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Xujiaweizi Rift Lower Cretaceous Yingcheng Group Volcanic Sequence Stratigraphic Features¹

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1. Introduction

Sequence stratigraphy is a discipline that is developed on the seismic stratigraphy (Vail, 1987). The concept of sequence stratigraphy is born since 1950' (Sloss, 1959), which is composed of LST, TST and HST. The theoretical system of sequence stratigraphy has been widely used by geologists after half a century of development. It is also developing from the classical three kinds system tracts to four systems tracts (Catuneanu, 2006). Although the schemes of sequence boundary division are different (Catuneanu, 2006; Catuneanu, 2009), but they have stressed the fact is that the inherent mechanism of sequence genesis and phase distribution is controlled by sea level change (Arimoto, 1997; Saydam, 2000; Caquineay, 2008). The theoretical framework of Chinese modern sequence stratigraphy is mainly composed of continental sequence stratigraphy (Shanley, 1994; Liu ZJ, 2002; Ji YL, 2002) and high resolution sequence stratigraphy (Deng HW, 2002). At the moment, the application fields of sequence stratigraphy have been developed from the research of the whole basin layers to a intrabasinal measure detailed study (Xu YX, 2001; Chen F, 2010; Wang QC, 2010). With the development of exploration technology, the division of the sequence is more and more detailed, the control factor research of sequence development is more in-depth. However, with the breakthrough of exploration field, a large number of oil and gas resources are found in the volcanic rocks. Sequence stratigraphy is facing new challenges, how to create a volcanic sequence is our new research hotspot (Fig.1).

Yingcheng formation is made up of volcanic and sedimentary rocks in Xujiaweizi depression. volcanic rocks include volcanic lava and pyroclastic rocks that is a direct result of volcanism (Wang PJ, 2008). sedimentary rocks include two sections: the one is the normal sedimentary rocks that occurred in the intermittent period of volcanism; the other is composed of weather worn volcanic which transport by water. Scholars (Stewart A L, 2006; Busby CJ, 2007; Wang P J, 2006) have carried out intensive research about the volcanic lithology and lithofacies. But the targeted research of volcanic action filling model has not been carried out. Volcanic eruption and accumulation can take place in the high position. so the volcanic occurrence are not controlled by the accommodation space of water bodies, which is the biggest difference between sedimentary strata. Lead to the base level of

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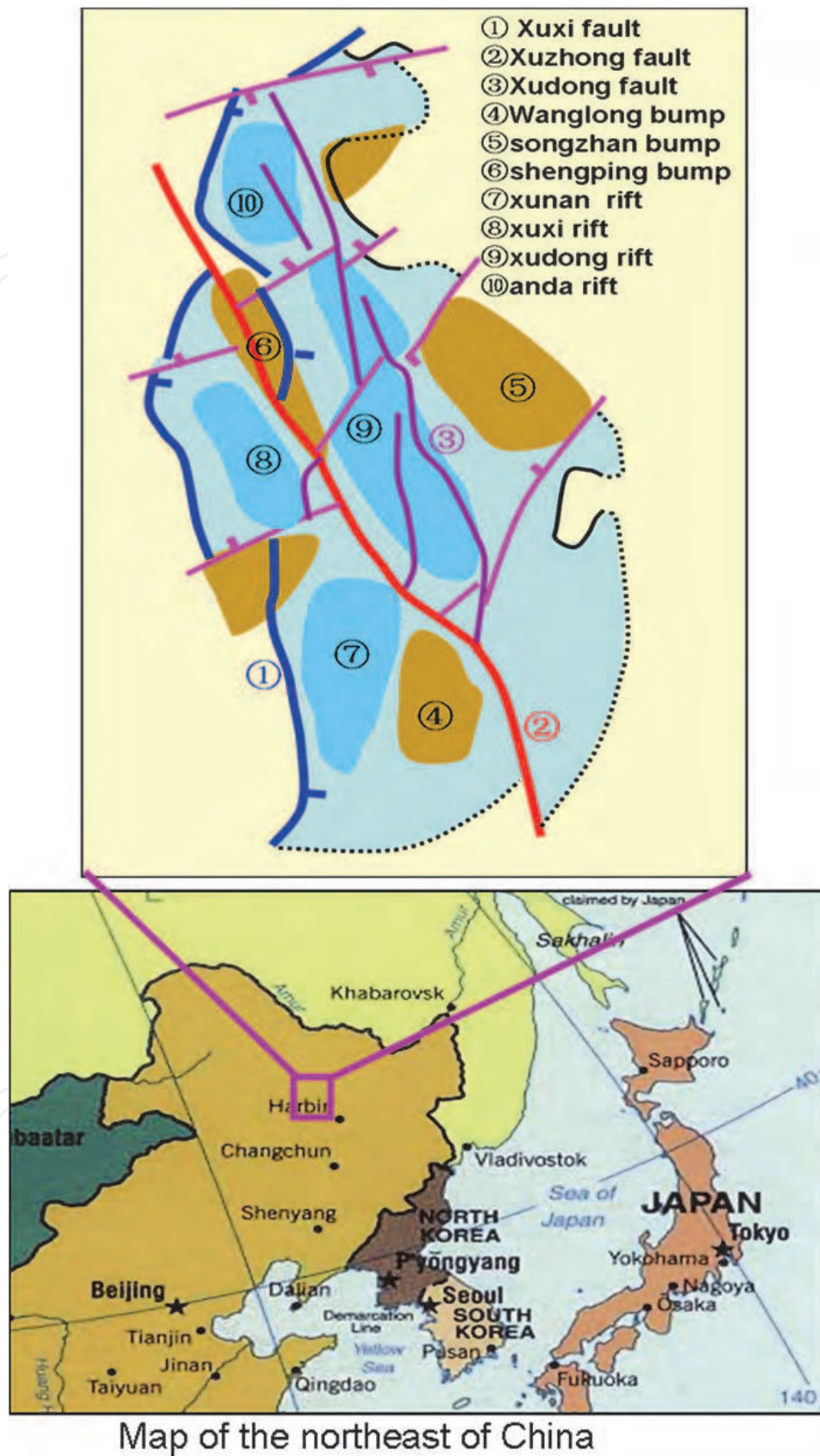


Fig. 1. Map of northeast of china ,in the upper shows locations of the fields mentioned in this article

traditional sequence stratigraphy is difficult to find and compare. In particular, when the volcanic eruption is strong and multi-stage, the phase sequence changes further complicated in the horizontal and vertical. It is more difficulty to find a unified datum in volcanic rock formation.

As the features of the volcanic eruption localized, the volcanism product is not the same in different parts of the sequence boundaries. Volcanic strata exploration must to face this problem. It is also the bottleneck restricting the development of volcanic exploration. The stratigraphic sequence of volcanic rocks is still in the exploratory stage for global scientists. The scholars of home and abroad (Gamberi F,2001; Schmincke H U,2004; Wang P J,2010) focus on the type, characteristics, causes of volcanic ejecta, etc. The volcanic rocks is usually considered to be filling sequence part of the sedimentary basin for more reseach, that the volcanic sequence develop in the ultra-sequence sets, super-sequence and the top of the bottom of the third sequence(Meng QA,2005; Dong GC,2005; Qiu C G,2006). With further research, the time and location of volcanic development is controlled by tectonic activity has been recognized (Cheng R H,2005;Tang H F,2007). However, these studies mentioned above have ignored the fact that volcanic sequence has the specific formation mechanism and controlling factors relative to sedimentary sequence.

Volcanic formation is an important part of fault basin. The rapid accumulation volcanic rock has important implications for the formation and evolution of stratigraphic sequence with volcanic rocks. In order to obtain new ideas for volcanic sequence research and establish a interpretation contrast mode of volcanic sequence strata, volcanism and its products should be analyzed together in this paper. Based on the new research results of construction and volcanic eruption mechanisms, We propose a new development model of volcanic sequence strata, in order to find out the distribution of volcanic rocks and the formation mechanism of volcanic reservoir.

2. Volcanism features of Yingcheng formation

Because the multi-center multiphase volcanic eruption, there is widely developed volcanic rocks in Yingcheng formation of Xujiaweizi fault depression (Fig.2). Volcanic strata have the feature of multiphase superposition in the vertical and migration in the horizontal. These kinds of feature indicate volcanic eruption with cycling and direction.

2.1 Multiphase volcanic rock superposition in the vertical

This appearance is common that volcanic rocks is vertical superposition in the wholly Xujiaweizi fault depression. The formation process that alternating layers of different volcanic rocks is more complex, which is also a record of volcanism processes. There should be two reasons for different volcanic rocks superimposed. The one is that the eruption of magma from different craters at different times and different distances superimposed in the same region. The other is that the volcanic rocks come from the same crater, but the volcanic rocks are different in different parts of the same volcanic edifice (Fig.3). This appearance is asynchronous volcanic action with the different features of eruptive material, effusive activity and affected area. The characteristic of volcanic rocks vertical development, resulting in a single well by volcanic sequences in different parts of the sequence have different characteristics. So it is not good to divide the volcanic sequence by the traditional way, we also can not expect to find a unified interface feature in the regional area.

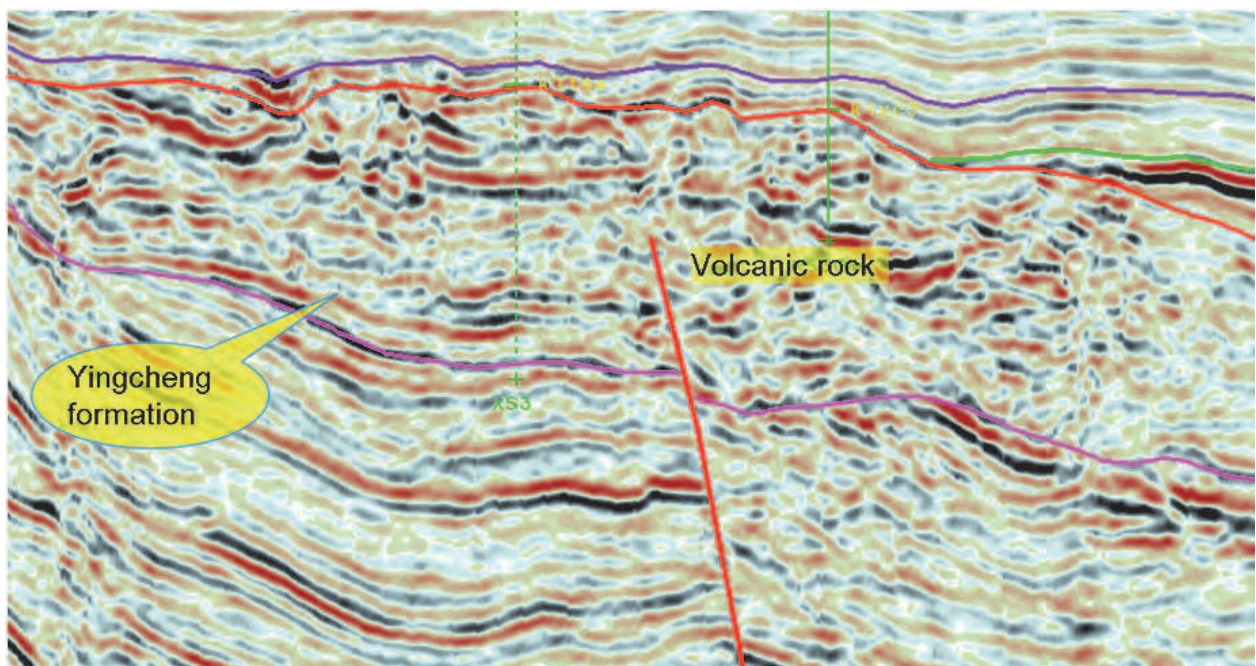


Fig. 2. Map of volcanic rocks development in Yingcheng formation

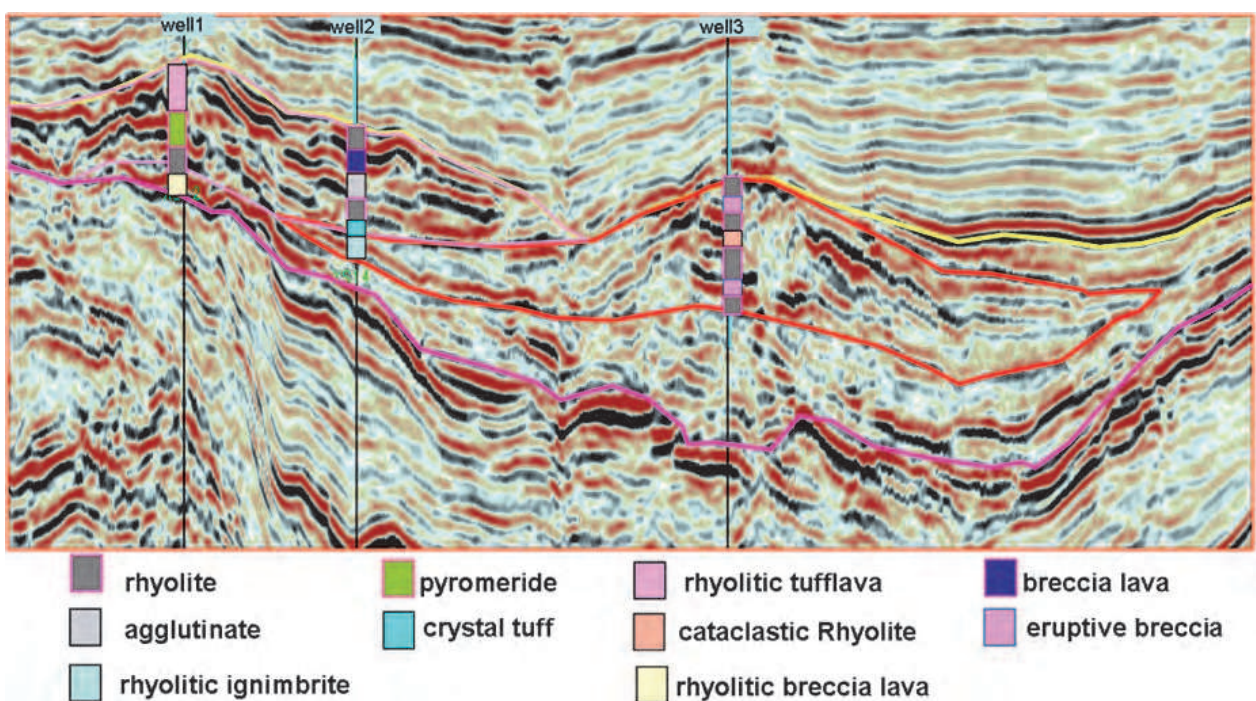


Fig. 3. Characteristic pattern of volcanic rock vertical superposition and horizontal change in Yingcheng formation

2.2 Volcanic eruption controlled by faults

Volcanic activity is related with the extensional movement of the mantle. When the unusual mantle bulge, causing supracrustal formation broken ground result in a volcanic eruption. The discordogenic fault that cut through the basement and earth's crust is the channel of magma upwelling. The Xuzhong and Xudong two major strike-slip fault systems (SSFS) and

their connected subsidiary fractures are the channels of magma eruption in Xujiaweizi fault depression. The thick volcanic rocks distribute along the strike-slip fault systems of Xuzhong and Xudong (Fig.4). According to drilling and geophysical data, the craters are mainly located in the transition location and intersection of fractures. Based on the correlation theory of rock fracture mechanics and structural geology, stress is concentrated in the end. However, the two endpoints of fracture are the stress concentration points, but also it is the weakest area. The volcanism is firstly happened in the weakest zone (Fig.5).

Because of the characteristics of SSFS, the strata are subjected to compressional and extensional coincident movement. There will be the phenomenon that magma is not eruption in various parts of the same fault at the same time along the strike-slip fault zone. The characteristics of the same fault activity are often different in different locations. There is a gradual process of change. The volcanic eruption first happened in the extensional location form the feature of multi-center fissure eruption. Because the alternating tension and compression effects. The characteristics of volcanic activity are different in different fault segments. The existence of such differences is the main reason for the volcanic superposition and migration in the horizontal (Fig.6).

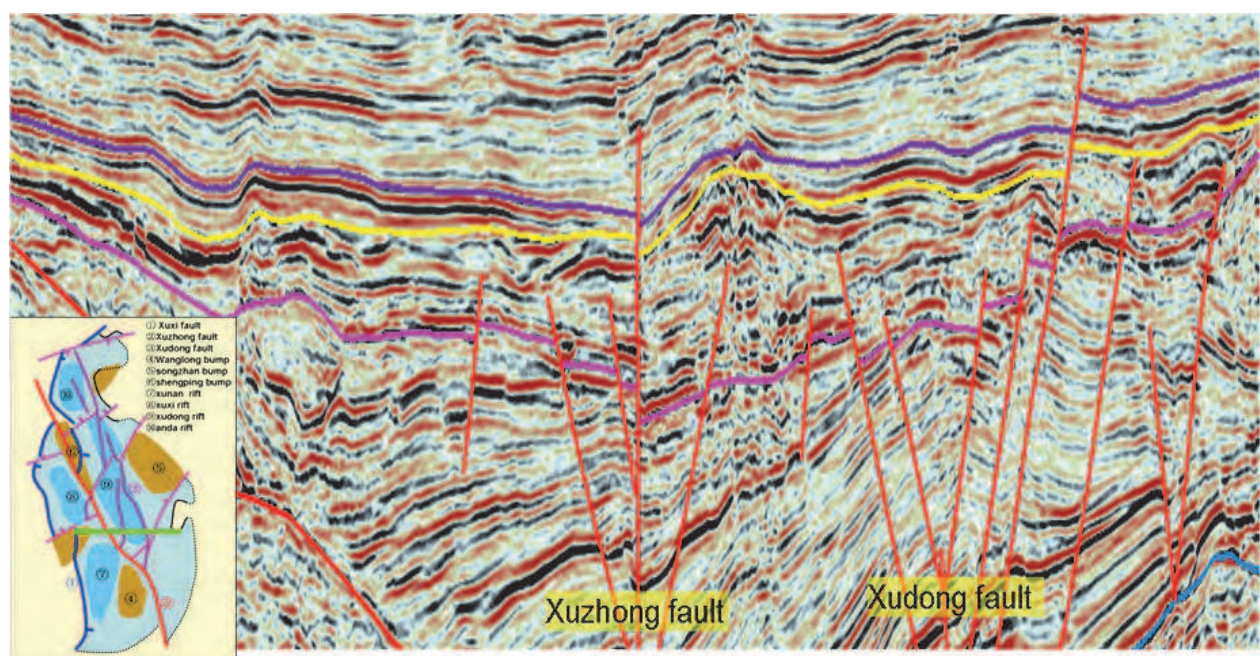


Fig. 4. The matched relationship of volcanic rocks thickness and fracture

2.3 The coexisting of volcanic and sedimentary rocks

The process of volcanic activity from start to finish is not continuous, but intermittent. The depositional interbedded stratum is the representative lithology for a quiet period of volcanic activity. Such as: there is about thickness of 45m deposition interlayer in the area of xs6 well volcanic rocks; there are also two sets of sedimentary sandwich thickness of 20m in the area of xs401 well. Regional deposition interlayer represents the interval of regional volcanic activity. There's a regional comparison deposition interlayer in the area of xs6-xs4-xs2-xs14-xs12 wells, which is the most obvious signs of volcanic cycle surface (Tang H F,2010).

The interbedded features of volcanic and sedimentary rocks, it is both on the evidence of intermittent volcanic activity, but also the evidence of underlying volcanic rocks below the

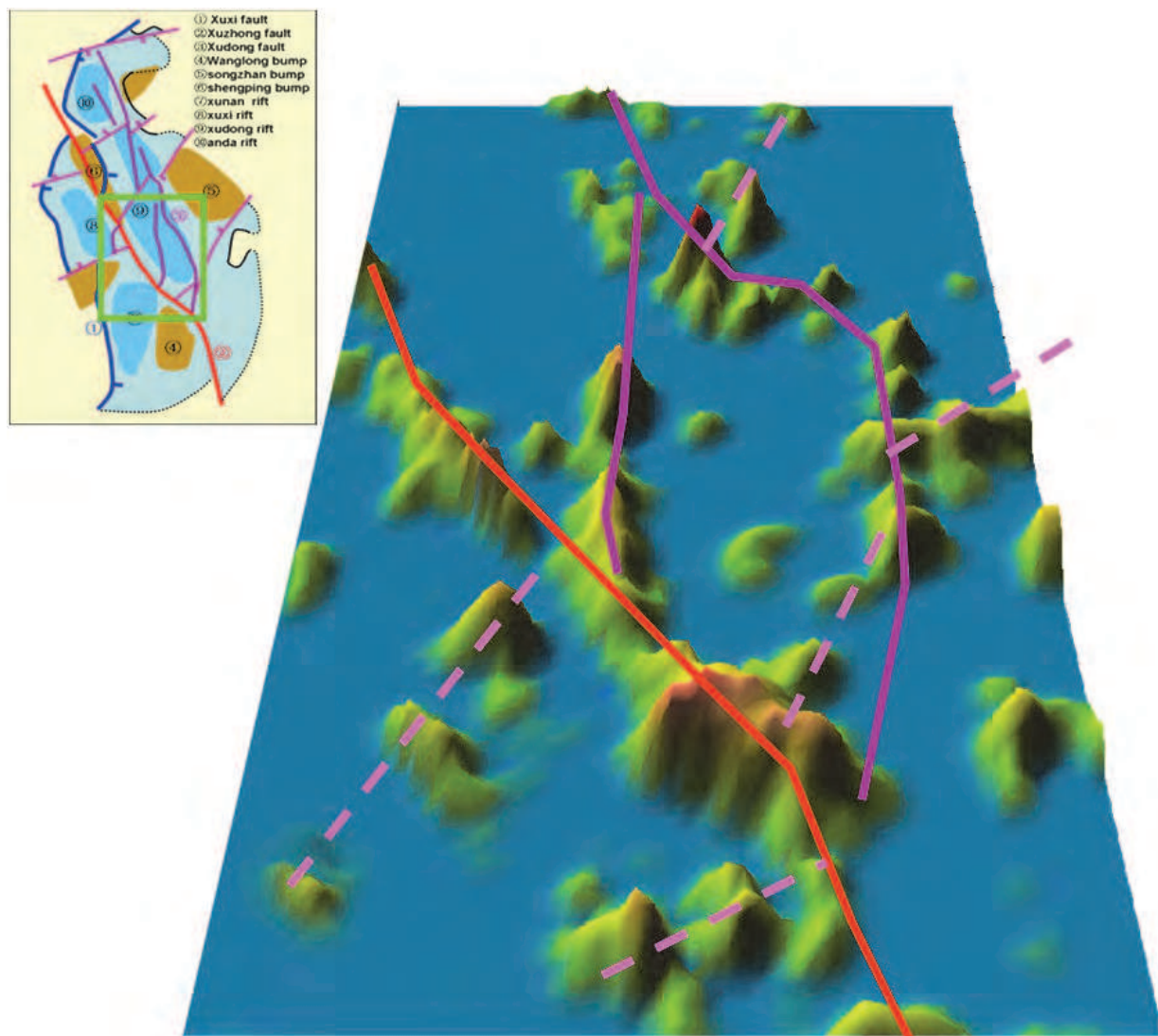


Fig. 5. The matched relationship of volcanic explosion vent and fracture

water surface a long period. This kind of sedimentary rocks indicates that the Yingcheng volcanic has the characteristics of subaquatic eruption. The perlite of xs2, xs5 and deposit ash tuff of xs1-4 wells drilled are further indicates the presence of lacustrine environment. There is a complete set of clastic rock containing volcanic in the Yingcheng formation in the area of zs14 well, which confirms a certain amount of lake present at the same time of volcanic eruption. The contact relationship is diverse between sedimentary and volcanic rock, some sedimentary rock is located in the middle of volcanic rocks, some is also located at the bottom of volcanic rock. The difference of occurrence location is controlled by volcanic eruptive sequence and affected area for sedimentary rock.

3. The division of volcanic sequence for Yingcheng formation

The accurate division and attribution of layers is the basis to restore stratigraphic evolutionary sequence. It's also the basis for oil&gas exploration and development. Because the multiphase volcanic eruption in the same area, volcanic edifices occur reformed in the vertical and lateral migration. It's difficult to propose a simple evolution model of general

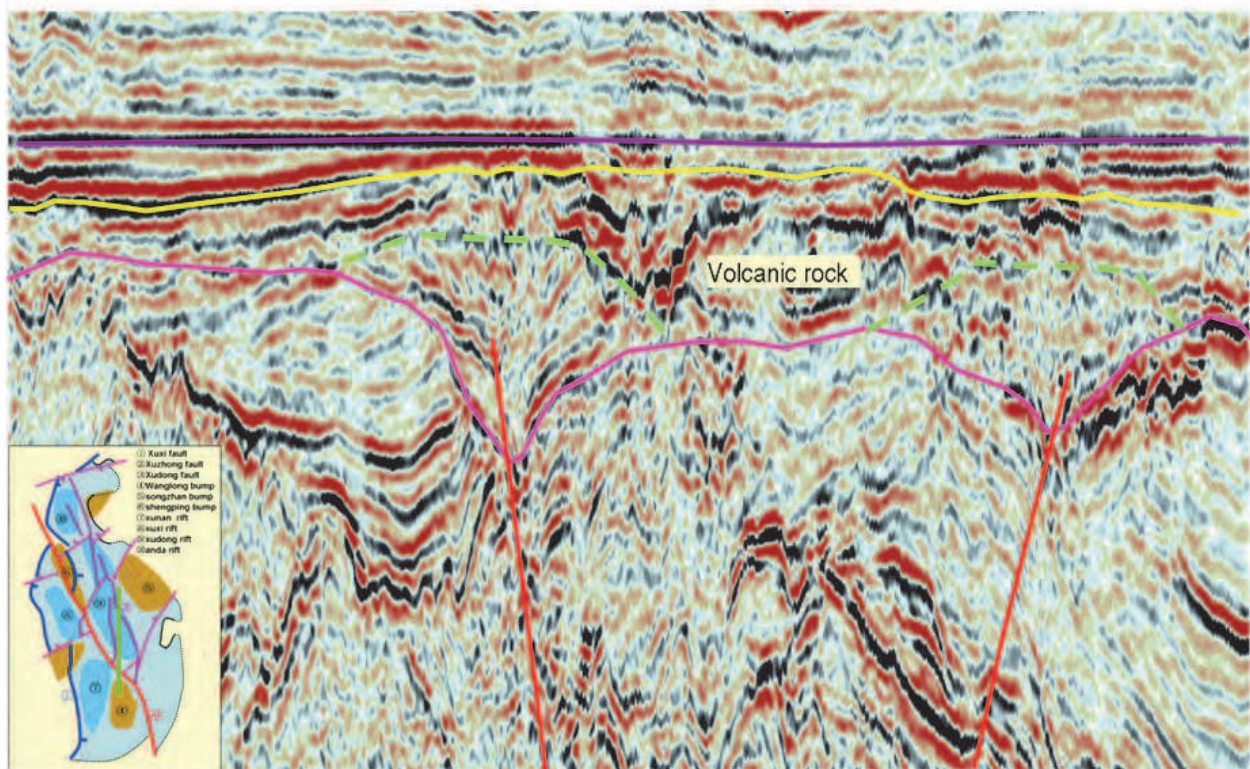


Fig. 6. The map of central vent eruption controlled by crack

application. It's also difficult to divide and compare volcanic sequence in accordance with this mode. Based on the summary of volcanic activity regular pattern, the authors analyze the volcanic sequence of the control factors and division and correlation in this article.

3.1 Distribution characteristics of Yingcheng strata

Based on the contrast from the regional stratigraphic features, there is main development of sedimentary rock strata containing volcanic material in the east and west sides of Xujiaweizi fault depression. In some areas of the rift center, such as xs801 well area, there is sedimentary rocks development in the lower part of Yingcheng formation. The set of sedimentary rocks is obviously different from the Shahezi sedimentary strata. The contact relationship of them is angle disconformity, this feature is very visible in the seismic profiles. It's further show that the volcanic rocks are not development in the whole Xujiaweizi rift in the period of volcanic eruption. It is jointly controlled by volcanic activities and sedimentary process for the temporal and spatial distribution of Yingcheng strata. It has the characteristics of multiphase volcanic eruption in the primary zone of volcanic eruption. Thus there is a large area of volcanic lava and athrogenic rocks development. There is the area of sedimentary rocks development in the outside of volcanic affected area in the Yingcheng formation. The construction feature of Yingcheng formation is associated with volcanic action and deposition (Fig.7).

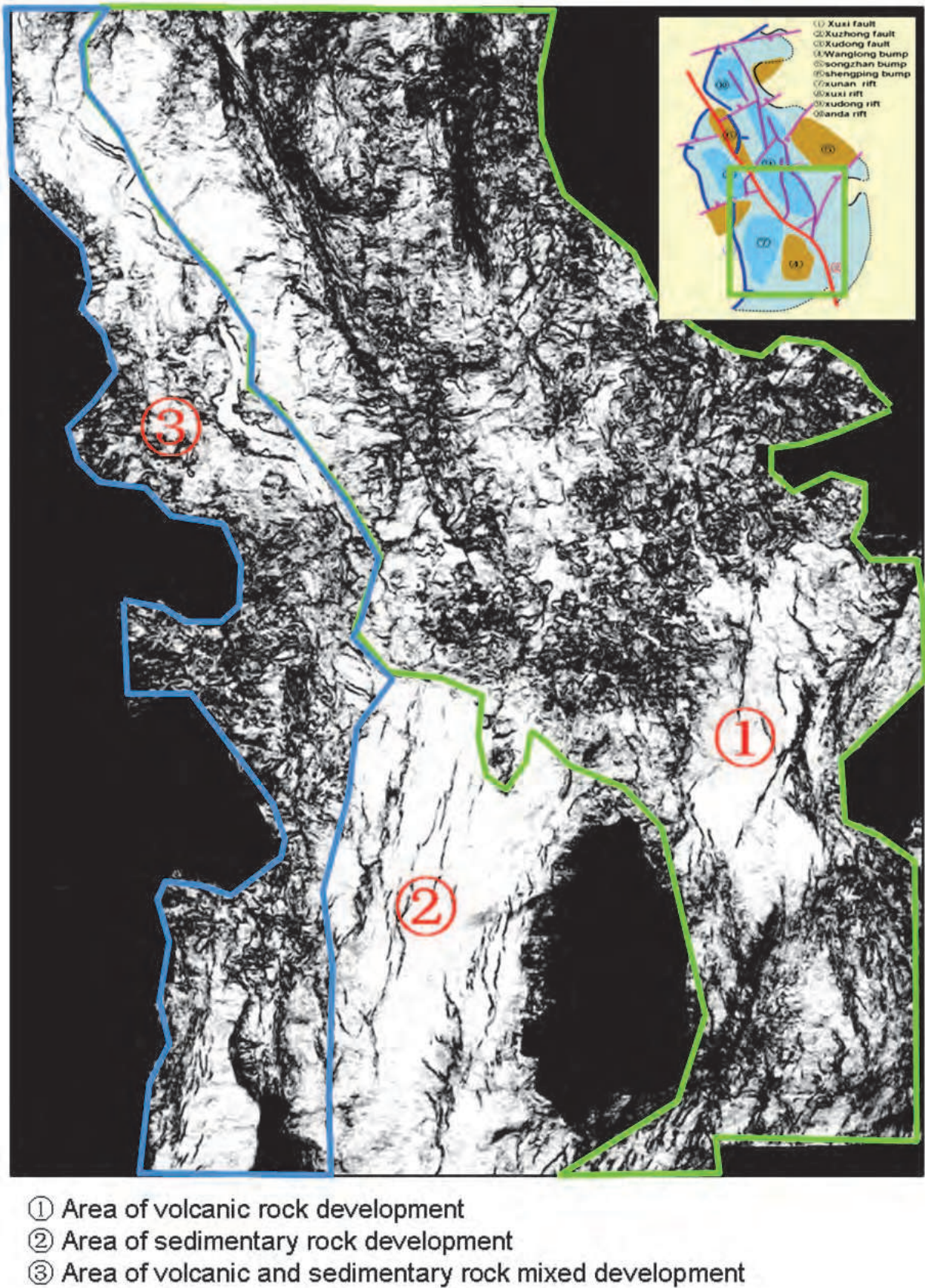


Fig. 7. The forecasting map of lithology using coherence cube

3.2 Volcanic sequence classification foundation

It is to find the formation boundary that the upper and lower strata can be distinguished and correlatable in the horizontal for volcanic sequence division. For a concentrated continuous volcanic activity, the material composition, eruption methods and effusive activity will occur on a regular variation, which changes regularly must be inevitably form a set of genetic relationship of the volcanic sequence. Based on the single well detailed breakdown of volcanic rocks, Scholars (Wang PJ,etal, 2010) divided different numbers of volcanic rocks cycles in different regions in the Xujiaweizi rift. But these cycles explained is difficult to compare with others in the horizontal. Lithologic correlation is wrong correlation marker for volcanic sequence. It can reflects the variation of volcanic activity that superimposed array mode of volcanic apparatus(Chen SM,2011).Therefore, the directivity and superimposed mode of volcanic activity is different for diachronous volcano, volcanic sequence can be divided.

Based on comprehensive analysis of the volcanic rocks development characteristics of Yingcheng formation, the four correlation markers are proposed that is suited for volcanic rocks comparing in XJWZ rift. The first one is depositional interbedded stratum and ash tuff that can be regional compared. It is an important foundation for volcanic cycle dividing. The second one is the structural surface, in the upper and lower of the structural surface. There is distinguished difference for effusive activity, lithology, facies. So it is easy to form unconformity and the angular unconformity for volcanic formation, it is the good foundation for volcanic comparison (Fig.8). The third one is the superimposed mode of volcanic apparatus that diachronous volcano has different directivity of superimposition (Fig.9). The fourth one is depositional interface in the same period of volcano. Because the sedimentary formation records the evidence of volcanic event, classical infilling mode of fault depression has been changed when the volcanic goes into the rift. Each volcanic eruption correspond a tectonic movement, so the coupling of structure and sedimentary strata also recorded the volcanic activity cyclicity (Fig.10).

3.3 The division of volcanic sequence

Combination of the regional tectonic evolution, according to the macro-migration of volcanic activity, the volcanic rocks of Yingcheng formation can be divided into two three-stage sequences. The lower volcanic sequence is Y1 section, the upper volcanic sequence is Y3 section. The Y1 is mainly controlled by xuzhong strike-slip fault and its associated faults, the maximum thickness of volcanic rocks is along the fault zone. It is mainly distribution in the central and southern rift. The direction of volcanic eruption is mainly from north to south.As with the fault distance increases, the content of volcanic strata gradually reduced until it evolved into sedimentary strata. The Y3 is mainly controlled by xudong strike-slip fault and its associated faults. The direction of volcanic eruption is mainly from south to north. The xs22 well field is the starting point for the period of volcanic activity. Since the rapid release of volcanic energy, the xs22 Well field form a large-scale collapse crater, and form a thick pyroclastic filling. Because of the volcanic activity have the feature of direction and migration, there is a large area of debris deposition in the northern area that is the outside of volcanic activity sweep area. With the more large-scale violent volcanic eruptions and flooding, the larger and broader coverage of volcanic filling.

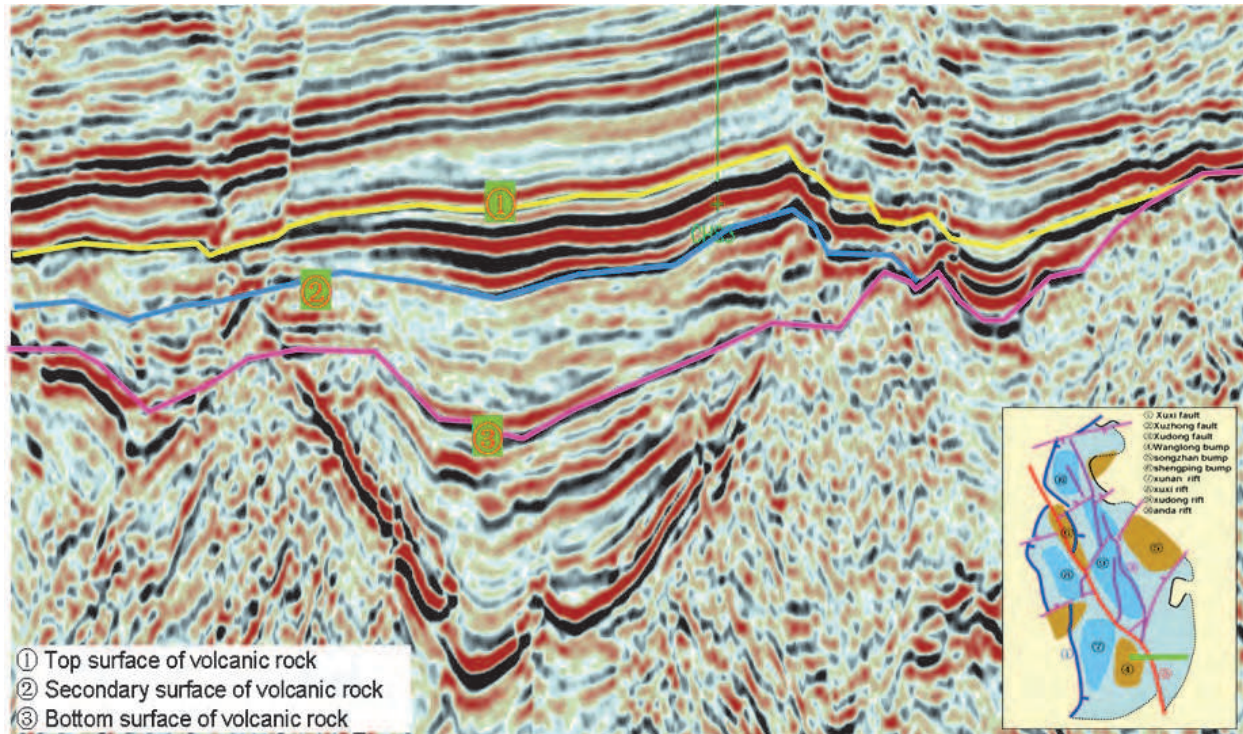


Fig. 8. The feature of sequence interface in volcanic rock

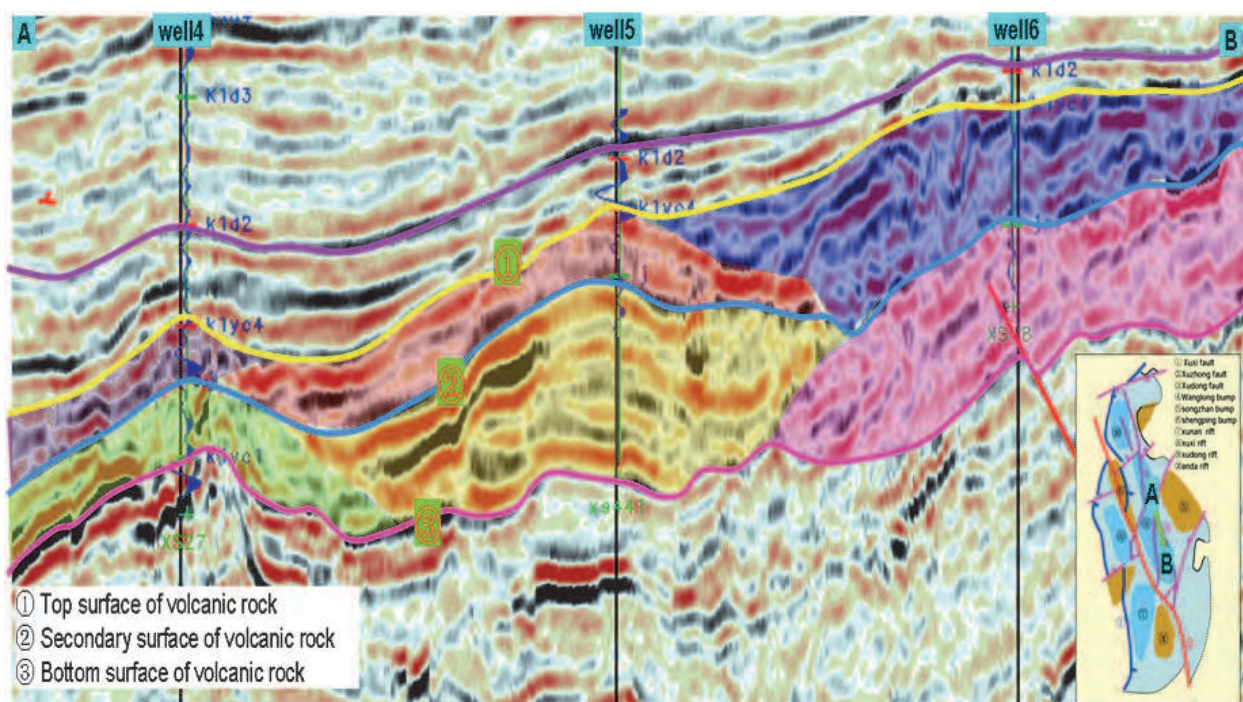


Fig. 9. The difference of volcanic edifice superimposed relationship nearby the volcanic sequence

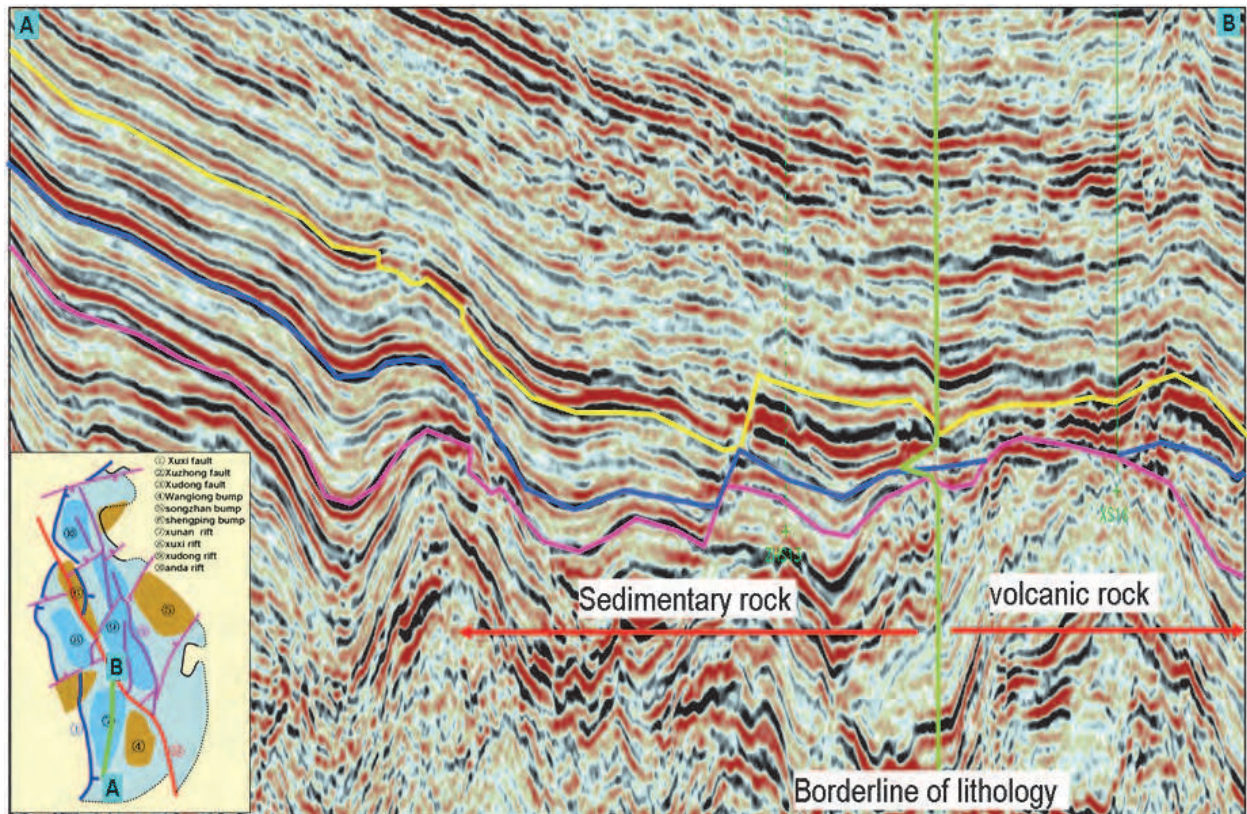


Fig. 10. The couple of sedimentary sequence and volcanic action

The volcanic sequence of Y1 and Y3 can be further identified three sub-sequences. they are the early volcanic eruption sequence(EVES), the strong volcanic eruption sequence(SVES) and the languid volcanic eruption sequence(LVES). Explosive eruption is primary in the EVES, there is also a certain amount of overflow phase developed. There is the area of sedimentary rocks development in the outside of volcanic affected area in the Yingcheng formation. The volcano shows the features of local central vent eruption along the cracks. Nowadays, the volcano of Wudalianchi has the same characteristics to EVES in the Heilongjiang province of China. The SVES has the typical feature that large-scale outbreak and the overflow happen simultaneously. There is the interbedded, and there is also some thick individual layer of lava flows and debris flows. The SVES is widely distributed in the large areas of sequence. It is not only the main volcanic sequence stratigraphy, but also the reservoir is the most development in the entire volcanic sequence. Local overflow and small-scale invasion is the main characteristics of the LVES, because the size of LVES is small, the feature of sequence is no obvious. it is usually combined with the SVES as a sequence. But the LVES is the most favorable sequence for volcanic reservoir communication with deep fluid. it is also the favorable position for deep fluid easier to charging in the process of volcanic accumulation. It become the favorable accumulation area for carbon dioxide gas reservoir. The current exploration results have confirmed this characteristic in XJWZ rift (Fig.11).

4. Developmental patterns of Yingcheng sequence stratigraphy

The base level of volcanic sequence is unstable and not uniform in the region. Because of the existence of early volcanic eruption highland, the late sequence is not good overlay with the early. Therefore, the two-step volcanic sequence boundary is difficult to form a stable feature in the region. It is also hard to find the unified reflecting boundary for tracking.

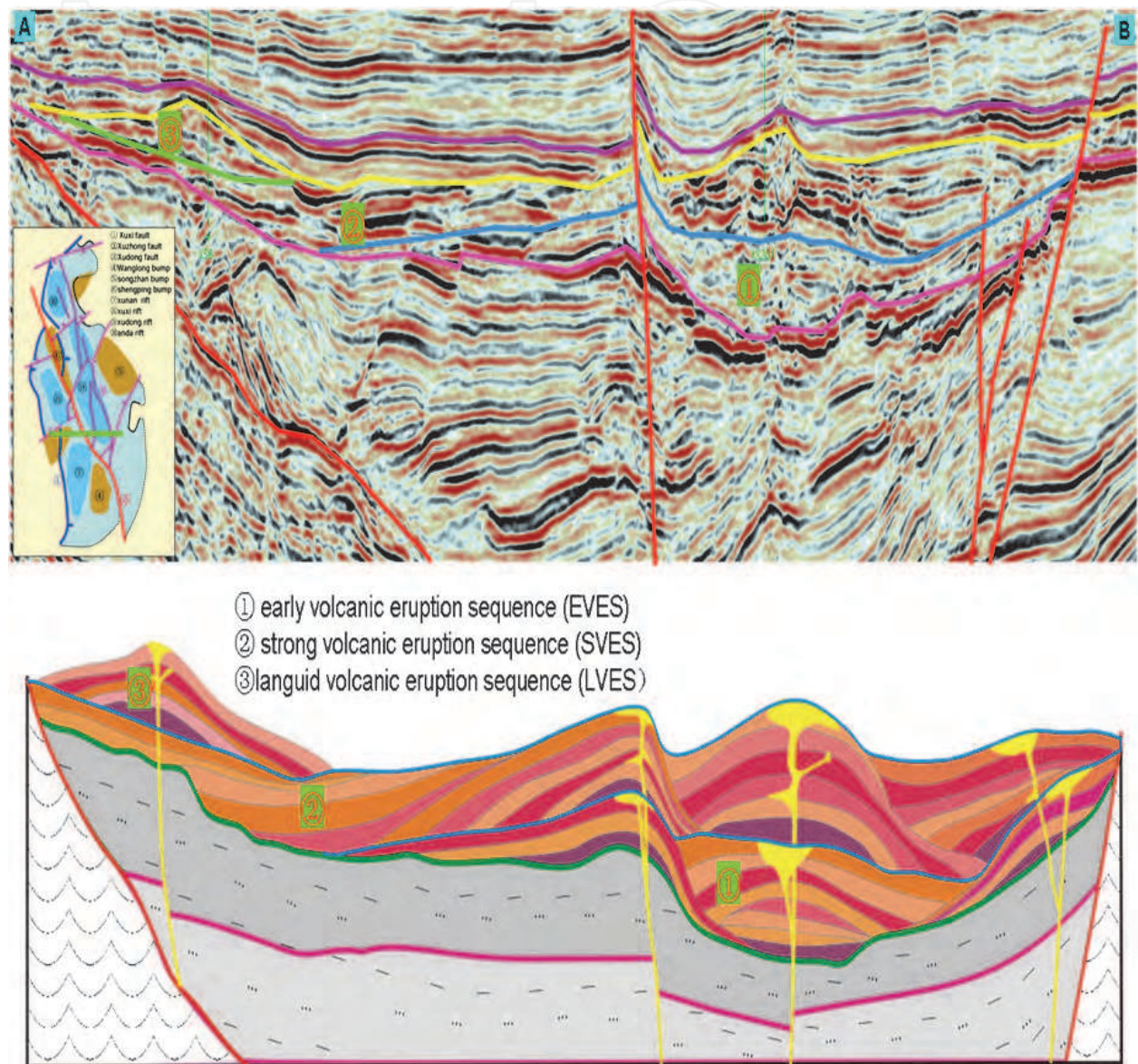


Fig. 11. The map of volcanic sequence division

4.1 The Y1 developmental patterns

The size of Y1 volcanic apparatus is certain scale, the general current occurrence height is above 300 meters. The early eruption of the volcano can be located above water level. Therefore, compared to the late period volcanic apparatus, the weather-worn extent of early is strong, such as: the transformation feature of volcano is relatively obvious in the north well field, there is thick layer weathering crust development; but the transformation feature

of volcano is significantly decreased in the south well field. This change indicates the order of volcanic action that is from north to south.

Volcanic activity is also accompanied by tectonic movement, resulting in frequent lake level fluctuation. When volcanic material quickly build-in the rift basin, the accommodation space is changed, resulting in level surface rising. The volcanic eruption early is located under the level surface, received clastic sediments. With the thickness of cumulo-volcano continuous increase, the late crater outcrop above the water level. Therefore, the interbedded phenomenon of sedimentary and volcanic rocks significantly reduced, there is mostly volcanic with high purity development in the upper volcanic rocks. There is the area of sedimentary rocks development in the outside of volcanic affected area. These sediments containing volcanic material is high, because the highland formed by volcanic eruption suffered weather worn activity, provide a filling material for the basin (Fig.12). Thus the unique geological feature is formed for Yingcheng formation. where the volcanic eruption, volcanic intermittent, erosion, deposition is interaction. The ancient landscape of Y1 is not flat where the north is lower, the south is higher.

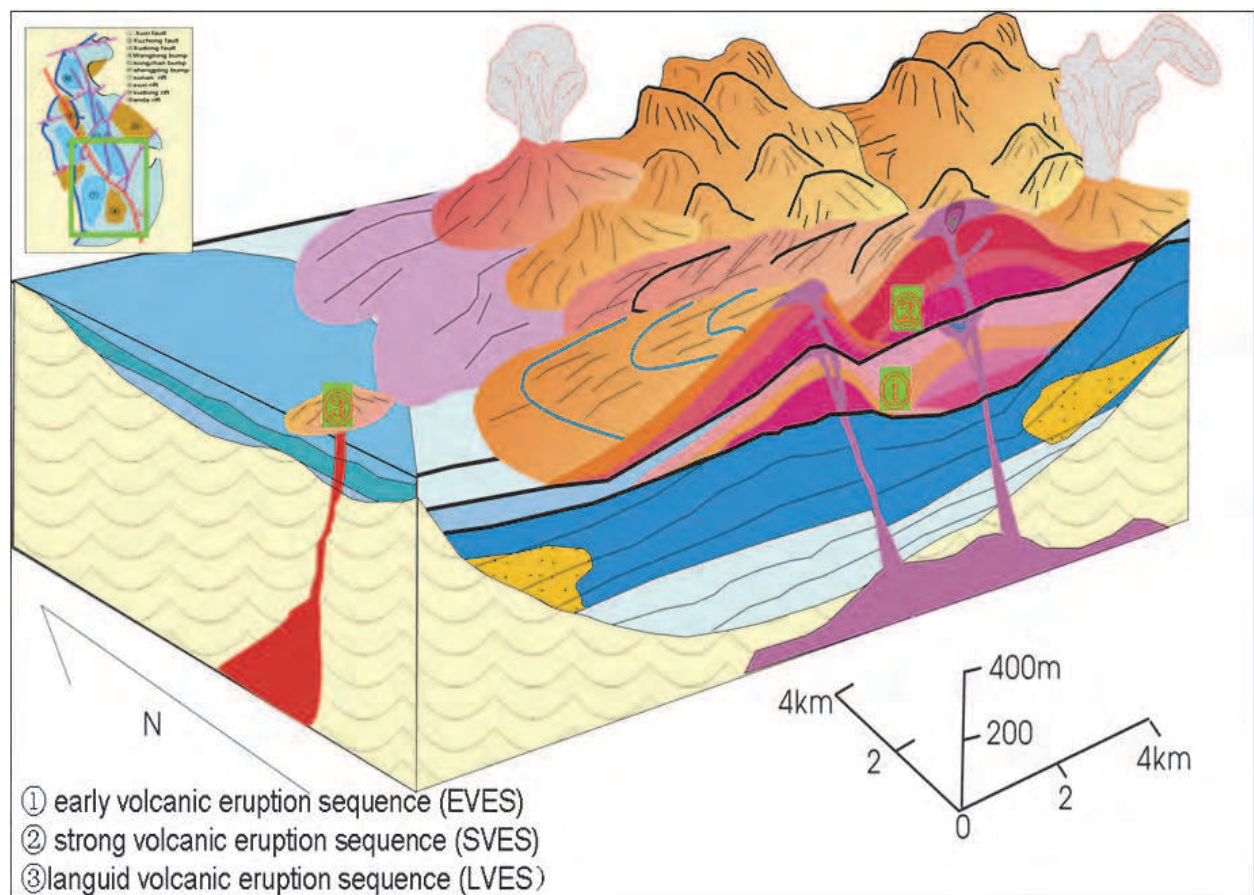
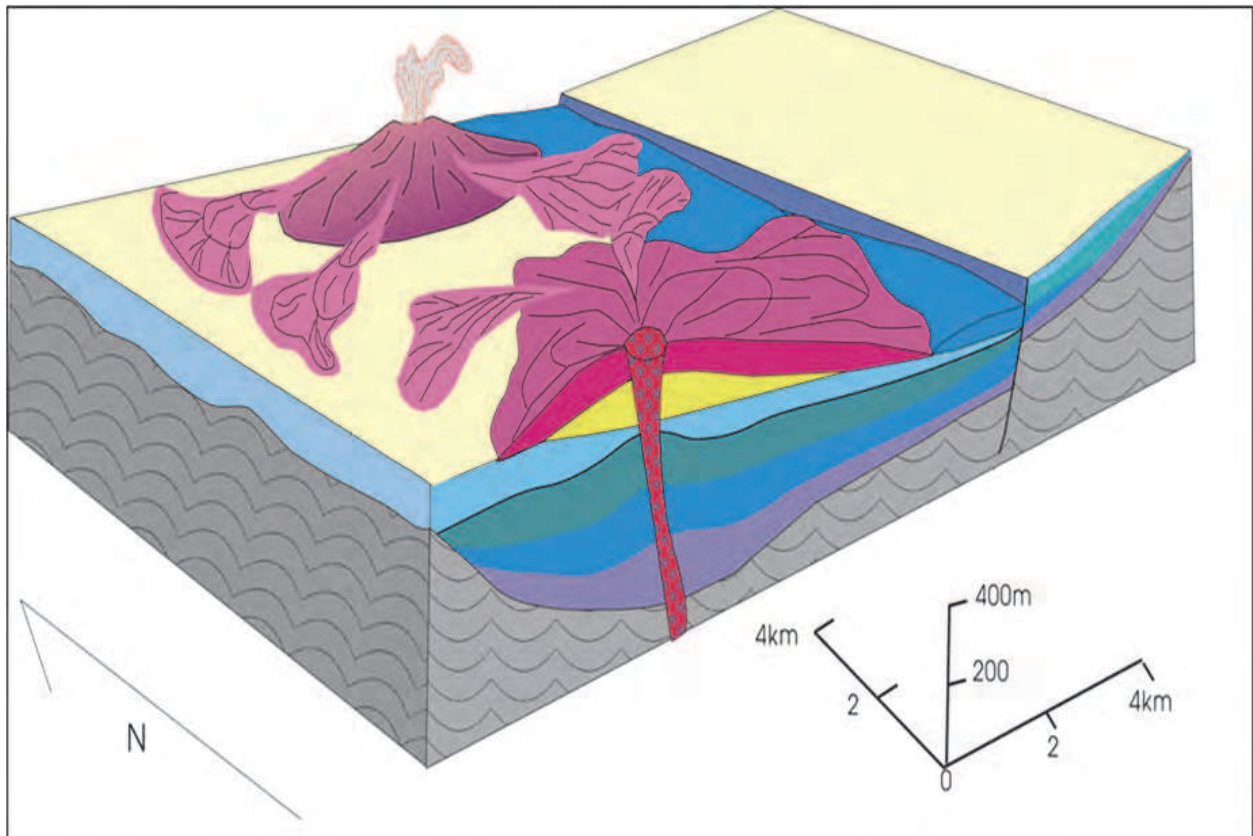


Fig. 12. The map of Y1 developmental patterns

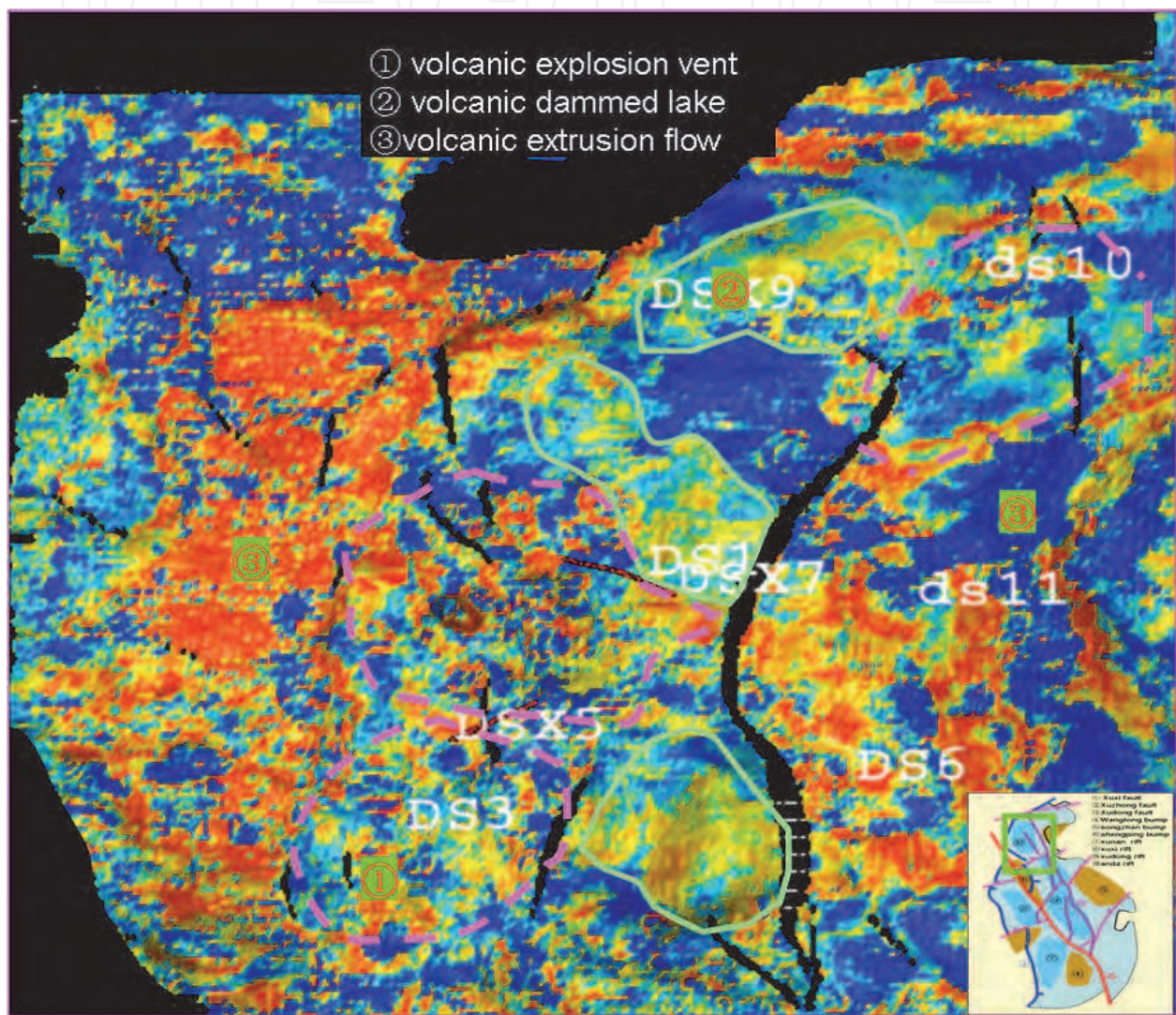
4.2 The Y3 developmental patterns

Because of the different nature of the magma, the Y3 development pattern is completely different from Y1. The Y1 is mainly composed of acidic volcanic, but the basic volcanic rock is mainly development in Y3. Compared with the acid volcanic rocks, the basic volcanic rocks has different vents feature. Such as the volcanic vents is smaller, the plane position is

relatively stable, the volcanic rocks is mainly volcanic lava. The local outbreaks characteristic of EVES is accompanied by fault activities. It is easy to form a barrier lake. Thus the formation of volcanic rocks and sedimentary rocks in symbiosis is the typical characteristic (Fig.13). When the volcano erupted violently, volcanic sub-sequence is in the stage of SVES. The rift basin is filled with volcanic material quickly, volcanic rock becomes the main rocks, and the sedimentary rock is little development. A large area of lava delta is development, in the vent, often accompanied by some small-scale outbreaks (Fig.14). The ancient landscape of Y3 is not flat where the north is higher, the south is lower.



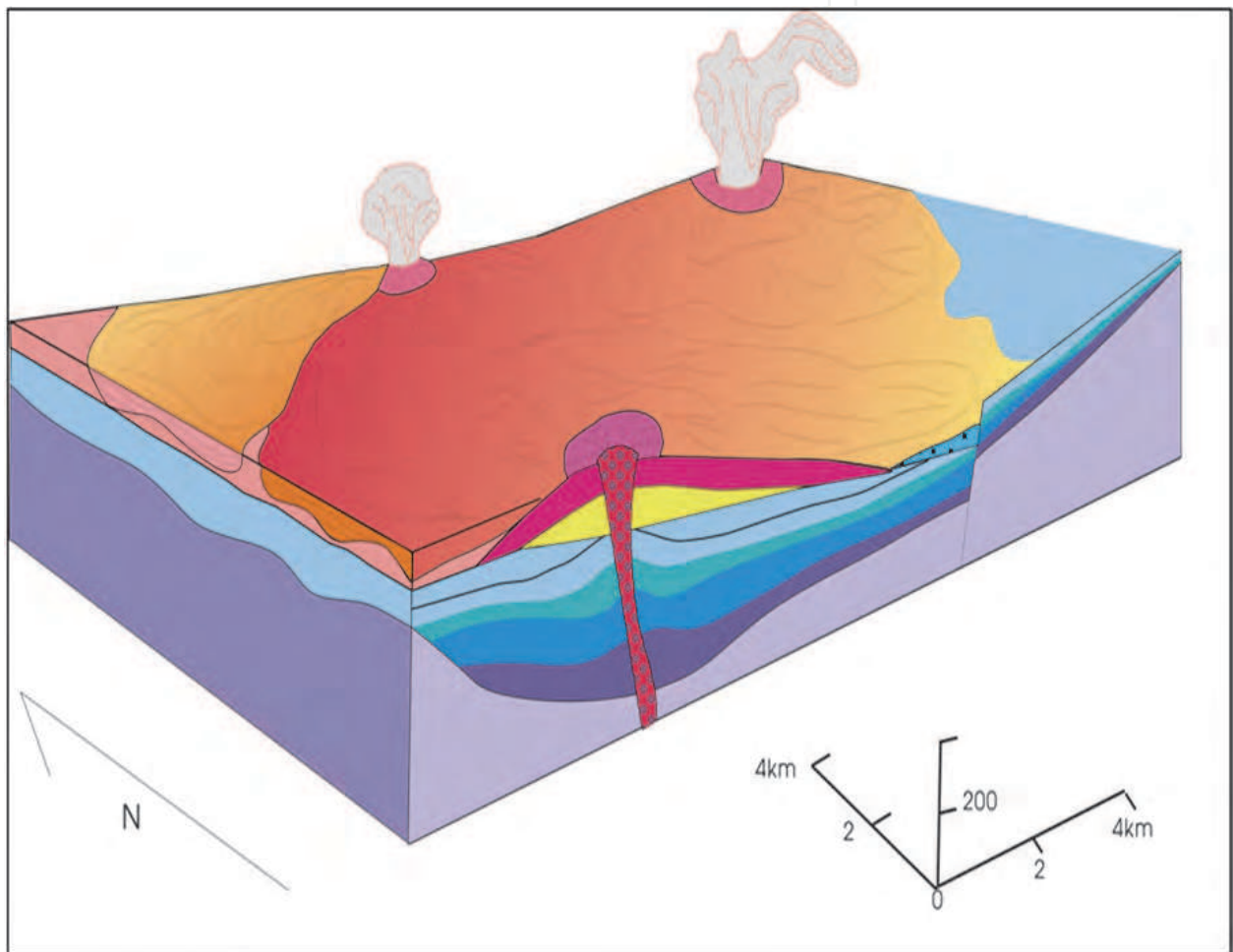
a. developmental patterns of EVES



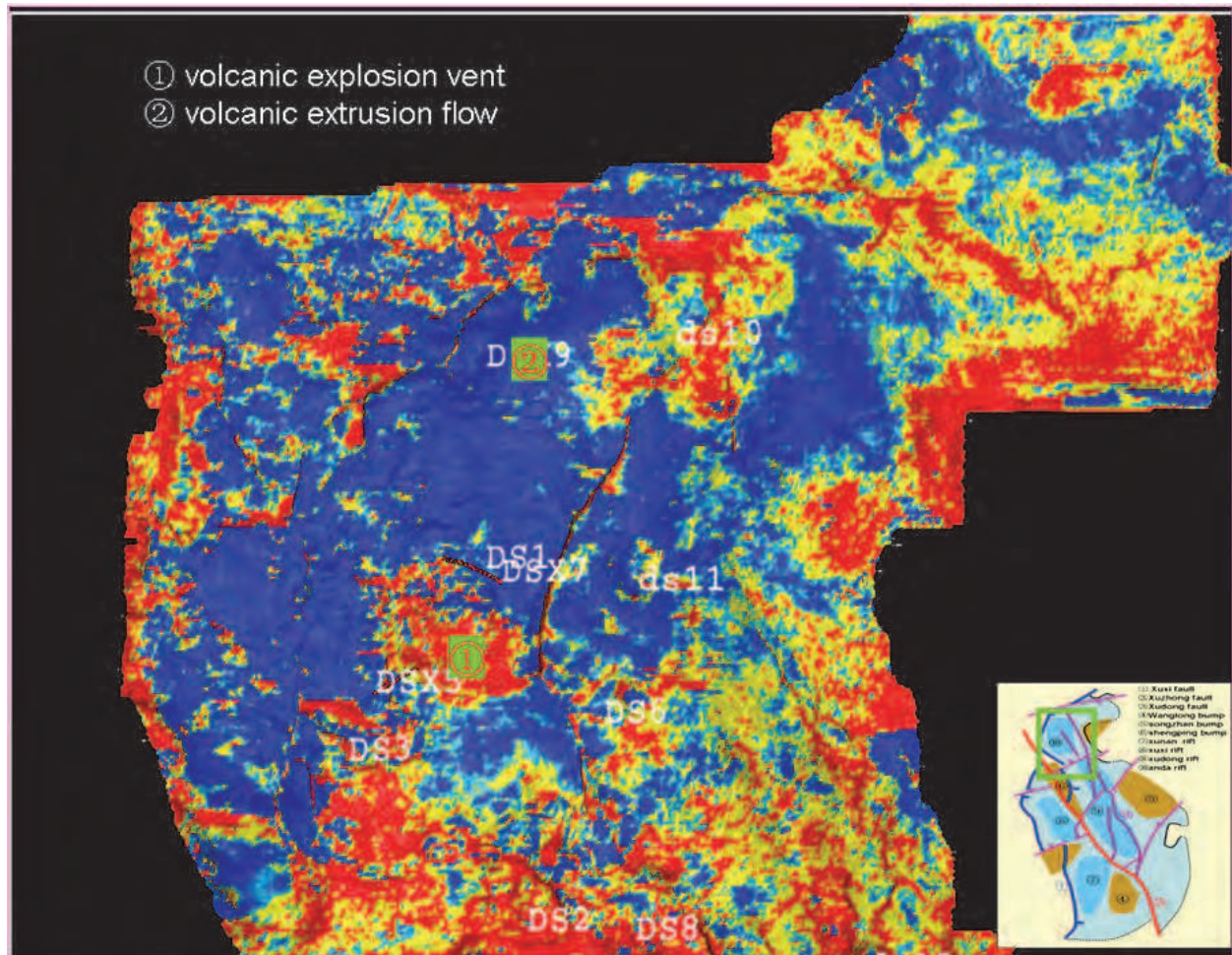
b. the example of EVES

Fig. 13. The map of Y3 developmental patterns(EVES)

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a. developmental patterns of SVES



b. the example of SVES

Fig. 14. The map of Y3 developmental patterns(SVES)

5. Summary

1. The volcanic eruption is controlled by strike-slip fault systems(SSFS) and their connected subsidiary fractures. Because the order of fault activity is different, so that the volcanic rock of Yingcheng formation can be divided the upper and lower volcanic sequence. The the lower sequence(Y1) is mainly controlled by Xuzhong strike-slip fault and its associated faults, the upper sequence (Y3) is mainly controlled by strike-slip fault and its associated faults. So the research of volcanic sequence, it is very important to find the faults that control the volcanic eruption.
2. The regional sedimentary is present in volcanic rock strata. It is both on the evidence of intermittent volcanic activity, but also the evidence of underlying volcanic rocks below the water surface a long period. This kind of sedimentary rocks indicates that the Yingcheng volcanic has the characteristics of subaquatic eruption. The environment of volcanic eruption is shallow-water lacustrine facies. The interaction of fire and water, the volcanic eruption cycle can be found in sedimentary sequence.
3. Different parts of the same fault has different activities time, it also control the order of volcanic eruption. So it is the characteristic appearance that fissure flow multi-point

- central vent eruption in XJWZ rift. The craters are mainly located in the transition location and intersection of fractures.
4. The difference of volcanic activity directional is the important basis of volcanic rock sequence division. It is also a reflection of plate movement. The direction change of volcanic activity is must be accompanied by the tectonic movement occurs.
 5. Sedimentary and volcanic rocks are uniform in the strata, there is mainly volcanic sequence stratigraphy in the volcanic eruption area; There is the area of sedimentary rocks development in the outside of volcanic affected area . Sedimentary rock strata records the cyclicity of volcanism.
 6. The volcanic sequence of Y1 and Y3 can be further identified three sub-sequences. They are the early volcanic eruption sequence(EVES), the strong volcanic eruption sequence(SVES) and the languid volcanic eruption sequence(LVES). It is mainly based on debris accumulation in EVES, it makes the reflection characteristics of chaotic and blank in seismic profile. The SVES usually have the reflection characteristics of strong energy in seismic profile. The LVES is local and sporadic development, it is difficult to find the regional characteristics compared in seismic profile. Therefore, it merged into the SVES. But it has the good indication for inorganic gas reservoir.
 7. They are very important signs for volcanic sequence divided. Such as superimposed mode of volcanic apparatus,depositional interbedded stratum and ash tuff can be regional compared, structural surface, sedimentary sequence interface With the same period of volcanic activities.

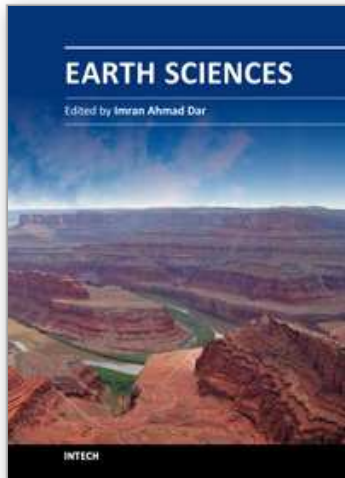
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