution features of lithofacies and lithologies determine the set-up of better volcanic reservoirs in the west and south and poorer volcanic reservoirs in the east and north of the Anda Sag. Volcanic rocks in the west with good gas-bearing properties mainly contain lithological-structural gas pools; while volcanic rocks in the east, with low porosity and permeability, generally gas-producing, mainly contain lithogasologic gas pools. Based on the lithofacies prediction results of various phases, we have outlined 950 km² favorable exploration area of volcanic reservoir beds in effusive facies, and confirmed $1000 \times 10^8$ m³ gas resources in the Anda Sag.

References


