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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...
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 Xujiawei 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 occurring and reacting with water to produce hydrogen in the organic matter into hydrocarbon conversion process. The reaction is as follows:

\[
6\left(\text{Mg}_{1.5}\text{Fe}_{0.5}\right)\text{SiO}_4 + 13\text{H}_2\text{O} \rightarrow 3\text{Mg}_3\text{SiO}_2\text{O}_5\text{(OH)}_4 + \text{Fe}_3\text{O}_4 + 7\text{H}_2
\]

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

| Stage      | Formation     | Member | Age (Ma) | Stratigraphic column | Lithology                                           |
|------------|---------------|--------|----------|----------------------|-----------------------------------------------------|
| Aptian     | Yingcheng    | K1y    | 100-110  |                      | Tuff                                                |
|            | (K1y)         | K1y1   |          |                      | Dark basalt                                          |
|            |               | K1y2   |          |                      | Sandstone, intercalated with siltstone              |
| Jurassic    | Baoshan       | K2b    | 130-150  |                      | Tuff                                                 |
|            | (K1b)         | K2b1   |          |                      | Coal bearing tuff                                   |
|            |               | K2b2   |          |                      | Dark fine clastics, coal bearing                     |
| Cretaceous | Zhaoling      | K1z    | 145-150  |                      | Brown andesite                                       |
|            | (K1z)         | K1z1   |          |                      | Bivalve, bivalve, tephra, conglomerate, and mudstone; coal interbedded |
|            |               | K1z2   |          |                      | Oolitic, and mudstone interbedded                    |
| Carboniferous | Wanshan       | K1w    | 150-190  |                      | Oolitic, and mudstone interbedded                    |
|            | (K1w)         | K1w1   |          |                      | Carboniferous, late-phyllosite, Caledonian to Yanshan Period; granite/diorite, syenite/leucite or Precambrian gneiss/granogranite |
|            |               | K1w2   |          |                      |                                                     |
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.
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 Xujiawei 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 CH₄ and CO₂ [57-60]. Carbon isotope of carbon dioxide (δ¹³C 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 δ¹³C CO₂ value is from +7 ‰ to - 39 ‰ in China, in which the organic origin
\( \delta^{13}C_{CO_2} \) value is from -10‰ to -39.14‰, with the main frequency scope of -12‰ ~ -17‰; the inorganic origin \( \delta^{13}C_{CO_2} \) 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 \( \delta^{13}C_{CO_2} \) 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\( \delta^{13}C_{CO_2} \) frequency (Dai [62, 65])](image)

### 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.
### Volcanogenic Sedimentary Facies

| Facies | Sub-Facies | Material and Transport | Diagenesis | Lithology | Structure | Texture | Sequence | Reservoir Space |
|--------|------------|------------------------|------------|-----------|-----------|---------|----------|----------------|
| V3     | Coal-bearing tuffaceous pyroclast | Tuffaceous pyroclast, plant-enriched tuff | 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 |
| V2     | Pyroclast reworked by fluid | Compaction and consolidation | Pyroclastic tuff | Pyroclastic structure with rounded gravel, no epilast | Cross bedding, trench bedding, graded bedding, massive | Depression between volcanic domes, conduit-close facies of large volcanic edifice | |
| V1     | Pyroclast dominating with epilast | | Tuffaceous pyroclast, plant-enriched turf | Epilastic structure with rounded gravel. Few epilast | | Depression between volcanic domes | |

### Extrusive Facies (late stage of cycle)

| IV 3 | Outer extrusive sub-facies | Lava front condense, deform, warp and wrap new and old rocks. The mixture wriggles under internal force | Condensing lava weld new and old rock fragments | Breccia lava with deformed fluidal structure | Welded breccia and welded tuff structure | Deformed fluidal structure | Outer part of extrusive facies, transition to effusive facies | Inter-breccia fissure, micro-fissure, fissure between fluidal structure |
| IV 2 | Middle extrusive sub-facies | Lava with high viscosity flows under internal force, domed near crater. | Lava condense and consolidate (quench) | Pillow or spherically shaped perlite | Vitric structure, perlitic structure, mortar structure | Massive, layered, lenticular and wraping | Middle part of extrusive facies | Primary micro-fissure, tectonic fissure, Inter-crystal pore |
| IV 1 | Inner extrusive sub-facies | | | | | | Core of extrusive facies | Inter-perlite sphere space, pores within loosely packing perlite, micro-fissure, Inter-crystal pore |

### Effusive Facies (middle stage of a cycle)

| III 3 | Upper effusive sub-facies | Crystals and syn-eruption breccia bearing lava | Lava condense and consolidate (quench) | Rhyolite with fluidal structure | Vitric structure, cryptocrystalline structure, microcrystalline structure | Viscous, amygdaled, lithophysae | Upper part of flow unit | Viscous, inner space of lithophysae, inner space of amygdaled |
| III 2 | Middle effusive sub-facies | Rhyolite flows on surface under gravity and propelling of subsequent lava | Lava condense and consolidate | Rhyolite with fluidal structure | Cryptocrystalline structure, microcrystalline structure, porphyritic structure | Fluidal structure, few Veiculair-amygdaloidal structure | Middle part of flow unit | Fissure between fluidal structure, vesicular, tectonic fissure |
| III 1 | Lower effusive sub-facies | Cryptocrystalline rhyolite, syngenetic breccia bearing rhyolite | Lava condense and aggregate | Rhyolite with fluidal structure | Vitric structure, cryptocrystalline structure, porphyritic structure, breccia structure | Massive, deformed fluidal structure | Lower part of flow unit | Slaty and wedge joint, tectonic fissure |

### Effusive Facies (middle stage of a cycle)

| III 3 | Upper effusive sub-facies | Crystals and syn-eruption breccia bearing lava | Lava condense and consolidate (quench) | Rhyolite with fluidal structure | Vitric structure, cryptocrystalline structure, microcrystalline structure | Viscous, amygdaled, lithophysae | Upper part of flow unit | Viscous, inner space of lithophysae, inner space of amygdaled |
| Facies | Sub Facies | Material and Transport | Diagenesis | Lithology | Structure | Texture | Sequence | Reservoir Space |
|--------|------------|------------------------|------------|-----------|-----------|---------|----------|----------------|
| II     | Explosive Facies (early stage of a cycle) | Air ejecting multiphase turbidity of gas-solid-liquid flows rapidly under gravity on surface (maximum velocity: 240km/hour) | Compaction | Crystal fragment, fragment bearing tuff | Pyroclastic structure, 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 pore |
| II 2   | Base surge deposit | Air ejecting | Compaction | Crystal fragment, fragment 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 pore |
| 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 | Fissure |
| I      | Conduit Facies (lower part of a edifice) | Detained lave in conduit, Collapse of crater | Lava condensation, welded tuff/breccia, compaction | Sub-volcanic rock, welded breccia/tuff, tuff | Porphyritic structure, welded 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 |
| I 2    | Dikes and sills | Syn or post magma intrusion | Lava condensation, welded tuff/breccia, compaction | Sub-volcanic rock, welded breccia/tuff | Porphyritic structure, welded 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 |
| I 3    | Crypto-explosive breccia | \[1.3\] | | | | | | |
| I 4    | Diatreme | Detained lava in conduit, Collapse of crater | Lava condensation, welded tuff/breccia, compaction | Sub-volcanic rock, welded breccia/tuff | Porphyritic structure, welded 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.
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%±), explosive facies → effusive 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 addition, 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 include 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 these 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.
Figure 4. Volcanic reservoir space types

A. Primary vesicular (4×)
B. Pore in lithophysae (core)
C. Pore in amygdaloideal (4×)
D. Inter-crystal pore (4×)
E. Matrix shrinkage fissure (4×)
F. Mineral cleavage (10×)
G. Eroded pore in crystal (5×)
H. Eroded pore in matrix (4×)
I. Inter- and intra-granular pore (5×)
J. Primary joint (10×)
K. Tectonic fissure (outcrop)
L. Partially filled tectonic fissure (10×)
M. Filled-eroded tectonic fissure (10×)
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   | high        | massive structure                         |
|            | (white)  |             |                                           |
| dark       | low      |             | fractures and pores                       |
| (brown, black) |        |             |                                           |
| mottle     | heterogeneous | heterogeneous rock mass | |
| dynamic    | bright   | high        | volcanic breccias, rock fragments, crystal fragments, magma fragments, amygdala |
|            | (white)  |             |                                           |
| yellow, orange | middle   |             | rock matrix or framework                  |
| dark       | low      |             | fractures and pores                       |
| (brown, black) |         |             |                                           |

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-amygaloidal 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,
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.
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).
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 further classified 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 

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

| Basin | Formation | Volcanic Rocks | Sedimentary Rocks |
|-------|-----------|----------------|------------------|
| Songliao Basin | Yingcheng Fm. | Acid lava | Limestone |
| | | Intermediate-basic lava | Sandstone |
| | | Complex lava | conglomerate |
| | | Acid pyroclastic | Dolomite |
| Bohai Bay Basin | Tanggou Fm. | Acid lava | Gypsum |
| | | Intermediate-basic lava | Conglomerate |
| | | Complex lava | Sandstone |
| | | Acid pyroclastic | Dolomite |

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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.
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 $10^3$ m$^3$/d | Typical well (Formation) |
|-------------------------------|-------------|---------------|-----------|---------------|------------------------------------------|--------------------------|-------------------------|
| Pyroclastic                    | Intergranular pore, Interstratified pore, Intercentric pore (breccia) | Dissolved pore | High-angle fracture | Faulted anticline | Vertical | 8 | YS3 (x, y) |
| Acid                          | Interstratified pore, Porosity fracture | Joints and High-angle fracture/ filling degree: 80% | Faulted nose | Lateral | Vertical | Gas show | SS1 (x, y) |
| Lava                          | Vesicle, Interstratified pore | High-angle fractures and oblique crossing fractures, Reticular partly, width: 0.5-2 mm | Anticline | Lateral | Vertical | Self generation and self preservation, lower generation and upper preservation | YS2 (x, y) |
| Complex                       | Vesicle, Interstratified pore, Porosity fracture | High-angle fractures and joints | Anticline | Lateral | Vertical | Self generation and self preservation, lower generation and upper preservation | YS1 (x, y) |
| Pyroclastic                    | Interstratified pore, Vesicle (breccia) | Dissolved pore | High-angle structural fractures | Anticline | Lateral | Lower generation and upper preservation | 5.6 | DS3 (x, y) |
| Intermediate-basic            | Micro-vesicle | Branch fractures, width 1 cm, filled by red magma, filling degree: 30%-100% | Faulted nose | Lateral | Vertical | Self generation and self preservation, lower generation and upper preservation | 0.4 | DB11 (x, y) |
| Lava                          | Amygdale, vesicle, Interstratified pore | Reticular fractures, width 2-50 mm, filled by calcite, filling degree: 10%-100% | Anticline | Lateral | Vertical | Lower generation and upper preservation | 4.2 | DXS/DS3-1 (x, y) |
| Complex                       | Amygdale, vesicle | Reticular fractures, width 2-5 cm, filled by calcite, filling degree: 10%-100% | Anticline | Lateral | Vertical | Lower generation and upper preservation | 5.0 | DS4 (x, y) |

Notes: /" shows not discovered by the cores/debris, $k_1y$ is Yingcheng Formation of Lower 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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References

[1] Einsele, G. Sedimentary Basins: Evolution, Facies, and Sediment Budget. Berlin: Springer (2000).

[2] Schutter, S. R. Occurrences of Hydrocarbons in and around Igneous Rocks. Geological Society, London, Special Publications (2003). doi:GSL.SP.2003.214.01.03, 214, 35-68.

[3] Benyamin, B. Facies distribution approach from log and seismic to identification hydrocarbon distribution in volcanic fracture. In: 9th SPWLA Japan Formation Evaluation SYMP (2007), 25-26.

[4] Dutkiewicz, A, Volk, H, Ridley, J, & George, S. C. Geochemistry of Oil in Fluid Inclusions in a Middle Proterozoic Igneous Intrusion: Implications for the Source of Hydrocarbons in Crystalline Rocks. Organic Geochemistry (2004), 35(8), 937-957.

[5] Feng, Z. Q. Volcanic Rocks as Prolific Gas Reservoir: A Case Study from the Qingshen Gas Field in the Songliao Basin, NE China. Marine and Petroleum Geology (2008).

[6] Kawamoto, T. Distribution and Alteration of the Volcanic Reservoir in the Minami-Nagaoka Gas Field. Journal of the Japanese Association for Petroleum (2001), 66(1), 46-55.

[7] Sruoga, P, & Rubinstein, N. Processes Controlling Porosity and Permeability in Volcanic Reservoirs from the Austral and Neuquen Basins, Argentina. AAPG Bulletin (2007), 91(1), 115-129.

[8] Beeskow, B, Treloar, P, J, Rankin, A, H, et al. A Reassessment of Models for Hydrocarbon Generation in the Khibiny Nepheline Syenite Complex, Kola Peninsula, Russia. Lithos (2006).

[9] Dai, J, X, Shi, X, & Wei, Y. Z. Summary of the Abiogenic Origin Theory and the Abiogenic Gas Pools (Fields). Acta Petrolei Sinica (2001). in Chinese with English abstract.

[10] Liu, W, H, Chen, M, J, Guan, P, et al. Ternary Geochemical-Tracing System in Natural Gas Accumulation. Science in China (Series D) (2007a), 50(10), 1494-1503.

[11] Othman, R, Arouiri, K, R, Ward, C, R, et al. Oil Generation by Igneous Intrusions in the Northern Gunnedah Basin, Australia. Organic Geochemistry (2001), 32(10), 1219-1232.
[12] Thomson, K. Volcanic Features of the North Rockall Trough: Application of Visualisation Techniques on 3D Seismic Reflection Data. Bulletin of Volcanology (2005)., 67(2), 116-128.

[13] Wang, X, Lerche, I, & Walter, C. Effect of Igneous Intrusive Bodies on Sedimentary Thermal Maturity. AAPG Bulletin (1989)., 73(9), 1177-1178.

[14] Jin, Q, Xu, L, Wan, C, et al. Interactions between Basalts and Oil Source Rocks in Rift Basins: CO₂ Generation. Chinese Journal of Geochemistry (2007)., 26(1), 58-65.

[15] Gu, L, X, Ren, Z, W, Wu, C, Z, et al. Hydrocarbon Reservoirs in a Trachyte Porphyry Intrusion in the Eastern Depression of the Liaohe Basin, Northeast China. AAPG Bulletin (2002)., 86(10), 1821-1832.

[16] Levin, L. E. Volcanogenic and Volcaniclastic Reservoir Rocks in Mesozoic-Cenozoic Island Arcs: Examples from the Caucasus and the NW Pacific. Journal of Petroleum Geology (1995)., 18(3), 267-288.

[17] Vernik, L. A New Type of Reservoir Rock in Volcaniclastic Sequences. AAPG Bulletin (1990)., 74(6), 830-836.

[18] Wang, P J, Chen, S M, Liu, W Z, et al. Relationship between Volcanic Facies and Volcanic Reservoirs in Songliao Basin. Oil & Gas Geology (2003). in Chinese with English abstract)

[19] Bergman, S C, Talbot, J P, & Thompson, P R. The Kora Miocene submarine andesite stratovolcano hydrocarbon reservoir, northern Taranaki Basin, New Zealand. In: New Zealand Oil Exploration Conference, Wellington, New Zealand, (1992)., 178-206.

[20] Liu, W, Z, Pang, Y, M, Wu, H, Y, et al. Relationship between Pore-Space Evolution and Deeply Buried Alteration during Diagenetic Stage of the Volcanic Fragments in Reservoir Greywacke from the Songliao Basin, NE China. Journal of Jilin University (Earth Science Edition) (2007). in Chinese with English abstract).

[21] Luo, J, L, Zhang, C, L, & Qu, Z H. Volcanic Reservoir Rocks: A Case Study of the Cretaceous Fenghuadian Suite, Huanghua Basin, Eastern China. Journal of Petroleum Geology (1999)., 22(4), 397-416.

[22] Rogers, K L, Neuhoff, P S, Pedersen, A K, & Bird, D K. CO₂ Metasomatism in a Basalt-Hosted Petroleum Reservoir, Nuussuaq, West Greenland. Lithos (2006).

[23] Zhao, H, L, Liu, Z, W, Li, J, et al. Petrologic Characteristics of Igneous Rock Reservoirs and their Research Orientation. Oil & Gas Geology (2004). in Chinese with English abstract).

[24] Chen, Z, Y, Huo, Y, Li, J, S, et al. Relationship Between Tertiary Volcanic Rocks and Hydrocarbons in the Liaohe Basin, People’s Republic of China. AAPG Bulletin (1999)., 83(6), 1004-1014.
[25] Yang, H, Zhang, Y, Zou, C. N, et al. Volcanic Rock Distribution and Gas Abundance Regularity in Xujiaweizi Faulted Depression, Songliao Basin. Chinese Journal of Geophysics, 49(4): 1136-1143 (in Chinese with English abstract).

[26] Stewart, S. A, & Allen, P. J. D Seismic Reflection Mapping of the Silverpit Multi-Ringed Crater, North Sea. Geological Society of America Bulletin (2005).

[27] Jiang, C. J, Feng, X. Y, Zhan, Y. J, et al. New Methodology to Explore Gasbearing Volcanic Reservoir in Xujiaweizi Fault Depression of the Northern Songliao Basin. Petroleum Geology & Oilfield Development in Daqing (2007), in Chinese with English abstract.

[28] Hansen, D. M, Cartwright, J. A, & Thomas, D. D Seismic Analysis of the Geometry of Igneous Sills and Sill Junction Relationships. Geological Society, London, Memoirs (2004), 29(1), 199-208.

[29] Wan, C. L, Jin, Q, & Fan, B. J. Current Research Situation on Hydrocarbon-Generating Evolution of Volcanic Minerals upon Hydrocarbon Source Rocks. Petroleum Geology and Recovery Efficiency (2001), in Chinese with English abstract.

[30] Reuter, J. H, & Perdue, E. M. Importance of Heavy Metal-Organic Matter Interactions in Natural Waters. Geochimica Et Cosmochimica Acta (1977), 41(2), 325-334.

[31] Mango, F. D. Transition Metal Catalysis in the Generation of Petroleum and Natural Gas. Geochimica Et Cosmochimica Acta (1992), 56(1), 553-555.

[32] Jin, Q. Hydrocarbon Generation in Rift Basins, Eastern China: Catalysis and Hydrogenation Interaction between Volcanic Minerals and Organic Matter. Advance in Earth Sciences (1998), in Chinese with English abstract.

[33] Zhang, J. L & Zhang, P. Z. A Discussion of Pyrite Catalysis on The Hydrocarbon Generation Process. Advance in Earth Sciences (1996), in Chinese with English abstract.

[34] Lu, Q, & Liu, H. F. Studies of Kerogen from Baize Basin, Guangxi-Also on Relationship of Evolution of Kerogen and Clay Minerals. Acta Sedimentologica Sinica (1993), in Chinese with English abstract.

[35] Wei, Y. N, & Zhang, D. D. Mineral Petrology. Beijing: China Coal Industry Publishing House; (2007).

[36] Luo, G. F. Crystallography and mineralogy. Nanjing: Nanjing University Press; (1993).

[37] Cheng, R. H, Wang, P. J, Liu, W. Z, et al. Influence of Tectonic Activity and Volcanism on Hydrocarbon Generation of Kerogen. Geological Science and Technology Information (2003), in Chinese with English abstract.

[38] Fjeldskaar, W, Helset, H. M, Johansen, H, et al. Thermal Modeling of Magmatic Intrusions in the Gjallar Ridge, Norwegian Sea: Implications for Vitritine Reflectance and Hydrocarbon Maturation. Basin Research (2008), 20(1), 143-159.
[39] Zhou, Q. H, Feng, Z. H, & Men, G. T. Present Geothermal Features and Relationship with Gas in Xujiaweizi Fault Depression, Songliao Basin. Science in China (Series D: Earth Sciences) (2007). SII): 177-188 (in Chinese with English abstract).

[40] Wang, C. Q, Du, X. R, & Liu, J. X. Keluo-Wudalianchi-Erke Volcanic Cluster, Chapter 17, Characteristics of Melt Inclusions and Diagenesis Temperatures of Volcanic Rocks. Journal of East China College of Geology (Natural Science Edition) (1987). in Chinese).

[41] Wang, J. F. A Preliminary Study on the Geochemical Behaviors of Trace Elements and the Origin of Mesozoic Volcanic Rocks in North-Western Zhejiang Province. Geochimica (1992), in Chinese with English abstract).

[42] Çiftçi, N. B, Temel, R. Ö, & Iztan, Y. H. Hydrocarbon Occurrences in the Western Anatolian (Aegean) Grabens, Turkey: Is there a Working Petroleum System? AAPG Bulletin (2010). , 94(12), 1827-1857.

[43] Farrimond, P, Bevan, J. C, & Bishop, A. N. Hopanoid Hydrocarbon Maturation by an Igneous Intrusion. Organic Geochemistry (1996).

[44] Liu, J. Q, & Meng, F. C. Hydrocarbon Generation, Migration and Accumulation Related to Igneous Activity. Natural Gas Industry (2009). in Chinese with English abstract).

[45] Schimmelmann, A, Mastalerz, M, Gao, L, et al. Dike Intrusions Into Bituminous Coal, Illinois Basin: H, C, N, O Isotopic Responses to Rapid and Brief Heating. Geochimica Et Cosmochimica Acta (2009), 73(20), 6264-6281.

[46] George, S. C. Effect of Igneous Intrusion on the Organic Geochemistry of a Siltstone and an Oil Shale Horizon in the Midland Valley of Scotland. Organic Geochemistry (1992). , 18(5), 705-723.

[47] Raymond, A. C, & Murchison, D. G. Development of Organic Maturation in the Thermal Aureoles of Sills and its Relation to Sediment Compaction. Fuel (1988). , 67(12), 1599-1608.

[48] Carslaw, H. S, & Jaeger, J. C. Conduction of Heat in Solids. New York: Oxford University Press;(1959).

[49] Dow, W. G. Kerogen Studies and Geological Interpretations. Journal of Geochemical Exploration (1977). , 7(0), 79-99.

[50] Galushkin, Y. I. Thermal Effects of Igneous Intrusions on Maturity of Organic Matter: A Possible Mechanism of Intrusion. Organic Geochemistry (1997).

[51] Chen, R. S, He, S, Wang, Q. L, et al. A Preliminary Discussion of Magma Activity on the Maturation of Organic Matter-Taking Geyucheng-Wenan Area of Hebei Province as an Example. Petroleum Exploration and Development(1989). in Chinese with English abstract).

[52] Zhu, D. Y, Jin, Z. J, Hu, W. X, et al. Effect of Igneous Activity on Hydrocarbon Source Rocks in Jiyang Sub-Basin, Eastern China. Journal of Petroleum Science and Engineering (2007).
[53] Lomonosov, M. Ma WJ (translator). Stratum. Beijing: Science Press; (1958).

[54] Tissot, B. P, & Welte, D. H. Petroleum Formation and Occurrence. Berling Heidelberg New York Tokyo: Springer; (1978).

[55] Hunt, J. M. Petroleum Geochemistry and Geology. San Francisco: W H Freeman; (1979).

[56] Liu, W. H, Huang, D. F, Xiong, C. W, et al. Advances in Hydrocarbon Generation Theory and Immature and Low Mature Oil and Gas Distribution and Research. Natural Gas Geoscience (1999). in Chinese with English abstract).

[57] Guo, Z. Q, & Wang, X. B. A Discussion of Abiogenic Natural Gas in the Songliao Basin. Science in China (Series B) (1994). in Chinese).

[58] Wang, X. B, Li, C. Y, Chen, J. F, et al. A Discussion of Abiogenic Natural Gas. Chinese Science Bulletin (1997). in Chinese)

[59] Yang, Y. F, Zhang, Q, Huang, H. P, et al. Abiogenic Natural Gases and their Accumulation Model in Xujiaweizi Area, Songliao Basin, Northeast China. Earth Science Frontiers (2000). in Chinese with English abstract).

[60] Wang, P. J, Hou, Q. J, Wang, K. Y, et al. Discovery and Significance of High CH₄ Primary Fluid Inclusions in Reservoir Volcanic Rocks of the Songliao Basin, NE China. Acta Geologica Sinica (2007). , 81(1), 113-120.

[61] Kerrick, D. M, Caldeira, K, & Metamorphic, C. O. Degassing and Early Cenozoic Paleoclimate. GSA Today (1994). , 4, 57-65.

[62] Dai, J. X. Abiogenic Gas in Oil-Gas Bearing Basins in China and Its Reservoirs. Natural Gas Industry (1995). in Chinese with English abstract).

[63] Tu, G. C. The Discussion on Some CO₂ Problems. Earth Science Frontiers (1996). in Chinese with English abstract).

[64] Yun, J. B, Pang, Q. S, Xu, B. C, et al. Research on the Formation Condition of CO₂ Gas Pool in the Southern Songliao Basin. Journal of Daqing Petroleum Institute (2000). in Chinese with English abstract).

[65] Dai, J. X. Composition Characteristics and Origin of Carbon Isotope of Liuhuangtang Natural Gas in Tengchong County, Yunnan Province. Chinese Science Bulletin (1989). , 34(12), 1027-1030.

[66] Cas RAFWright JV. Volcanic Successions: Ancient and Modern. London: Allen and Unwin; (1987).

[67] Fisher, R. V, & Schmincke, H. U. Pyroclastic Rocks. Berlin-Heidelberg-New York: Springer; (1984).

[68] Lajoie, J. Facies Models 15: Volcaniclastic Rocks. Geoscience Canada (1979). , 6(3), 129-139.
[69] Qiu, J. X. Volcanic Lithofacies and their Characteristics. Geological Science and Technology Information (1984). in Chinese with English abstract.

[70] Wang, D. Z, & Zhou, X. M. Volcanic Petrology. Beijing: Science Press; (1982).

[71] Wang, P. J, Chi, Y. L, Liu, W. Z, et al. Volcanic Facies of the Songliao Basin: Classification, Characteristics and Reservoir Significance. Journal of Jilin University (Earth Sciences Edition) (2003). in Chinese with English abstract).

[72] Li, N, Qiao, D. X, Li, Q. F, et al. Theory on Logging Interpretation of Igneous Rocks and Its Application. Petroleum Exploration and Development (2009). in Chinese with English abstract).

[73] Pan, B. Z, Li, Z. B, Fu, Y. S, et al. Application of Logging Data in Lithology Identification and Reservoir Evaluation of Igneous Rock in Songliao Basin. Geophysical Prospecting for Petroleum (2009). in Chinese with English abstract).

[74] Guo, Z. H, Wang, P. J, Yin, C. H, et al. Relationship between Lithofacies and Logging Facies of the Volcanic Reservoir Rocks in Songliao Basin. Journal of Jilin University (Earth Science Edition) (2006). in Chinese with English abstract).

[75] Wang, M, Xue, L. F, & Pan, B. Z. Lithology Identification of Igneous Rock Using FMI Texture Analysis. Well Logging Technology (2009). in Chinese with English abstract).

[76] Yao, R. S, Wang, P. J, Song, L. Z, et al. Imaging Logging Response to Volcanic Pores and Fractures of Yingcheng Formation in the Songliao Basin. Progress in Geophysics (2011). in Chinese with English abstract)

[77] Zhang, Y, Pan, B. Z, Yin, C. H, et al. Application of Imaging Logging Maps in Lithologic Identification of Volcanic. Geophysical Prospecting for Petroleum (2007). in Chinese with English abstract).

[78] Tang, H. F, Wang, P. J, Jiang, C. J, et al. Application of Waveform Classification to Identify Volcanic Facies in Songliao Basin. Oil Geophysical Prospecting (2007). in Chinese with English abstract).

[79] Xu, Z.S, Wang, Y. M, Pang, Y. M, et al. Identification and Evaluation of Xushen Volcanic Gas Reservoirs in Daqing. Petroleum Exploration and Development (2006). in Chinese with English abstract).

[80] Chen, Z. Y, Li, J. S, Zhang, G, et al. Relationship between Volcanic Rocks and Hydrocarbon within Liaohe Depression of Bohai Gulf Basin, China. Petroleum Exploration and Development (1996). in Chinese with English abstract).

[81] Zou, C. N, Zhao, W. Z, Jia, C. Z, et al. Formation and Distribution of Volcanic Hydrocarbon Reservoirs in Sedimentary Basins of China. Petroleum Exploration and Development (2008). in Chinese with English abstract).

[82] Magara, K. Volcanic Reservoir Rocks of Northwestern Honshu Island, Japan. Geological Society, London, Special Publications (2003). , 214(1), 69-81.
[83] Petford, N, & Mccaffrey, K. Hydrocarbons in Crystalline Rocks: An Introduction. Geological Society, London, Special Publications (2003). doi:GSL.SP.2003.214.01.01, 214(1), 1-5.

[84] Tang, H.F, Pang, Y.M, Bian, W.H, et al. Quantitative Analysis on Reservoirs in Volcanic Edifice of Early Cretaceous Yingcheng Formation in Songliao Basin. Acta Petrolei Sinica (2008). in Chinese with English abstract).

[85] Huang, Y.L, Wang, P.J, & Shao, R. Porosity and Permeability of Pyroclastic Rocks of the Yingcheng Formation in Songliao Basin. Journal of Jilin University (Earth Science Edition) (2010). in Chinese with English abstract).

[86] Guo, Z.Q. Volcanic Activity versus Formation and Distribution of Oil and Gas Fields. Xinjiang Petroleum Geology (2002). in Chinese with English abstract).

[87] Li, C.G. Oil and Gas Related to the Volcanic Rocks in Dongying and Huimin Depressions. Explorationist (1997). in Chinese with English abstract).

[88] Fu, G, Hu, M, & Yu, D. Volcanic Cap Rock Type and Evaluation of Sealing Gas Ability: An Example of Xujiaweizi Depression. Journal of Jilin University (Earth Science Edition) (2010). in Chinese with English abstract)

[89] Lee, G.H, Kwon, Y.I, Yoon, C.S, et al. Igneous Complexes in the Eastern Northern South Yellow Sea Basin and their Implications for Hydrocarbon Systems. Marine and Petroleum Geology (2006)., 23(6), 631-645.
