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Analysis of Seismic Response Characteristics of Cenozoic Igneous Facies and Hypothesis of Annular Eruption Pattern, Bohai Area-A Case Study

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Abstract
Based on the study of the igneous rocks of X structure, Bohai Bay Basin, the seismic response characteristics of the igneous facies in the entire area were described and summarized. Aimed at the special seismic response characteristics of the igneous rock in the study area, based on the three types of traditional eruption patterns, a new type of volcanic eruption pattern, annular eruption pattern, was propose for the first time. Annular eruption pattern meant that the volcanic conduit represented zonal distribution in the plane. The characteristics of annular eruption pattern and its impact on hydrocarbon accumulation were fully demonstrated. Annular eruption pattern was firstly proposed in the study field of igneous rocks, which can effectively guide the analysis of the risk and potential of the oil field.

Key words: Seismic response; Igneous facies; Eruption pattern

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INTRODUCTION

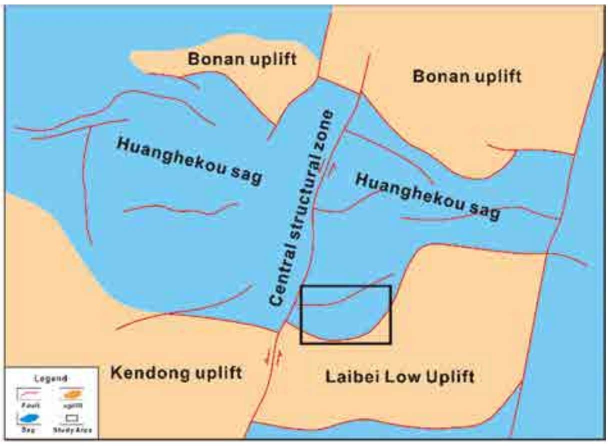


Figure 1
Location of X Struction

The Huanghekou Sag is located in the northeast of Zhahua Sag and the south of Bozhong Sag in the Bohai Bay Basin. It is a half graben sag, with fault in the north, overlap in the south and fault terrace zones in the east and west, which are adjacent to Miaoxi Sag and Zhanhua Sag, respectively. EW-trending and NNE-trending faults are mainly developed. EW-trending faults are extensional normal faults, which control the framework of the sag. While NNE-trending faults as the middle branch of Tan-Lu strike-slip fault zone are strike-slip faults, which divide Huanghekou Sag into western sub-sage, central uplift zone and eastern sub-sag, forming a structural framework of "one bulge held by two sags". X structure is a complex faulted block. It is located in the southern slope of Huanghekou Sag and adjacent to the middle branch of Tan-Lu fault, where the tectonic movement is intense and fault system is well-developed. Drilling results reveal that the Cenozoic-Paleogene strata in this area are constituted by Shahejie Formation and Dongying Formation (Dong3 Member, Dong2 Member and Dong1 Member) from bottom to top. Igneous rocks are drilled in all the strata, indicating volcanic activity is intense and igneous rocks are widespread.

In this paper, the seismic response characteristics of different volcanic rock facies in X structure were analyzed, the pattern of volcanic facies was summarized and the seismic response characteristics of special rock facies were described.

1. CHARACTERISTICS AND SEISMIC RESPONSE OF VOLCANIC FACIES

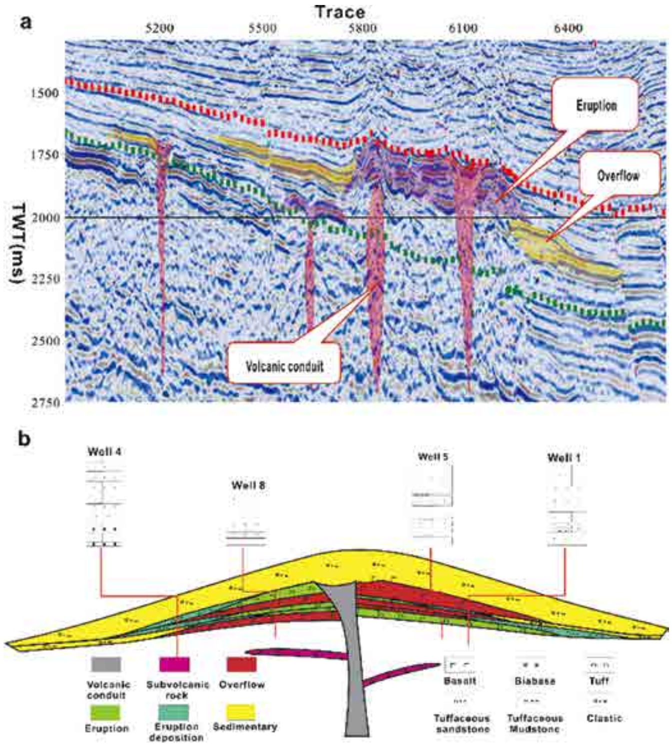
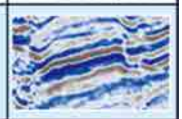
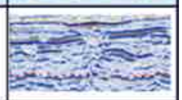
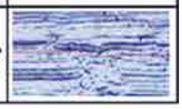


Figure 2
a. Volcanic Seismic Facies Interpretation.
b.Volcanic Lithofacies Model According to Wells and Seismic

The Cenozoic igneous rocks in X structure are dominated by intermediate rocks and basic rocks. The igneous rocks of Dong1 Member and Dong2 Member are superimposed and contiguous, with a thickness of 217.1～446.3m. However, the igneous rocks are poorly developed in Dong3 Member and Shahejie Formation, with a thickness of only 7.2～72.0m, which are only drilled in Well 8. There are various types of igneous rock associations in Dong1 Member and Dong2 Member, including the association of basalt and sedimentary tuff as well as the association of basalt of tuff sandstone. The rock associations are alternately superimposed in vertical, reflecting large-scale volcanic activity. There is only one type of igneous rock associations in Dong3 Member and Shahejie Formation, which is a large set of clastic rocks interbed with a set of isolated igneous rocks (association of igneous rocks and clastic rocks), reflecting localized volcanic activity with small scale (Table 1). In vertical, the igneous rocks are more widespread in Dong1 and Dong2 Member than in Dong3 Member and Shahejie Formation. Dong1 and Dong2 Member and their underlying strata have significantly different igneous rock type, overall thickness and rock associations.

Table 1
Seismic Identification Chart of Igneous Rocks

Feature / Facies		Lith type	Physical Property	Formation	Seismic facies	Identifiable	Example
Eruption		Tuff	Vel.:2700-3500m/s, Den:2.1-2.5g/cm	Dong1,Dong2	Lensing Disordered reflection	Difficult	
Overflow		Basalt	Vel.:4400-5800m/s, Den:2.5-2.85g/cm	Dong1,Dong2	Mid & low frequency, high-amplitude, Stable occurrence	Normal	
Subvolcanic		Diabase	Vel.:5200-6000m/s, Den:2.55-2.7g/cm	Dong1, Shahejie formation	Mid & low frequency, high-amplitude, layered continuous	Easy	
Volcanic conduit	Central	Mutitype	Various lithology, No well drilled	The Paleogene, large span vertically	Simpe shapes, good imaging	Normal	
	Fissure				Various shapes, Poor imaging	Specified conditions, Confusion easily	

The igneous facies of X structure includes eruption facies, overflow facies, subvolcanic facies and volcanic conduit facies (Figure 2a, b).

There are various types of igneous rocks in Dong1 and Dong2 Member, which have covered almost all the types of igneous rocks identified in the study area. They belong to overflow facies and eruption facies. Eruption facies is composed of tuff and sedimentary tuff. The gas in magma generates huge pressure on surrounding rocks; thereby eruption facies is formed under intense explosion. The igneous rocks of eruption facies are characterized by low velocity, low density and low impedance, which can't be easily distinguished from sandstone. Since they are generally mixed with other rocks, they represent lenticular chaotic reflection in seismic profile and are difficult to be identified. Overflow facies is composed of basalt. Basalt is a type of basic igneous rocks, with low viscosity and strong fluidity. Compared with sandstone and mudstone, basalt has higher velocity and density, so it can form obvious impedance interface. At the same time, the overflow facies has stable occurrence since it is formed as a result of the flowing, cooling and consolidation of magma. The overflow facies in X structure can be identified in seismic profile since it is characterized by sheet-like reflection with low-medium frequency and strong amplitude.

There are few types of igneous rocks in lower Dong2 Member, Dong3 Member and Shahejie Formation, which are dominated by basalt and diabase, with minor basaltic andesite and tuff. They belong to volcanic conduit facies and subvolcanic facies. Subvolcanic facies is formed as a result of magma intruding into the structure. The igneous rocks of subvolcanic facies are dominated by basic diabase with strong fluidity. Just like basalt, they are characterized by high velocity, high density and prone to intrude into surrounding rocks, so it can form significant impedance interface with surrounding rocks. The subvolcanic facies can be easily identified in seismic profile since it is characterized by low-medium frequency, strong amplitude and continuous reflection.

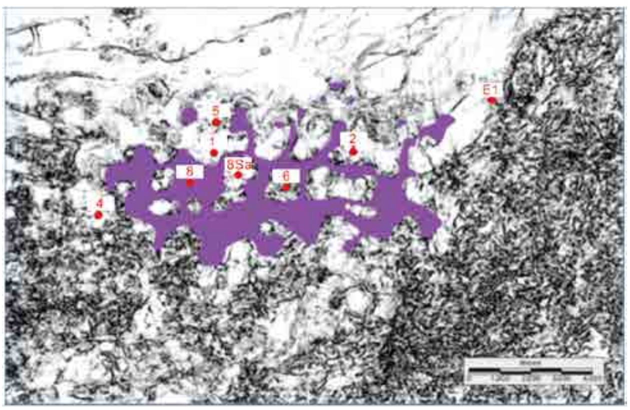


Figure 3
Igneous Rock Distribution of X Structure (Purple area); Background is Coherent Slice.

Volcanic conduit refers to the entire magmatic transport system from magma chamber to the top of crater and it is complex in lithology. It is not drilled in this area but it can be identified based on seismic response. The volcanic conduit can be divided into two types according to their shapes, which is center type and fissure type. Center-type volcanic conduit can be easily identified in seismic profile, which generally represents columnar or finger-like shape, with inverted cone-shaped volcanic vents at top. Fissure-type eruption can form various types of igneous rocks. The erupted magmatic materials can form clear wave impedance interface and represent stratified reflection in seismic profile due to good fluidity. However, they are difficult to be distinguished from normal sedimentary strata.

2. SPECIAL ERUPTION PATTERN OF X STRUCTURE

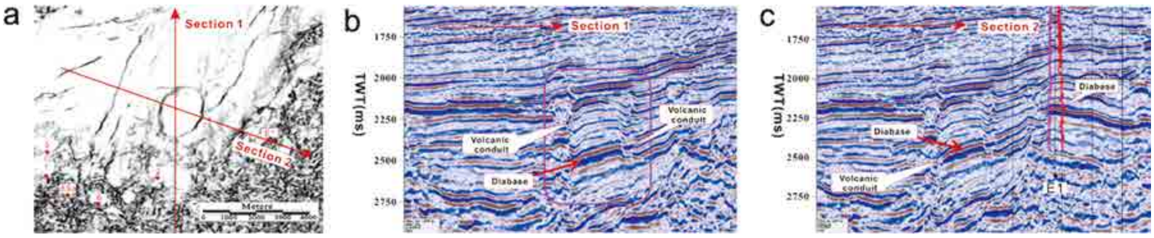


Figure 4
Typical Annular Eruption Sections(Collapse Down One Side)

The shape of volcanic conduit is related to the type of volcanic eruption. According to the type of volcanic conduit, the volcanic eruption pattern can be divided into center-type eruption (point-source type) and fissure-type eruption (line-source type) (Jiang et al., 2010; Cole, Milner, & Spinks, 2005).

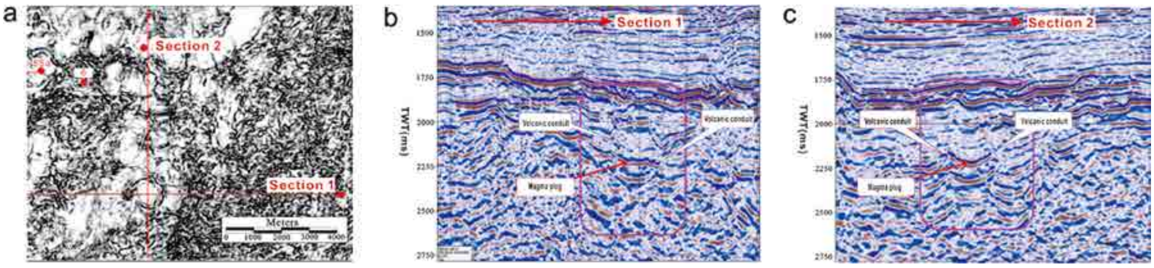


Figure 5
Typical Annular Eruption Sections (Central Collapse)

The seismic interpretation results and coherent slice of the igneous facies belt of Dong1 and Dong2 Member show that the volcanic eruption pattern of X structure is point-line composite type. The igneous rocks are constituted by the magma flow with large eruption amount and extensive distribution(Figure 3). The magma comes from the volcanic vents of single-source fissure type, which tends to cover the entire eruption zone and gradually make the topography flat. Fissure-type volcanic vents will gradually expand with the melting of the surrounding rocks in the vicinity of volcanic vents and then evolve into a number point-source volcanic vent due to concentration. The accumulation of magma flow can constitute the magma cover with low dip angle (Yi et al., 2014; Kuang & Guo, 2010).

In term of seismic response, the volcanic vent of center-type volcanic conduit in X structure represents mound shape, with mushroom-like volcanic cone structure in the upper part and blank scattered reflection in the interior. Fissure type eruption represents strong parallel to sub-parallel seismic reflection at the top and bottom and blank stratified reflection in the interior. The reflection at the top and bottom of center-type and fissure-type eruption weakens to both sides. The weakening rate of center-type eruption is generally faster than that of fissure type eruption(Wang et al., 2007; Wang et al., 2011; Zhang et al., 2008).

In addition to center-type eruption pattern and fissure-type eruption pattern, X structure may have a special eruption pattern - annular eruption pattern. In the variance body slice, obvious annular structure can be identified, which is similar to volcanic vent. However, the interior of annular structure represents stratified and continuous reflection with moderate-strong amplitude, but no disordered reflection that is just like center-type eruption. The bottom of annular structure represents continuous reflection with moderate-low frequency and strong amplitude. Moreover, there are multiple sets of mushroom-like disordered reflection in the vicinity of annular structure (Figure 4, Figure 5). Drilling results reveal that the stratified and continuous reflection in the interior of annular structure represents a set of diabase, while the mushroom-like disordered reflection represents volcanic conduit (Lu et al., 2008; Zhang et al., 2010; Planke et al., 2000).

The volcanic vent of annular eruption pattern is neither point shape (center-type eruption pattern) nor linear shape (fissure type eruption pattern), but annular shape (Figure 4a, Figure 5a). The magma with high fluidity intrudes into the crater that is temporarily quiet and re-deposited after the first eruption through fault or flow expansion. Under the obstruction of surrounding rock, the magma converges in the sedimentary strata, forming shield or dish-like magma plug. When the volcano is active again, the magma in the lower part jacks up the sedimentary strata and magma plug. Since the cooled magmatic vent that formed at early stage is more easily melted than sedimentary rocks at late stage and magmatic plug is poorly contacted with surrounding rocks, the magma extrudes from the edge of magma plug, forming volcanic cone through tubular or finger-like new volcanic conduit after eruption (Figure 4b, 4c, 5b, 5c). The magma plug began to collapse down due to magma emptying and pressure drop at the lower part (Figure 6) (Wang, Jian, & Chen, 2013).

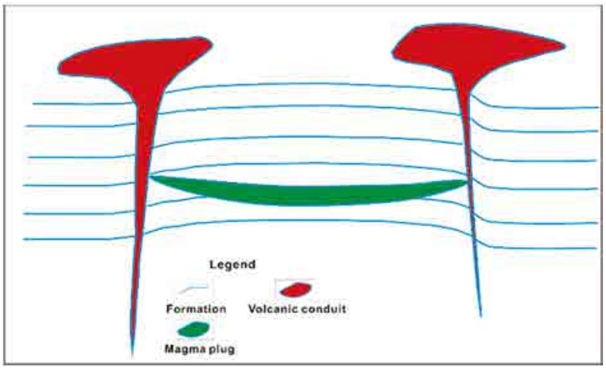


Figure 6
Scheme of Annular Eruption Pattern

Annular eruption pattern has the following characteristics:

(a) It generally occurs after the re-deposition of crater, when is the intermittent period of volcano eruption.

(b) The magma has viscosity and strong mobility.

(c) Intruded shape is mostly shield or dish-like.

(d) After re-eruption, the intrusive rocks become pot-like due to the transformation of the collapse at center.

Volcanic annular eruption has a favorable effect on hydrocarbon accumulation. Although reservoir is rarely formed in diabase, magmatic intrusion is generally controlled by deep large faults, which provides a pathway for oil and gas migration. The crater is subjected to magma intrusion after sedimentation, forming a magmatic plug overturned beneath its sedimentary strata. The igneous rocks with compressive strength much larger than that of the sedimentary rocks bear most pressure produced by overlying strata and make the underlying sedimentary strata become "soft ground". The loose rock structure provides an ideal reservoir space. The upper strata of magma plug can obtain sufficient oil and gas supply. In addition, they have good lateral sealing conditions after the cooling and consolidation of annular volcanic conduit. The diabase with high density and low porosity is good caprock.

CONCLUSIONS

(a) X structure is dominated by basic volcanic rocks. The magma erupted is mainly volcanic ash with high fluidity. The volcanic facies can be divided into eruption facies, overflow facies, subvolcanic facies and volcanic conduit facies. Different volcanic facies represent different seismic responses.

(b) X structure may have special eruption pattern, which is annular eruption pattern. This pattern is formed by the multiple times of eruption of basic volcano. Annular eruption pattern is favorable for hydrocarbon accumulation.

(c) The in-depth study of annular eruption pattern can effectively guide the exploration and development of the structure for the next step.

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