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Chapter 4

Volcanic Rock-Hosted Natural Hydrocarbon Resources: A Review

Jiaqi Liu, Pujun Wang, Yan Zhang, Weihua Bian, Yulong Huang, Huafeng Tang and Xiaoyu Chen

Additional information is available at the end of the chapter

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1. Introduction

Evolution and the hydrocarbon bearing capacity of basins are closely related to volcanic activity, and not only source rock maturity, but also hydrocarbon trapping are influenced by volcanism within a basin. Volcanic rocks act as important basin filling material in different types of basins, for instance, rift basins, epicontinental basins, basins in a trench-arc system, back-arc foreland basins, etc. [1]. Volcanic accumulation of oil and gas is a new global field of hydrocarbon exploration and has been proved in more than 300 basins in 20 countries and regions [2]. The Cenozoic volcanic rocks, especially Jurassic, Cretaceous and Tertiary, contribute about 70% of the total preservation globally [3-7].

Derivations of hydrocarbon in volcanic accumulation have organic as well as inorganic sources [8-10]. Volcanic rocks could act as a reservoir or cover within hydrocarbon traps, whose thermal effects could accelerate the maturity of source rocks or destroy preserved hydrocarbon [11-13]. Primary hydrocarbon accumulations could be reformed or destroyed during tectonic and volcanic processes, the preserved hydrocarbon remobilized to other traps or the ground surface [14]. Effective reservoirs have been found in most lithology [15-17]. Lithofacies, including deposits and rocks formed by explosive, effusive, extrusive and subvolcanic processes, could bear hydrocarbon, and the facies combination close to a volcanic conduit shows better porosity and permeability due to an increased number of fractures and reservoir spaces, or an elevated volume of coarse-grained fragmented rocks [7, 18]. Reservoir spaces within volcanic rocks are composed of primary pores, secondary pores and fissures with significant heterogeneity [19]. Tectonism, weathering and fluid saturation and/or movement could modify reservoir space [6, 20-23]. Upward cover and lateral seal of volcanic rocks could form hydrocarbon traps [24]. Lateral distribution of volcanic rocks can be mapped based on

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aeromagnetic and gravity data [25]. The reflective seismic features of volcanic rocks are summarized [26] and visualized [12] based on qualified seismic data. Volcanic edifice is identified by trend surface analysis and spectrum imaging methods [27]. A volcanic reservoir has been predicted based on seismic wave impedance [28].

Over the last half a century the Songliao Basin (Figure 1) has been the most productive basin in China for hydrocarbon and the Xujiaweizi fault depression has been proved as a typical volcanic accumulation. Based mainly on the achievements of hydrocarbon exploration in volcanic rocks in the Songliao Basin, the authors reviewed the hydrocarbon-related volcanic impacts, volcanic lithofacies and key geophysical techniques for volcanic accumulation exploration.

2. Volcanism impacts on the formation of oil and gas accumulation

2.1. Volcanic activity provides a catalyst for the evolution of organic matter

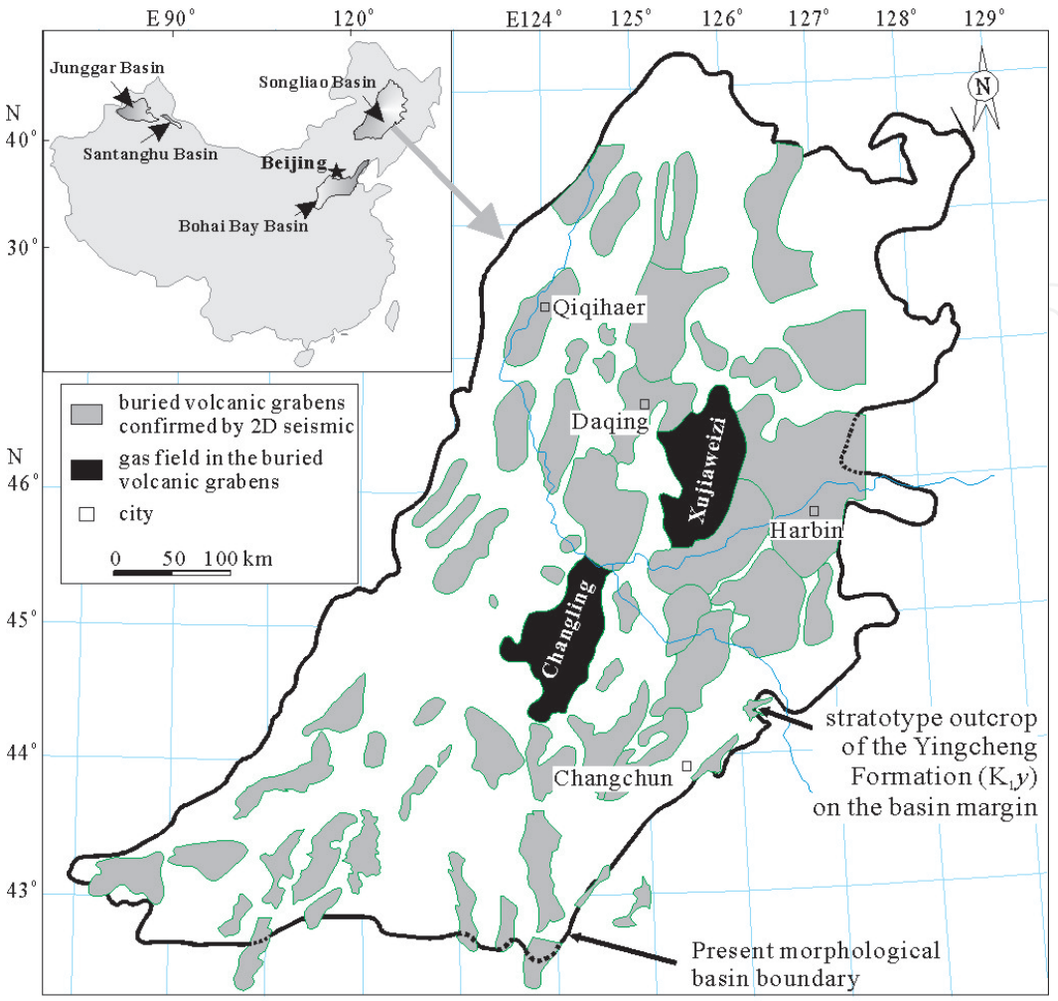
During the transformation from organic matter to hydrocarbon, the role of volcanic is mainly to supply a catalyst and thermal energy. Volcanogenic zeolite and olivine can be a catalyst in turning organic matter into hydrocarbon [29]. Hydrothermal liquid contains many transition metals, such as Ni, Co, Cu, Mn, Zn, Ti, V etc. [30]. The transition metals are catalysts for organic matter thermal degradation [31]. Studies have shown that some volcanic minerals undergo catalysis and hydrogenation which can produce more oil and gas source rocks at lower temperature and pressure. Jin [32] performed a catalysis and hydrogenation experiment on volcanic minerals and source rocks. He used zeolite as a catalyst collected from volcanic rocks, olivine as intermediates of accelerating hydrogen generation and type II and type III organic matter as source rocks. The experimental results show that the hydrogen production rate increased after olivine addition, while when adding zeolite and olivine hydrogen, the production rate still improved. This is due to olivine alteration occuring and reacting with water to produce hydrogen in the organic matter into hydrocarbon conversion process. The reaction is as follows:

$$6(Mg_{1.5}Fe_{0.5})SiO_4 + 13H_2O \rightarrow 3Mg_3SiO_2O_5(OH)_4 + Fe_3O_4 + 7H_2$$

The results show that after the source rocks interact with zeolite and olivine, the production rate of methane improved 2 to 3 times, which is related to the hydrogen increasing. The results also show that the better the organic matter or kerogen types, the higher the production rate of hydrogen and methane. However, the catalytic minerals are not only the clay minerals such as zeolite, but also pyrite.

Pyrite can be found in kerogen commonly, whose mass fraction is closely related to the type of kerogen. The data analysis of the Songliao Basin from Zhang et al. [33] shows that pyrite mass fraction is up to 38% ~ 76% in type I kerogen, which is 10% to 30% in type II kerogen and 2.5% to 3.5% in type III kerogen, i.e., the better the kerogen type, the higher the pyrite mass fraction. Electron microscopy reveals that type I and type II kerogen often closely coexist with pyrite and kerogen, exhibiting obvious zoning around pyrite [34]. Kerogen forms have some

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Stage	Formation	Member	Age (Ma)	Stratigraphic column	Lithology
	Yingcheng (K_1y)	K_1y^4	110		Tuff
Aptian		K_1y^3			Dark basalt
		K_1y^2			sandy conglomerate, intercalated with seam
Barremian		K_1y^1			Tint rhyolite
Hauterivian	Shahezi (K_1s)	K_1s^2	130		Coal bearing tuff
Valanginian					
Berriasian		K_1s^1			Dark fine clastics, coal bearing
Tithonian	Huoshiling (J_3h)	J_3h^2	145		Brown andesite
Kimmeridgian					
Oxfordian		J_3h^1			Bastaltic andesite, tephra, conglomerate and mudstone; coal interbedded.
⋮	Wanbao (J_3w)		158		
Sinemurian	Hongqi (J_3h)				Greysiltstone and mudstone interbed
	Pre-Triassic		192		Carbono-Permians late-phyllite, Caledonian to Yanshan Period granite/diorite, eopaleozoic or Precambrian gneiss/granogneiss.

Figure 1. Geological structure and stratigraphic framework of the fault-depression sequence of the Songliao Basin, China

connection with pyrite forms, different kerogen forms and different pyrite forms: type III kerogen is a mainly contour shape without microcrystal pyrite inclusion; type III kerogen is mainly amorphous with rich microcrystal pyrite inclusion; type II kerogen form is a mixed type whose relative proportion of components change greatly.

Pyrite is the most widely distributed sulphide in the crust, which can be formed in a variety of different geological conditions [35]. Copper containing a pyrite layer hosted in volcanic rock series is the largest pyrite mass fraction deposit, formed by volcanic sedimentation and hydrothermal processes [36]. Although most pyrite in the kerogen is usually of organic origin, pyrite mass fraction in kerogen will undoubtedly be affected by volcanism. Sulphur-rich material provided by the volcanism can increase the sulphur content in an aqueous medium participating in the formation of pyrite related to kerogen, while volcanic rocks or pyroclastic rocks can form pyrite directly [37].

2.2. Volcanic activity provide thermal energy for the evolution of organic matter

The thermal effect of volcanic activity has a dual function on organic matter hydrocarbon generation, which can accelerate the maturation of immature source rocks and hydrocarbon generation [38], and also can make mature source rocks over-mature or destroy oil and gas reservoirs formed earlier [39]. The temperature of magma can be more than 1,000 degrees Celsius [40-41], which of hydrothermal fluid can be up to 300-400 Celsius degree, making it a carrier with large amounts of heat energy. The heat will accelerate the maturity of organic matter [42-44]. Studies at the Illinois Basin by Schimmelmann et al. [45] have shown that R_o values increased from 0.62% to 5.03% within 5 metres at the coal contact to large intrusion, while R_o values increased from 0.63% to 3.71% within 1 metre at the coal contact to small intrusion. George [46] found that intrusion made R_o rise from 0.55% to 6.55% when he investigated the maturity of the Scottish Midland Valley oil shale. Raymond and Murchison [47] found that vitrinite reflectance was significantly higher around bedrock in the carboniferous strata, Midland Valley, Scotland.

The research data show that the igneous body's effect on organic matter maturity incidence is relevant to the igneous body's size. Carslaw and Jaeger [48] thought that the sphere of influence of the intrusion is in the range of 1-1.5 times rock mass thickness. Through the vitrinite reflectance analysis of rocks around intrusion, Dow [49] concluded that influence scope can be up to twice the thickness of the intrusive body. According to the study of sill and dike on the east Siberia platform, Galushkin [50] considered the scope of sill and dike to be in general within 30-50% sill or dike thickness, rarely more than the thickness. Chen [51] thought that influence range of a sill to organic matter is from less than the sill thickness to more than double thickness, even reaching four times the thickness of the sill. Galushkin [50] reached the conclusion that the intensity of intrusion alternation was in the range of 50-90% sill or dike thickness through many analysed examples. Zhu et al. [52] thought that only within a 15m scope, was organic matter obviously affected by sill. When Raymond and Murchison [47] studied the sediments in in carboniferous strata, Midland Valley, he found that vitrinite reflectance of the organic matter in the tuff close to the volcanic neck is significantly higher

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than that in the sedimentary rocks. So the magmatic intrusion effect on the evolution extent of organic matter requires further study.

3. Biogenic and abiogenic hydrocarbon related to volcanic reservoirs

3.1. Organic hydrocarbon generation

The origin of oil and gas has been a long debated theoretical issue. There are two opposing points of view: 1) the organic origin theory and 2) the inorganic origin theory. Organic origin theory considers oil and gas to come from biological processes. Inorganic origin theory explains the origin of oil and gas through inorganic synthesis and mantle degassing. The earliest organic origin theory was proposed by Lomonosov in 1763 [53]. He thought that fertile substances underground, such as oil shale, carbon, asphalt, petroleum and amber, originated in plants. The hydrocarbon formation theory of kerogen thermal degradation proposed by Tissot and Welte [54] and Hunt [55] are the representatives of the organic hydrocarbon generation theory.

The hydrocarbon formation theory of kerogen thermal degradation is based on the diagenesis of organic matter resulting from biopolymers into geopolymers, then kerogen. Kerogen is the main precursor material of oil compounds during the process of hydrocarbon generation, when thermal degradation plays a major role [54]. For sufficient hydrocarbon class and commercial oil gathering, sedimentary rocks must experience the hydrocarbon generation and temperature threshold. Mass hydrocarbons are formed at temperatures from 60 to 150°C by heated organic matter [55]. According to this theoretical model, the sedimentary organic matter maturity, especially for kerogen, becomes the key factor for evaluating hydrocarbon potential. When the threshold burial depth reaches, kerogen will be changed from immature to mature. Oil and gas generates by series of thermal degradation.

Thus the organic origin theory of petroleum has been completely established - it is consistent with the object geological facts, especially the basic law of sedimentary organic matter evolution. The theory has been accepted gradually by the majority of petroleum geologists and plays a major role in oil and gas exploration [56].

3.2. Inorganic hydrocarbon generation

Although organic origin theory has been the guiding theory of modern oil exploration, with foundation of immature oil and ultra-deep liquid hydrocarbon, inorganic origin theory has aroused much attention among geologists. Take the Xujiaweizi area where the Daqing oilfield as an example (Figure 1). Here many reservoirs have been found to contain a lot of alkane gas and non-hydrocarbon gas with inorganic origin, such as CH_4 and CO_2 [57-60]. Carbon isotope of carbon dioxide ($\delta^{13}C_{CO2}$) is an important indicator to identify the carbon dioxide origin, and many domestic and foreign scholars have undertaken research on this [58, 61-64]. Dai [65] pointed out that the $\delta^{13}C_{CO2}$ value is from +7 ‰ to - 39 ‰ in China, in which the organic origin

$\delta^{13}C_{CO2}$ value is from - 10 ‰ to - 39.14 ‰, with the main frequency scope of -12 ‰ ~ -17 ‰; the inorganic origin $\delta^{13}C_{CO2}$ value is from +10 ‰ to -8 ‰ with the main frequency scope of -3 ‰ ~ -8 ‰ (Figure 2). Inorganic origin CO_2 can be divided into mantle-derived, carbonate pyrolysis, magma degassing and so on. The $\delta^{13}C$ value of mantle-derived CO_2 is around - 6‰, which of carbonate pyrolysis is from +3‰ to -3‰. CO_2 volume fraction of Well FS9 in the Xujiaweizi area, Songliao Basin, is 89.73%, and the $\delta^{13}C$ value is from -4.06‰ to -5.46‰. The $\delta^{13}C_{CO2}$ value is -6.61‰ of Well FS6, which confirms that CO_2 of the Xujiaweizi region belongs to the mantle-derived category.

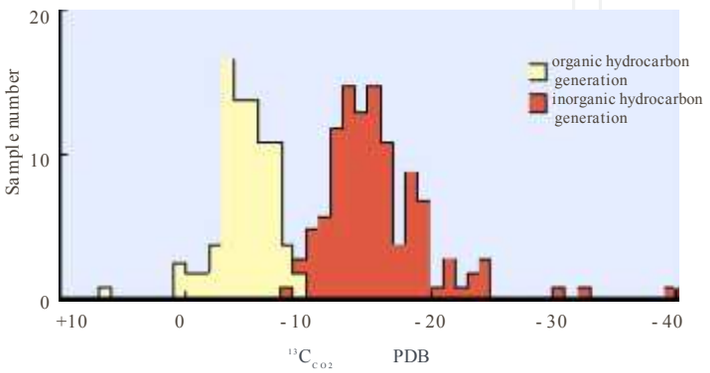


Figure 2. Organic and inorganic origin$\delta^{13}C_{CO2}$ frequency (Dai [62, 65])

4. Volcanic lithofacies related to oil and gas accumulation

Current classification of volcanic lithofacies is mainly based on the style of volcanism or eruptive and/or pyroclast/volcaniclast transport, and corresponds to a modern volcano architecture that forms volcanic rocks [66-70]. The diagenetic process significantly influences the porosity and permeability of volcanic deposits turning to volcanic rocks during burial in a sedimentary basin. According to the characteristics of volcanic rocks and the hydrocarbon exploration situation in the Songliao Basin (Figure 1), Wang et al. [71] introduced a classification system on volcanic lithofacies (Table 1). Volcanic lithofacies are classified as "*5 facies and 15 sub-facies*", and distinguished with representative features. These features include the transportation mechanism and origin, diagenesis style, representative lithology and structure, facies sequence and rhythm, and potential reservoir spaces. The classification emphasizes the relationship between lithofacies and reservoir capability, and will facilitate the recognition of volcanic lithofacies in various scales of outcrop section, well core, well cutting and thin section. Lithofacies can be identified with seismic and logging data by proper correlation. The reservoir capability of volcanic rocks can be primarily evaluated based on their facies and sub-facies.

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Facies	Sub Facies	Material and Transport	Diagenesis	Lithology	Structure	Texture	Sequence	Reservoir Space
V Volcanogenic Sedimentary Facies	V3 Coal-bearing tuffaceous sediment	Tuffaceous pyroclast, plant-enriched turf	Compaction and consolidation	Interbedded tuff and coal seam	Pyroclastic/ clastic structure	Rhythmic bedding, horizontal bedding	Swamp, close to volcanic dome	Intergranular pore, primary and secondary pore, fissure, porosity and permeability similar to sedimentary rock
	V_2 Reworked volcanogenic sediment	Pyroclast reworked by fluid		Layered pyroclastic rocks/ tuff	Pyroclastic structure with rounded gravel, no epi-clast.	Cross bedding, trench bedding, graded bedding, massive	Depression between volcanic domes, conduit-close facies of large volcanic edifice	
	V_1 Epiclast-bearing volcanogenic sediment	Pyroclast dominating with epiclast		Epiclast-bearing tuff (tuffaceous sandy conglomerate)	Pyroclastic / clastic structure with rounded gravel. Few epi-clast		Depression between volcanic domes	
IV Extrusive Facies (late stage of a cycle)	IV3 Outer extrusive sub-facies	Lava front condense, deform, scrap and wrap new and old rocks. The mixture wriggles under internal force	Condensing lava weld new and old rock fragments	Breccia lave with deformed fluidal structure	Welded breccia and welded tuff structure	Deformed fluidal structure	Outer part of extrusive facie, transition to effusive facies	Inter-breccia fissure, micro-fissure, fissure between fluidal structure
	IV2 Middle extrusive sub-facies	Lava with high viscosity flows under internal force, domed near crater.	Lava condense and consolidate (quench)	Massive pearlite and cryptocrystalline rhyolite	Vitric structure, perlitic structure, mortar structure	Massive, layered, lenticular and wrapping	Middle part of extrusive facie	Primary micro-fissure, tectonic fissure, Inter-crystal pore
	IV 1 Inner extrusive sub-facies			Pillow or sphericity shaped perlite		Spherical, pillow, dome	Core of extrusive facies	Inter-perlite sphere space, pores within loosely packing perlite, micro-fissure, Inter-crystal pore
III Effusive Facies (middle stage of a cycle)	III3 Upper effusive sub-facies	Crystals and syn-eruption breccia bearing lava flows on surface under gravity and propelling of subsequent lava	Lava condense and consolidate	Vesicular rhyolite	Spherulitic structure, cryptocrystalline structure, microcrystalline structure	Vesicular, amygdaloidal, lithophysae	Upper part of flow unit	Vesicular, inner space of lithophysae, inner space of amygdaloidal
	III 2 Middle effusive sub-facies			Rhyolite with fluidal structure	cryptocrystalline structure, microcrystalline structure, porphyritic structure	Fluidal structure, few Vesicular-amygdaloidal structure	Middle part of flow unit	fissure between fluidal structure, vesicular, tectonic fissure
	III 1 Lower effusive sub-facies			Cryptocrystalline rhyolite, syn-genetic breccia bearing rhyolite	Vitric structure, cryptocrystalline structure, porphyritic structure, breccia structure	Massive, dashed deformed fluidal structure	Lower part of flow unit	Slaty and wedge joint, tectonic fissure

Facies	Sub Facies	Material and Transport	Diagenesis	Lithology	Structure	Texture	Sequence	Reservoir Space
II Explosive Facies (early stage of a cycle)	II3 Pyroclastic flow deposti	Volatile bearing hot mixture of pyroclast and magma slurry flows on surface under gravity and propelling of subsequent lava	Lava condensation and consolidation as well as compaction	Crystal fragment, vitric fragment and magma slurry and lithic fragment bearing welded tuff (lava); lava cemented polymictic conglomerate	Welded tuff structure, pyroclastic structure	Massive, normal grading, inversed grading, orientated vesicular and vitric, matrix support	Early stage of cycle, Upper part of explosive facies, transition to effusive facies	Intergranular pore, vesicular, loose deposit of condensing unit
	II 2 Base surge deposit	Air ejecting multiphase turbidity of gas-solid-liquid flows rapidly under gravity on surface (maximum velocity: 240km/hour)	Compaction	Crystal fragment, vitric fragment and magma slurry bearing tuff	Pyroclastic structure (crystal fragment bearing tuff structure dominating)	Parallel bedding, cross bedding, regressive sand wave bedding	Middle-lower part of explosive facies, interbedded with air fall deposit, normal grading, thinning bedding upward, cover the palaeo-slope	Loose deposit within volcanic body, intergranular pore, inter-breccia fissure
	II 1 Air fall deposit	Free fall of air ejecting solid and plastic material (under influence of wind)	Compaction	Bomb and pumice bearing agglomerate, breccia, crystal fragment bearing tuff	Agglomerate structure, breccia structure, tuff structure	Granular support, normal grading, trajectory falling blocks	Lower part of explosive facies, normal grading, thinning bedding upward, intercalated bedding	
I Conduit Facies (lower part of a edifice)	I3 Crypto-explosive breccia	Volatile-enriched magma intrudes and explodes within surrounding rocks underground. Surrounding rocks were in-situ broken and cemented by magma. Explosion and cementation function simultaneously.	Cement by condensation of hydrothermal or fine pyroclast	Cyrpto-explosive breccia	Crypto-explosive breccia structure, self-mortar structure, cataclastic structure	Column, layered, dike, branch, fissure filling	Near crater, top of sub-volcanic rock, fingered in surrounding rock	Inter-breccia pore, filled primary micro fissure
	I2 Dikes and sills	Syn or post magma intrusion	Lava condensation and crystallization	Sub-volcanic rock, porphyrite and porphyry	Porphyritic structure, holocrystalline structure.	Chilled border, flow plane, flow line, columnar and tabular, xenolith	Several to fifteen hundreds of meters beneath volcanic edifice, fingered with other lithofacies and surrounding rocks	Slaty and columnar joint, fissure between dike and surrounding rock
	I1 diatreme	Detained lave in conduit, Collapse of crater	Lava condensation, lava welding pyroclast, compaction	Lava, welded breccia/tuff lave, tuff/breccia	Porphyritic structure, welded structure, breccia/tuff structure	Packing structure, ring or radial joint, belted lithology	Diameter of hundreds of meters, vertical occurrence, penetrate other facies	Inter-breccia pore, ring and radial fissure

Table 1. Classification of volcanic facies and corresponding characteristics for each sub-facies

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Sequences of facies and sub-facies assemblage follow certain principles. In the Songliao Basin, the felsic sequences are explosive facies → effusive facies/extrusive facies (probability: 50%±), conduit facies → effusive facies/extrusive facies (probability: 30%±) and explosive facies → conduit facies →extrusive facies/explosive facies (probability: 20%±). The intermediate – basic sequences are effusive facies → explosive facies (probability: 50%±), effusive facies → volcanogenic sedimentary facies (probability: 30%±), effusive facies → explosive facies → volcanogenic sedimentary facies (probability: 20%±). The sequences of felsic rocks inter-bedded with intermediate – basic rocks are more complex and mainly include effusive facies → explosive facies → volcanogenic sedimentary facies (probability: 30%±), explosive facies → volcanogenic sedimentary facies (probability: 20%±), explosive facies → effusive facies → volcanogenic sedimentary facies (probability: 20%±) and effusive facies → conduit facies → extrusive facies (probability: 10%±). Sequences of facies are the basis of volcanic lithofacies modelling, geological interpretation of seismic data and prediction of volcanic reservoir.

According to facies assemblage in drill cores and outcrops, lava of explosive facies and effusive facies can be directly linked to the pyroclastic rocks of volcanogenic sedimentary facies, especially in the proximity of a volcanic conduit, while most volcanogenic sedimentary facies form along volcanic edifice flanks. In general, felsic eruptive sequences start with explosive facies, while in conduit-close regions, they starts with conduit facies (Figure 3).

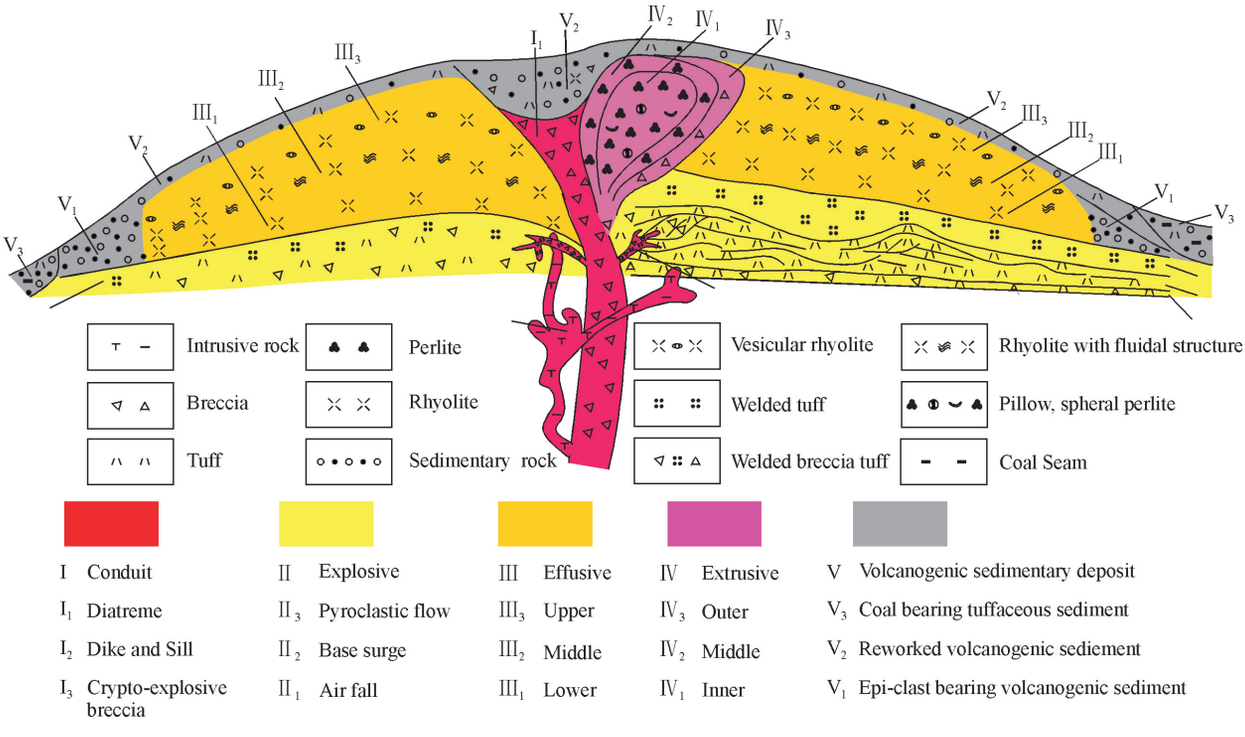


Figure 3. Model of the facies of Mesozoic acidic volcanic rocks in the Songliao Basin, China

Since diagenesis of volcanic lava is condensing consolidation-dominated, its porosity-change influenced by the burial is less pronounced than for sedimentary rocks, thus, volcanic rock will contribute more reservoirs when burying depth exceeds a threshold value. In the Songliao Basin, the threshold burying depth is about 3,500 m. Beneath this depth, sandstone is densely compacted and loses reservoir capability, the reservoir is volcanic rock-dominated. Reservoir spaces within volcanic rocks show complex structures and strongly heterogeneous distribution. Based on observation of well core, cutting and analysis of micro-structure, reservoir spaces of volcanic rocks in the Songliao Basin are classified as primary pores, secondary pores and fissures which include 13 types of elemental components (Figure 4). In general, the reservoir space of volcanic rocks has a dual-component of pore and fissure.

Primary vesicular pores and tectonic joints well develop within upper sub-facies of effusive facies, effectively connected intergranular pores are found within loose deposits between sub-facies of explosive facies, primary fissures and intergranular pores well develop within inner sub-facies of extrusive facies. Exploration of hydrocarbon accumulation in volcanic rocks should target these sub-facies in case of the existence of source rocks and traps.

5. Identification of volcanic reservoirs by well-loggings

Identification of volcanic lithology and lithofacies by logging is primarily based on calibration with drilling cores and cuttings, then logging parameters are used to make cross-plots and frequency distribution histograms. In addtion, logging facies' analysis and FMI image interpretation is used so as to discriminate volcanic rocks as well as their textures and structures.

5.1. Discrimination analysis of volcanic lithology and lithofacies by cross-plots of logging parameters

Cross-plots of logging parameters are simple and effective methods which are generally used to discriminate volcanic lithology and lithofacies in drilled wells [72-73]. Primary logging parameters includ natural gamma (GR), natural gamma-ray spectral logging (U, Th and K), electrical resistivity (RT), NPHI porosity, RHOB density, acoustic log (DT), photoelectric absorption coefficient (Pe) as well as compound parameters M and N. Two of theses parameters are plotted in a X and Y coordinate system, different regions are divided by the concentration of data points, then will be assigned with corresponding geological information. Generally, this method is used firstly on well sections with known lithology and lithofacies, so as to make master plates which are then applied to the other unknown sections in the same area. Applications in the Songliao Basin show that GR-Th, Pe-Th and M-N cross-plots are the most effective methods for discriminations of volcanic lithologies (Figure 5). Moreover, logging facies' analysis and FMI image interpretation are used to identify the textures and structures of volcanic rocks, and then finally determine the discrimination of volcanic lithology and lithofacies in detail.

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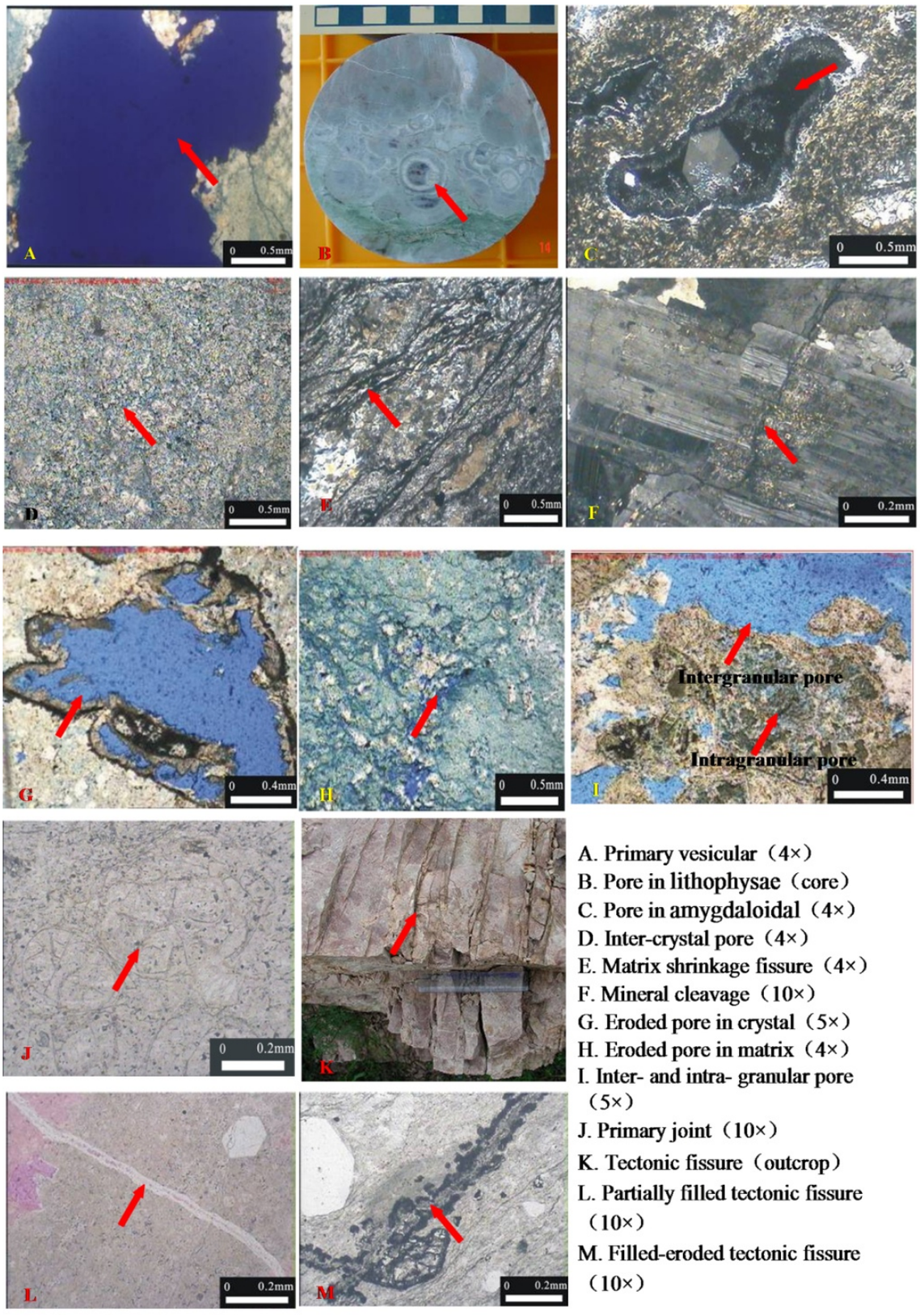


Figure 4. Volcanic reservoir space types

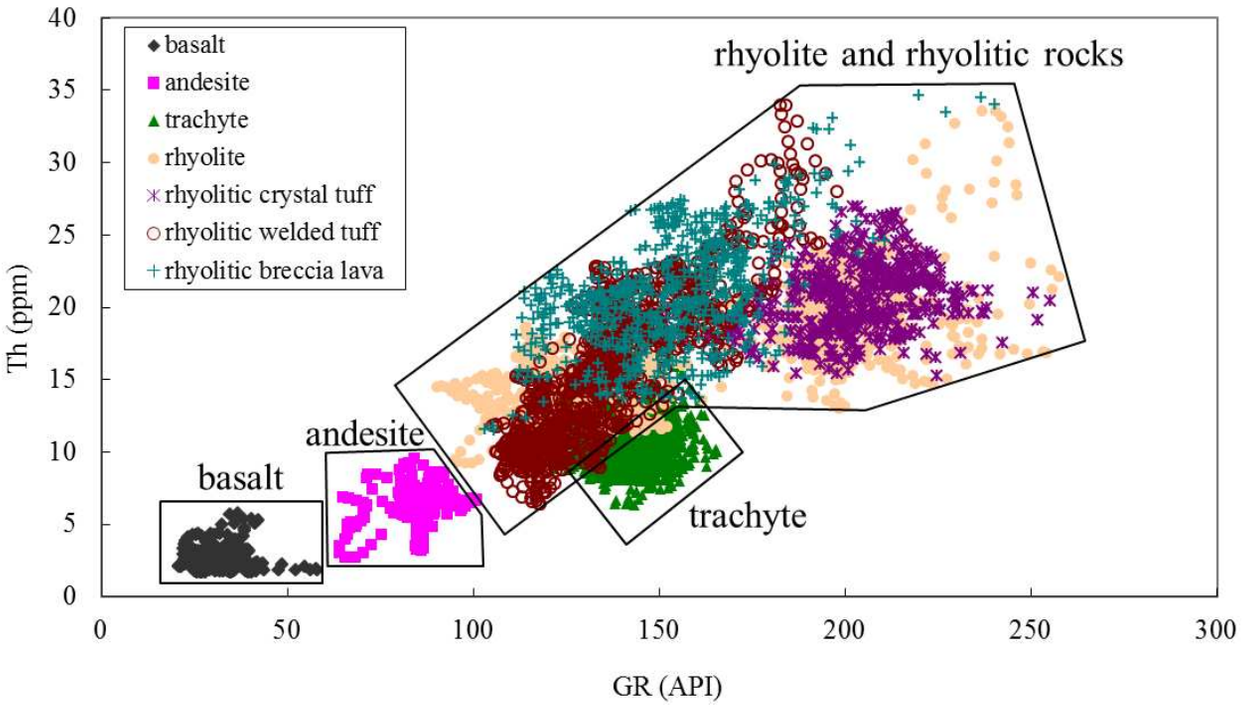


Figure 5. Cross-plot of GR versus Th for lithological identification of volcanic rocks of the Lower Cretaceous Yingcheng Formation in the Xujiaweizi depression, Songliao Basin, China

5.2. Logging facies' analysis of volcanic rocks

Comparative analysis between the volcanic facies and logging facies of drilling core sections is aimed at revealing and summarizing the relationship between geologic properties and logging responses, so as to solve the multiplicity of interpretation by logging parameters, and then set up identification standards of logging facies in the study area. Identification of logging facies is by means of configuration analysis of logging curves including SP, GR, RT, ML, RHOB, as well as dip logging interpretation. Moreover, the standard logging facies could be interpreted as lithofacies on the basis of geologic data.

Electrical conductivity of volcanic reservoirs is mainly influenced by lithology, porosity and permeability, saturation, content of metal elements and also burial depth. Occurrence of hydrocarbons will greatly increase the resistivity, while it will obviously decrease with water. The shape of logging curves and their assemblages are related closely to volcanic lithologies as well as their textures and structures which have become good markers for discrimination of volcanic lithofacies. For massive volcanic rocks, the framework is the main medium of conduction. Under this circumstance, lithology, lithofacies and burial depth are the main controlling factors to the conduction of rocks and changes of logging curve shapes. For example, intermediate-felsic volcanic rocks of vent facies are characterized with high-GR and mid-RT, and their logging curves appear as a high amplitude dentiform and peak shape. While basalts of volcanic vent facies show low-GR and the tuff displays low-RT.

The Mesozoic volcanic rocks are the most important gas reservoirs in the northern Songliao Basin. Five lithofacies and 15 sub-facies have been recognized in the volcanic rocks. The best reservoirs were generally found in three of the 15 sub-facies including pyroclastic bearing lava flow, upper effusive and inner extrusive sub-facies. The corresponding logging characteristics are as follows. The pyroclastic rock-bearing lava flow sub-facies show high-GR values with high amplitude dentiform and medium to mid-high RT with low frequency, low amplitude dentiform. The upper effusive sub-facies show high GR with high amplitude dentiform and mid-high RT with finger and peak shapes. The inner extrusive sub-facies show high GR with medium amplitude dentiform and mid-high to high RT with medium amplitude dentiform. In addition, crypto-explosive and outer extrusive sub-facies may also be good reservoirs. The occurrence of hydrocarbons will cause a remarkable increase of resistivity, while water does the contrary. The changing of resistivity without influence of fluids from low to high are respectively followed as volcanogenic sedimentary facies, extrusive facies, explosive facies, volcanic conduit facies and effusive facies [74].

5.3. Identification of volcanic textures and structures by FMI image interpretation

With the characteristics of high resolution, total borehole coverage and visibility, FMI image interpretation may reveal continuous geologic information such as lithology, textures and structures, as well as pores and fractures by means of calibrations with drilling core sections. Sizes and shapes of volcanic breccia and conglomerates, as well as features of rock structures and beddings, can give much geologic information on volcanic lithofacies and pore spaces, especially for well sections lacking drilled cores [75-77].

Features displayed by FMI images of volcanic rocks are the synthesized effects of logging response units including volcanic fragments, framework, fractures and pores. On the FMI images, bright tone corresponds to high resistivity, while dark tone relates to low resistivity, and warm colours, such as yellow and orange, indicate medium resistivity (Table 2).

Image type	Tone	Resistivity	Geological interpretation
static	bright (white)	high	massive structure
	dark (brown, black)	low	fractures and pores
	mottle	heterogeneous	heterogeneous rock mass
dynamic	bright (white)	high	volcanic breccias, rock fragments, crystal fragments, magma fragments, amygdala
	yellow, orange	middle	rock matrix or framework
	dark (brown, black)	low	fractures and pores

Table 2. Image interpretation of volcanic imaging logging (Li et al. [72])

Comparatively, rock fragments generally display bright tones due to high resistivity, while matrix shows dark as a result of low resistivity, and these features are common in pyroclastic lava rocks and pyroclastic rocks. The transformation of bright and dark zones on a FMI image not only indicates resistivity changes, but also reflects the contact relations among different parts of rocks. Descriptions of drilled cores reveal that there is great difference between volcanic fragments (breccia, conglomerates, rock fragments, crystal fragments and magma fragments) and their surrounding matrix (lava framework or volcanic ash) due to distinguishing colour, content and shape, which may result in colour diversities of the FMI images according to resistivity changes. Standard interpretation models of volcanic textures and structures which are used to identify lithofacies have been summarized through calibrations of FMI images with geologic information, for example, lava texture, welded texture, tuff texture, breccia texture and massive structure, vesicular-amygdaloidal structure, flow structure (Figure 6).

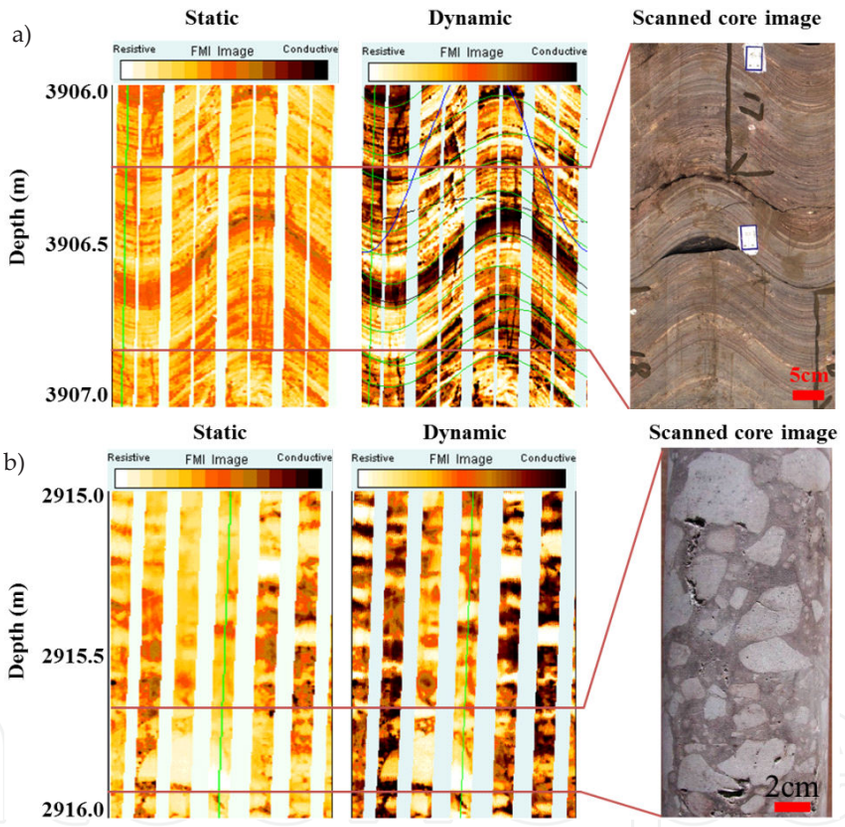


Figure 6. Typical lithological structures on FMI logging image. a) Flow bandings of extrusive rhyolite; b) Volcanic breccia structure of explosive facies.

6. Identification of volcanic reservoirs by seismic data

At the exploration stage, the volcanic facies mapping relies mainly on the artificial seismic facies' analysis and is under the control of well facies or according to an experience template,

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converted into a volcanic facies map. At the development stage, the volcanic facies planar prediction relies mainly on the waveform classification method for obtaining the seismic facies map. The volcanic facies is interpreted under the control of facies of wells and the volcanic edifice belts [78-79]. This method can identify the volcanic facies and its combination. Now it is widely used in the volcanic exploration of the Songliao Basin. The waveform classification method of volcanic facies' identifying is explained in this paper.

The actual seismic facies were calculated by combining different amplitude, frequency, phase and time intervals. A seismic facies map can be obtained by the waveform classification calculation. Volcanic facies is predicted through observing the combination and distribution characteristics of the model trace in the seismic facies map. The number of waveform classifications (model trace) can be ensured by the seismic characteristics of volcanic facies. After that, we conduct the waveform classification experiment by selecting multiple waveform classifications or by using different thickness of time intervals. Lastly, the stability of the calculation results need be checked. The optimal time interval of the waveform classification calculation is between half a wavelength to two wavelengths.

Taking the volcanic rocks of the upper Yingcheng Formation in the Changling rift YYT work area of the southern Songliao Basin as an example (Figure 1), we introduce the prediction method of the volcanic facies plane. The volcanic facies is predicted by selecting 7 or 15, respectively, as the number of waveform classification. The prediction results of volcanic facies show good consistency. Volcanic facies is predicted by number waveform classification being set to 7. Firstly, overlap the volcanic seismic facies maps with the structure maps. The results show that, in some high tectonic areas, the waveforms characteristics of the seismic facies have unorganized distribution, but in the relatively flat tectonic area, the waveforms characteristics of seismic facies show continuous distribution. Next, the waveform classification characteristics of the seismic facies can be calibrated with well facies, the waveform characteristics of seismic facies in the central region of volcanic edifices are multi-waveform clutter distribution, while the waveform characteristics of the far-source area far away from the centre of volcanic edifices are continuous distribution (Figure 7). In this way, the centre's facies belt (volcanic conduit / effusive facies) distribution of volcanic edifices can be predicted. The different waveforms' seismic facies are calibrated by volcanic facies revealed by the well. A waveform classification planar map should be converted to the volcanic facies map. The seismic characteristics of volcanic conduit facies and its combination are rounded, massive, banded and messy reflection, in the edge is ring banded. The seismic characteristics of explosive facies and their combination are banded, messy, good continuous reflection. The seismic characteristics of effusive facies and their combination are mottled massive, middle-bad continuum reflection. According to the seismic characteristics, volcanic facies planar distribution is identified in the YYT area. The effusive facies distribution is dominating, and the explosive facies distribution is less. The effusive facies distribute mainly on both sides of the central fault. Explosive facies distribute mainly in the southeast far away the central fault. There are two volcanic facies sequences, one is the volcanic conduit facies-effusive facies, the other is the volcanic conduit facies-explosive facie/volcanic sedimentary facies.

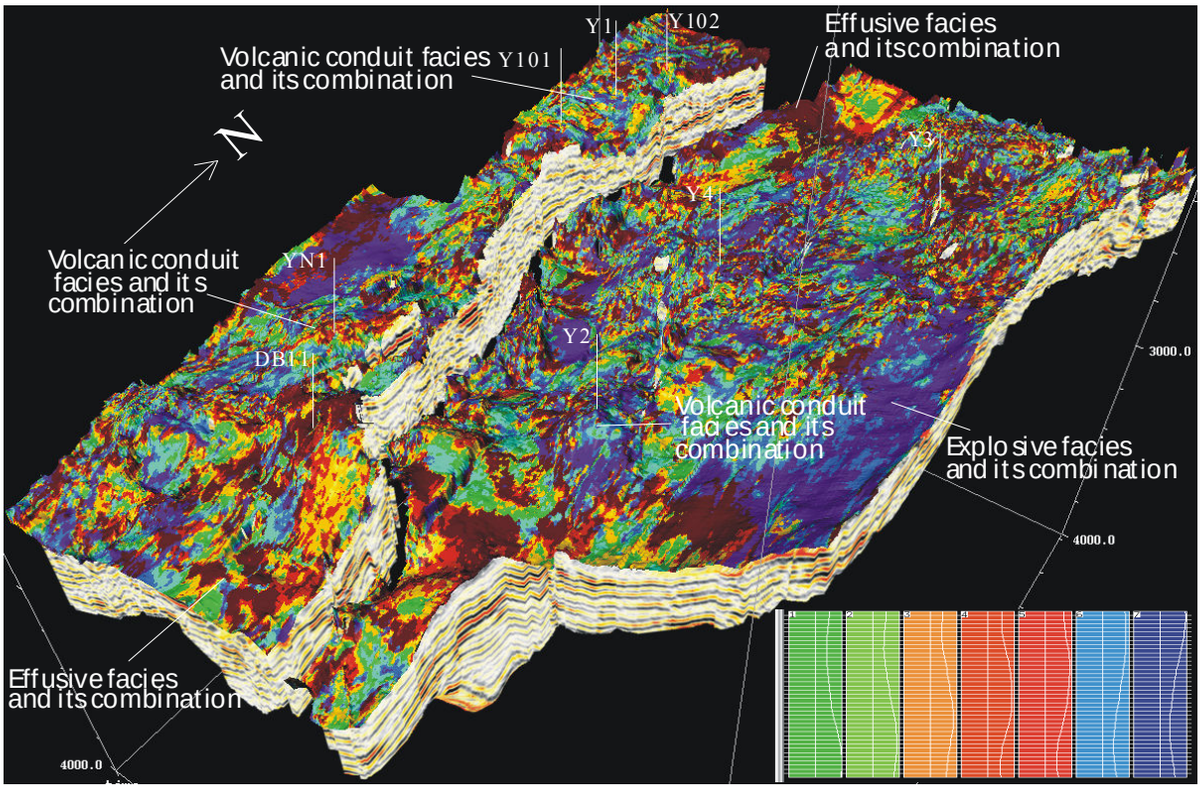


Figure 7. Waveform classification (seismic facies) map of volcanic rocks of the upper Yingcheng Formation in the YYT work area

7. Mechanism and geological occurrence of oil and gas accumulation

Volcanic oil and gas reservoirs are mainly not only accumulations in volcanic rocks, but also those hydrocarbon reservoirs with volcanic rocks as seals or forming traps. The formation and distribution of hydrocarbon accumulations in volcanic rocks is different from non-volcanic (silici-)clastic rocks. Since volcanic rocks cannot produce hydrocarbons, neighbouring source rocks are essential to the formation of oil and gas accumulations in volcanic rocks, thus it will be more favourable for better matching relationships between volcanic reservoirs and source rocks [80-81].

7.1. Volcanic rocks as oil and gas reservoirs

Since the porosity and permeability of volcanic rocks do not decrease remarkably according to the increase of burial depth, they are more favourable for hydrocarbon accumulations compared to sedimentary rocks in the deep part of the basin. So far, hundreds of volcanic reservoirs, such as the Niigata Basin in the Honshu Island of Japan [82], Austral and Neuquen Basins of Argentina [7] and the Bohai Bay Basin, Songliao Basin and Junggar Basin in China have been found [5, 24, 71, 81]. As a whole, the volcanic reservoirs are mostly Cenozoic and Mesozoic, especially Jurassic, Cretaceous and Tertiary, which may be related to the frequent

global volcanism in these epochs. As revealed by petroleum explorations, occurrences of hydrocarbons have been found in almost all types of volcanic rocks, and in detail, basalts have the largest proportion while the rest follow as andesite, rhyolite and pyroclastic rocks [83]. Prolific volcanic reservoirs have been found in explosive, extrusive and volcanic-sedimentary facies, while considering inside a volcanic edifice, they have generally the best reservoir properties in volcanic vents and near vent facies [71, 84]. Vertically, favourable reservoirs are developed in the upper part of volcanic sequences due to post-eruption weathering, leaching and dissolving [85].

7.2. Formation of oil traps related to volcanic activities

Besides being reservoirs, volcanic rocks can also be good cap rocks. After volcanic ash falls into water, it will inflate and form layers of bentonite or mudstone with bentonite which may become excellent cap rocks [86]. While mudstone lacks sealing abilities in the mid-shallow part of basins, unaltered massive basalts are generally rather better cap rocks, taking the Scott Reef oil field in the Browse Basin of Australia and Eastern Sag in the Liaohe Basin of China as examples [2, 24]. Some layered intrusive rocks may also be good cap rocks, for example, the Lin 8 oil trap in the Huimin depression of the Bohai Bay Basin, north China [87]. In the deep part of the Xujiaweizi depression of the Songliao Basin, two types of volcanic rocks have been found to be cap rocks including the pyroclastic type and lava type. Due to better sealing abilities, the pyroclastic type cap rocks control the regional accumulation and distribution of gas in volcanic reservoirs, while the lava type only control the local accumulation and distribution of gas in volcanic rock bodies [88]. Besides, diverse oil and gas traps can be formed by the local structures of intrusions as well as their matching with sedimentary layers, commonly forming arched uplifts and lateral barriers [24, 89].

All aspects of the common hydrocarbon accumulating conditions and their favourable matching relationships are also necessary to the volcanic oil and gas reservoirs. So far, most of the discovered volcanic oil and gas reservoirs are structural-lithologic and stratigraphic. Near-source accumulations are formed when volcanic rocks emplace close to source rocks, developing concentration zones of volcanic oil and gas reservoirs. While there is a long distance between source rocks and volcanic rocks, certain accumulations may also form due to communications of faults and unconformities. There are two accumulation patterns divided by volcanic reservoir forming conditions such as near-source play and distal play [81]. Near-source plays are mostly discovered in eastern Chinese depressions, for example, the Paleogene mafic volcanic rocks in the Bohai Bay Basin and the Lower Cretaceous felsic volcanic rocks which developed prolific oil and gas accumulations emplaced right on the top of high-quality source rocks. Both near-source and distal plays are found in western Chinese basins, for instance, volcanic rocks and source rocks have developed together in carboniferous-Permian of the Junggar and Santanghu Basins which formed near-source plays, and the source rocks mainly developed in the Lower Paleozoic while the reservoir volcanic rocks emplaced in the Permian, thus forming distal plays in the Sichuan and Tarim Basins (Figure 8).

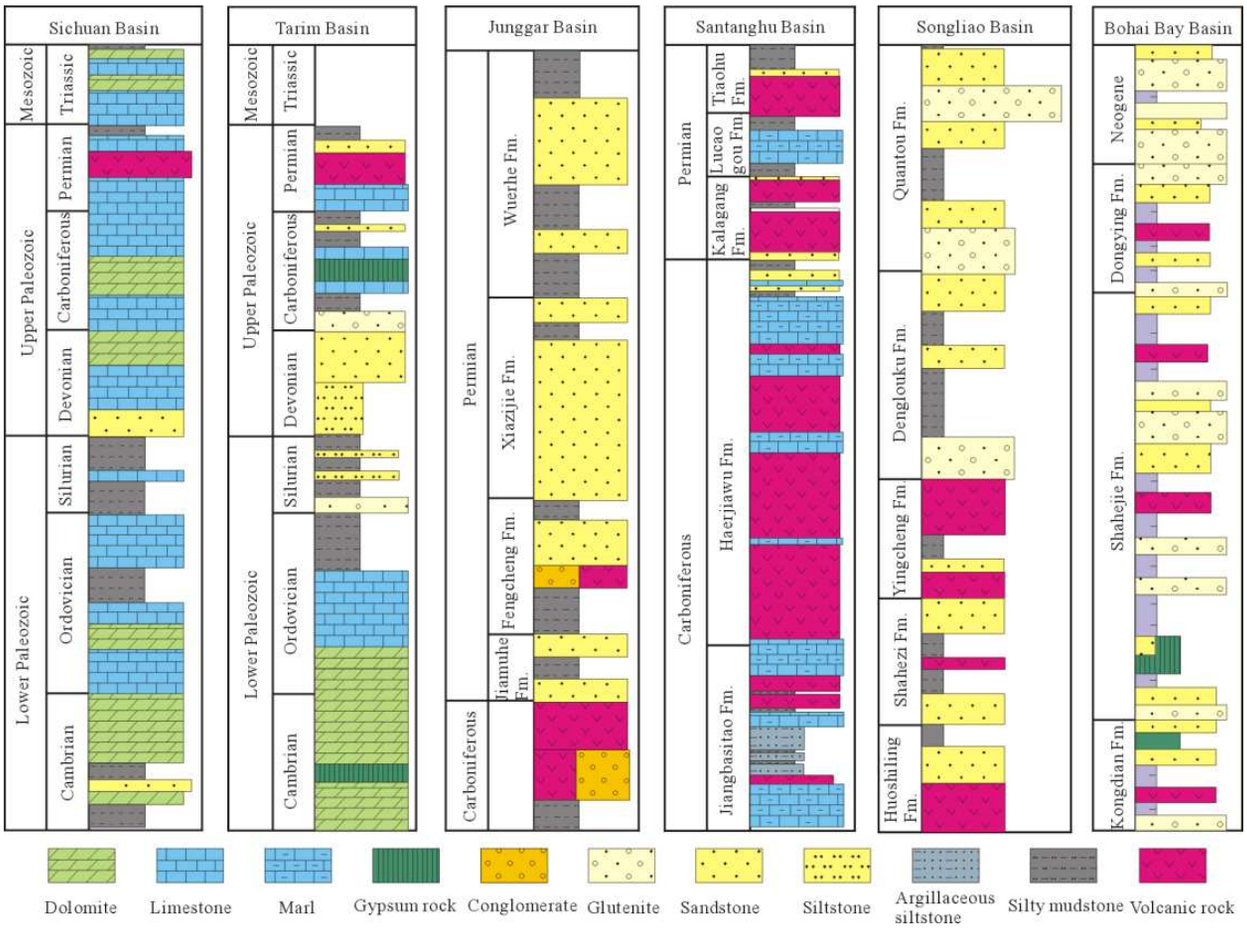


Figure 8. Source-reservoir-cap assemblages of the volcanic oil and gas accumulations in main petroliferous basins of China (Zou et al. [81])

8. Exploration of volcanic accumulation of oil and gas

8.1. The characteristics of volcanic oil and gas accumulation

The characteristics of volcanic oil and gas accumulation mainly include volcanic reservoirs and reservoir forming elements. Taking the characteristics of volcanic oil and gas accumulation in the Songliao Basin as an example, volcanic gas accumulation can be classified into acid type and intermediate-basic type by lithology. By the characteristics of volcanic edifices, these two types mentioned above can be furthe rclassified into six sub-types, including acid pyroclastic sub-type, lava sub-type, complex sub-type and intermediate-basic pyroclastic sub-type, lava sub-type, complex sub-type. Great differences have been discovered in developmental degrees among the types in the volcanic gas accumulation (Figure 9). The acid and intermediate-basic lava sub-types account for 72% of volcanic gas accumulation of the Yingcheng Formation in the north of the Songliao Basin, and the contribution degree of acid lava sub-type can reach 50%. The acid type accounts for 92% of volcanic gas accumulation in the south of the Songliao

Basin, while only the intermediate-basic lava sub-type gains industrial gas. The highest deliverability in a single well is gained in the acid complex sub-type; the deliverability of the intermediate-basic type is lower than the acid type. There are few differences among the intermediate-basic pyroclastic sub-type, lava sub-type and complex sub-type. However, there are great differences among the acid pyroclastic sub-type, lava sub-type and complex sub-type.

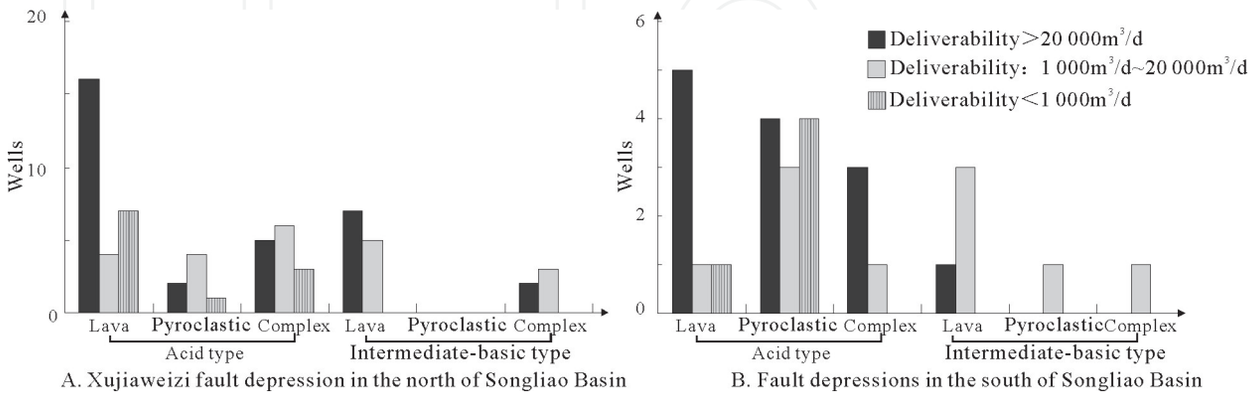


Figure 9. The relationship between hydrocarbon accumulations and volcanic edifices in the Songliao basin

By analysing the relationship between reservoirs and reservoir forming structures, most of the volcanic gas accumulations are structural-lithologic gas accumulations. The gas mainly originated from the mud and coal-bearing strata of the early Cretaceous Shahezi Formation and Huoshiling Formation. The fluid transforming system is made up by the faults, joints and high porosity-permeability transforming zones. The distribution range of gas layers is not absolutely controlled by the structural trap. When above the water-gas contact (WGC), the high porosity-permeability zone forms a gas layer, the medium-low porosity-permeability zone forms a poor gas layer and the zone which has fewer pores and fractures forms a dense layer or baffle layer. The proportion of poor gas layers increases gradually from the acid complex type to the acid pyroclastic sub-type to intermediate-basic lava sub-type (Figure 10). WGC is an uneven contact surface caused by the peculiarity of the stratigraphic construction of volcanic edifices. There are great differences in shape among the different volcanic edifices. The gas thickness of acid pyroclastic sub-type and acid complex sub-type changes little, forming a tabular and sill-like shape. There are great changes in the gas thickness of intermediate-basic lava sub-type, the maximum thickness is 2~3 times thicker than the minimum thickness and forms a mound or wedge shape. Moreover, in the same gas layer, the deliverability is also different in the different locations.

8.2. The reservoir forming elements of volcanic oil and gas accumulation

By the comparison between industrial gas wells and other wells, the advantages of forming high production gas include reservoir space diversity, high porosity, good source rocks, anticlinal /faulted anticline traps and the vertical migration pathway. The reservoir forming effects will be poor once one of the above conditions is absent.

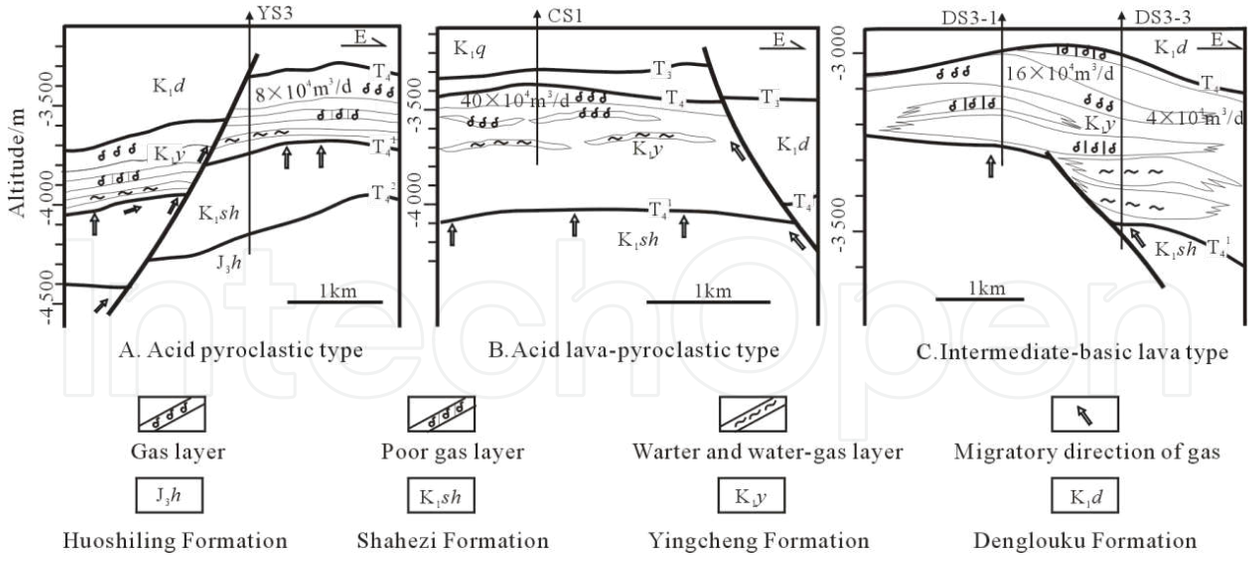


Figure 10. Forming pattern of gas pools of volcanic edifices in the Songliao Basin

For example, although having good source rocks, a DB10 well only gains low producing gas because of unitary reservoir spaces and poor porosity-permeability. A YN1 well does not even gain industrial gas because of poor source rocks and porosity-permeability despite having diversiform reservoir spaces. An SS1 well has good porosity-permeability and diversiform reservoir spaces, while its source rock is poor, it does not gain industrial gas. The wells show that overlying strata on the volcanic rocks of the Yingcheng Formation can be regional caps in the Songliao Basin and there are a wealth of high angle joints and faults in the volcanic rocks of the Yingcheng Formation. So the main reservoir forming elements of volcanic gas accumulation include effective source rocks, faults connecting to the source rocks and reservoir porosity-permeability.

9. Summary

Hydrocarbon exploration in volcanic rocks is a relatively new and important topic today. As a typical example in China, the Songliao Basin has been introduced here.

Natural transformation from organic matter to hydrocarbon is a slow process. This slow process can be accelerated by volcanic heat that is the thermal effect of volcanic activity. In addition, it can also be catalyzed by volcanogenic minerals, such as zeolite and olivine, and transition metals in hydrothermal liquid, such as Ni, Co, Cu, Mn, Zn, Ti, V, etc.

The origin of natural gas hosted in volcanic reservoirs can be both biogenic and abiogenic. In the Songliao Basin of China, most of hydrocarbon has been proved as having organic derivation, a few alkane gas and non-hydrocarbon gas have inorganic derivation. The origin of hydrocarbon can be distinguished with isotopes such as C and He.

Volcanic gas accumulation type		Primary pore		Secondary pore		Trap type	Migration type	Relations among source, reservoir and cap	Deliverability $10^4m^3/d$	Typical well (Formation)
Type	**Sub-type**	**Pore**	**Fracture**	**Pore**	**Fracture**					
Acid	Pyroclastic	Intergranular pore, Intercrystalline pore, Intercentric pore (breccia)	Crash fractures, width : 0.1 mm , filling degree: 95%	/	High-angle fractures, width : 1~2 mm, upper part with no fill, lower part filled by calcite filling degree: 100%	faulted anticline trap	vertical	self generation and self preservation, lower generation and upper preservation	8	YS3 (k_1y)
		Interbreccial pore, Corrosion pore	Intercrystalline crash fractures	Dissolved pore	High-angle fracture	fault nose trap	lateral, vertical	self generation and self preservation, lower generation and upper preservation	gas show	SS1 (k_1y)
	Lava	Intercentric pore	Crash fractures	/	Joints and high-angle fracturesfilling degree: 80%	fault nose trap	lateral	self generation and self preservation	gas show	YN1 (k_1y)
		Vesicle, Intercentric pore	Intercrystalline crash fractures	/	High-angle fractures and oblique crossing fractures, reticular partly, width: 0.5~2 mm	anticline trap	lateral vertical	self generation and self preservation, lower generation and upper preservation	30	YS2 (k_1y)
	Complex	Vesicle, Interbreccial pore, Corrosion pore	Intercrystalline crash fractures	Dissolved pore	high-angle fractures and Joints	anticline trap	lateral vertical	self generation and self preservation, lower generation and upper preservation	40	YS1 (k_1y)
		/	Crash fractures, filled by calcite	/	Branched fractures, width:1 cm, filled by red magma, filling degree: 30%~100%	fault nose trap	lateral vertical	self generation and self preservation, lower generation and upper preservation	gas show	YS4 (k_1y)
intermediate-basic	Pyroclastic	Interbreccial pore, vesicle (breccia)	Crash fractures	Dissolved pore	High-angle structural fractures	anticline trap	vertical	lower generation and upper preservation	5.6	DS3 (k_1y)
	Lava	Micro-vesicle	/	/	High-angle fractures, width: 2~30 mm, filled by calcite, filling degree: 10%~100%	fault nose trap	lateral vertical	self generation and self preservation, lower generation and upper preservation	0.4	DB11 (k_1y)
		Amygdale, vesicle, Interbreccial pore	Crash fractures	/	Reticular fractures, width:2~50 mm, filled by calcite, filling degree: 10%~100%	anticline trap	lateral vertical	lower generation and upper preservation	4.2	DX5,DS3-1 (k_1y)
	Complex	Amygdale, vesicle,	/	/	Reticular fractures, width:2~5 cm, filled by calcite, filling degree 10%~100%	anticline trap	lateral vertical	lower generation and upper preservation	5.0	DS4 (k_1y)

Notes:"/"shows not discovered by the cores/debris, k_1y is Yingcheng Formation ofLower Cretaceous

Table 3. The characteristics of gas pool forming of volcanic edifices of faulted sequences in the Songliao Basin

Volcanic lithofacies can be classified into "*5 facies and 15 sub-facies*" with respect to the lithification mechanism and reservoir significance. In general, a felsic sequence starts with explosive facies, and an intermediate – basic sequence starts with effusive facies. The reservoir spaces of volcanic rocks are composed of primary pores, secondary pores and fissures. The upper part of effusive facies, loose intercalation in between explosive facies, and inner sub-facies of extrusive facies are the main targets for hydrocarbon exploration in the Songliao Basin because of their good porosity and permeability.

Volcanic lithology and lithofacies in drilled wells are effectively discriminated with cross-plots of different logging parameters. The most effective methods are GR-Th, Pe-Th and M-N cross-plots for lithological discrimination. Lithofacies are characterized by GR and RT with respect to amplitude, outer shape and frequency. The texture and structure information of volcanic rocks can be depicted with FMI images.

The spatial distribution of lithological and lithofacies associations can be characterized by seismic parameters, such as amplitude, frequency, phase and time intervals. Seismic facies are mapped with waveform classification between half a wavelength to two wavelengths. Geological facies are interpreted from seismic facies coupled with core section description and well-log information.

Volcanic rocks mainly act as reservoir or seal rocks in hydrocarbon accumulations. Most of the discovered volcanic oil and gas reservoirs are structural-lithologic and stratigraphic. Source rocks are essential to the formation of oil and gas. Although plays of proximal facies are predominant, distal facies have also been discovered to be productive in the Songliao Basin.

Porosity and permeability in volcanic rocks are more heterogeneous than sedimentary rocks. High resolution data are necessary for hydrocarbon exploration in volcanic rocks. Furthermore, diagenesis of volcanic rocks is one of the most important topics in the future because it is the controlling factor on the porosity and permeability of volcanic reservoirs.

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Author details

Jiaqi Liu[1], Pujun Wang[1*], Yan Zhang[1], Weihua Bian[1], Yulong Huang[1], Huafeng Tang[1] and Xiaoyu Chen[2]

*Address all correspondence to: WangPJ@jlu.edu.cn

1 College of Earth Sciences, Jilin University, Changchun, China, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China

2 Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China

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