The spatial and temporal distributions of the late Mesozoic volcanic successions in the Changling fault depression of the Songliao Basin, NE China, and their controlling effects

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   - Magmatic control
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5. Conclusion
The volcanic petroleum reservoirs are widely distributed, especially in the northeast and northwest of China.

From 2002, incremental reserve additions of gas and oil in the volcanic reservoirs in the Songliao and Bohaiwan continental rift basins are $3900 \times 10^8$ m$^3$ and $3.7 \times 10^8$ t respectively.
Introduction to the Songliao Basin

- The Songliao Basin (SB) is the largest Cretaceous oil-gas producing lacustrine basin in China, covering an area roughly 260,000 km².

- A series of Late Jurassic to Early Cretaceous separated rift basins, such as the Changling fault depression develop

Zhou et al., 2008

Basin filling of the SB can be obviously subdivided into the upper and lower layers by regional unconformity. The lower layer is characterized by a fault-bounded volcanogenic succession. The upper part is composed of a normal sedimentary sequence.
Introduction to the Songliao Basin

Stratigraphic column for the Songliao Basin

Syn-rift Stage Graben Half Graben

Post-rift Stage L. Sag Basin

Volcanogenic Succession

Fluvial Deposits Syn-Sedimentary Deformation

Oil Shale Lake Deposits
Research status

- Lithology and Facies
- Geochronology and geochemistry
- Volcanic succession
- Geophysical recognition techniques
- Volcanic reservoir
- Gas accumulation

Seismic inversion (Porosity profile)

Microcosmic

Micropore

Macrography

Vesicle
Objective of this study

- **Study area:** The Changling fault depression
- **Objective**
  - Volcanic succession
  - Time attribute
  - Geochemical attributes
  - Spatial distribution attributes
  - Basin tectonic attributes
  - Magmatic control
  - Basin tectonic control

- 3 secondary structural units: the central sag belt, the western steep slope zone and the eastern gentle slope zone
- 3 Types of fault: Boundary faults; The major syngenetic faults; Secondary faults

Gas reserve in the volcanic reservoirs is $1716 \times 10^8$ m$^3$
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Method - Seismic volcanic stratigraphy

- Well-seismic correlation
- Establish seismic volcanic stratigraphic framework (accurately identifies eruption stages)
- Limit the isotopic chronology and geochemical data
Method - Geochronology

Samples are limited by the seismic volcanic stratigraphic framework.

The LA-ICP-MS zircon U-Pb analyses were performed.
Method - geochemistry

Major analysis

Supplementary table 2 Major elements analysis data

<table>
<thead>
<tr>
<th>No</th>
<th>Stage</th>
<th>H₂O°</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>TFe₂O₃</th>
<th>MgO</th>
<th>CaO</th>
<th>Na₂O</th>
<th>K₂O</th>
<th>TiO₂</th>
<th>P₂O₅</th>
<th>MnO</th>
<th>LOI</th>
<th>Total</th>
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<td>D1-4581-1</td>
<td>K1yc1-S1</td>
<td>0.74</td>
<td>46.72</td>
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<td>10.99</td>
<td>6.29</td>
<td>8.87</td>
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<td>1.49</td>
<td>2.59</td>
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<td>D1-4581-2</td>
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<td>L1-4525-1</td>
<td>K1yc1-S1</td>
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<td>L1-4525-2</td>
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<td>53.18</td>
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<td>4.71</td>
<td>1.96</td>
<td>2.45</td>
<td>0.41</td>
<td>0.13</td>
<td>4.62</td>
<td>100.95</td>
</tr>
</tbody>
</table>

Trace element analysis
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Volcanic successions - Time attribute

- The volcanic rocks in the Changling fault depression can be divided into three eruption cycles and 7 eruption stages.

- $K_1y^c_3^3$-S3 and $K_1y^c_3^3$-S4 are approximately 103 Ma.
- $K_1y^c_3^3$-S2 is 105-104 Ma.
- $K_1y^c_3^3$-S1 is 106 Ma.

- $K_1yc_1$-S2 at 109-106 Ma.
- $K_1yc_1$-S1 at 115-111 Ma.

- $K_1h$ is 122-118Ma.
Volcanic successions - Geochemical attributes

<table>
<thead>
<tr>
<th>Period</th>
<th>Epoch</th>
<th>Stratigraphy</th>
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<td>Aptian</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Cenomanian</td>
<td></td>
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</tbody>
</table>

Bimodal

Basic-intermediate endmember

Acidic endmember

Basic-intermediate endmember

Almost in the alkaline field
Volcanic successions - Geochemical attributes

- Basic-intermediate endmember
  - Similar patterns in the chondrite-normalized diagram and the primitive mantle-normalized diagram
  - Strongly fractionated REE enrich LREEs, Lack significant Eu anomalies
  - Enrich LILEs, HFSEs, HREEs
  - No negative Ta or Nb anomalies carry indicateds no subduction component
Volcanic successions - Geochemical attributes

Acidic endmember

Trace elements of K1h

Medium negative Eu anomalies

(B)K,h

Negative Ta and Nb anomalies

Trace elements of K1yc1-S2

Strong negative Eu anomalies

No Ta and Nb anomalies
Volcanic successions - Geochemical attributes

Trace elements of K1yc3-S2

Trace elements of K1yc3-S3

Trace elements of K1yc3-S4

Acidic endmember

- Similar patterns in the chondrite-normalized diagram and the primitive mantle-normalized diagram in each stages
- Similar patterns in compared with the acidic rocks in K1yc1-S2
Volcanic Successions—Spatial and Basin Tectonic Attributes

$K_1h$ : volcanic rocks in $K_1h$ that are mainly distributed around the boundary of the basin;

$K1yc1$ : the eruption of $K1yc1$ migrated from the south to the central part of the basin;

$K1yc3$ : the volcanic rocks of $K1yc3$ first erupted in the central sag of the Changling fault depression and gradually migrated to the eastern abrupt slope.
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Controlling effects - Magmatic control

Petrogenesis of the Basic-intermediate endmember

- Basic-intermediate volcanic rocks in the stages $K_1^h$, $K_1yc^1$-$S1$ and $K_1yc^3$-$S1$ have similar magma sources
- The basic magma originates from the enriched asthenospheric mantle (Similar to OIB),
- The magma source is affected by the metasomatism of mantle fluid.
Controlling effects- Magmatic control

- Trace elements in primitive mantle-normalized diagram are similar to those of ocean island basalt (OIB)
  - $\text{Ce/Pb} = 21.18 (\text{Ce/Pb}_{\text{OIB}}=25)$, $\text{La/Nb} = 0.87$ ($\text{La/Nb}_{\text{OIB}}=0.77$)
- These volcanic rocks plot on the MORB-OIB mantle trend near OIB
Controlling effects - Magmatic control

- Magma that formed from the asthenosphere is characterized by relatively low LREE/HFSE ratios.
- Basalt from the asthenospheric mantle presents La/Nb<1.5 in the basin and range province of the United States (Fitton et al., 1988)
- La/Ta<22 in Colorado of the United States (Leat et al., 1988)

The basic and intermediate rocks in $K_1h$ and $K_1yc$ present La/Nb=0.59-1.03 and La/Ta=10.86-18.02, which are consistent with the features of the asthenosphere
**Controlling effects - Magmatic control**

- **K₁h**: The rhyolite in K₁h was formed by the melting of pre-existing granite.
- **K₁yc³-S3**: The andesitic, dacitic, and trachytic volcanic rocks in K₁yc³-S3 were likely generated by fractional crystallization.
- **K₁yc¹-S2, K₁yc³-S2 and K₁yc³-S4**: The acidic volcanic rocks in these stages are caused by partial melting of the newly formed basic lower crustal rocks.
Acidic volcanic rocks in the $K_1yc^1-S2$, $K_1yc^3-S2$ and $K_1yc^3-S4$

- Generated by the fractional crystallization of basic magma
- Generated by the partial melting of crustal rocks caused by the underplating of basic magma

Not be generated by fractional crystallization according to their large volume.

The Rb/Ba of the acidic volcanic rocks has a large range of variation and indicates that the magma is derived from partial melting.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Rb/Ba</th>
<th>Nb/Ta</th>
<th>Zr/Hf</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Range</td>
<td>Average</td>
<td>Range</td>
</tr>
<tr>
<td>K1h</td>
<td>0.48</td>
<td>0.48</td>
<td>11.16</td>
</tr>
<tr>
<td>$K_1yc^1-S2$</td>
<td>0.08-7.10</td>
<td>1.59</td>
<td>8.90-19.03</td>
</tr>
<tr>
<td>$K_1yc^3-S2$</td>
<td>0.06-6.56</td>
<td>2.90</td>
<td>14.53-19.74</td>
</tr>
<tr>
<td>$K_1yc^3-S3$</td>
<td>0.19-0.75</td>
<td>0.53</td>
<td>14.74-17.62</td>
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<tr>
<td>$K_1yc^3-S4$</td>
<td>0.20-2.76</td>
<td>1.04</td>
<td>13.52-17.79</td>
</tr>
</tbody>
</table>

- Nb/Ta ≈ primitive mantle (17.5) and > the crust (11); Zr/Hf > the primitive mantle (36.25) and > the average value of the crust (33.33). These ratios indicate that the acidic volcanic rocks have mantle compositions (Boynton, 1984).

Therefore, partial melting may have originally occurred in newly formed basic lower crustal rocks.
Controlling effects - Magmatic control

K₁yc³-S3

- A small volume and may have been generated by a high degree of fractional crystallization of basic magma
- The composition of the magma in this stage is complex, it reflects the nonlinear progress of fractional crystallization.
- The small variation range of Rb/Ba (0.19 - 0.75) is justified by fractional crystallization.
- The ratios of Nb/Ta and Zr/Hf are equal to or larger than those of the primitive mantle, indicating mantle compositions.
Controlling effects—Magmatic control

The ratios Nb/Ta and Zr/Hf (Table 2) are close to the average ratios of the crust (Nb/Ta=11 and Zr/Hf=33) and have no mantle characteristics.

Negative Nb and Ta anomalies are observed, which indicate that the rhyolite magmas are inextricably bound with crustal material.

The chondrite-normalized figure shows moderate negative Eu anomalies, which indicate that fractional crystallization was not strong.
Controlling effects- Basin tectonic control

- The distribution of the volcanic rocks in $K_1h$ is **controlled by the boundary fault**
- The distribution of volcanic rocks in $K_1yc^1$ and $K_1yc^3$ is mainly **controlled by the major syngenetic and corresponding secondary faults**
- The volcanic rocks developed along the **secondary fault system** are similar to those of the nearby major syngenetic fault.
The early stages of basic-intermediate rocks in $K_1yc^1$ and $K_1yc^3$ are distributed along the entire syngenetic fault; however, the later stages of the acidic rocks are generally distributed in the northern part of the syngenetic fault, where the fault has a large separation.
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Conclusions

- Three volcanic eruption cycles and sever eruption stages are observed in the Changling fault depression.

- The multiple cycles and stages of the vertical volcanic successions are controlled by magmatism. The basic-intermediate endmembers of $K_1^h$, $K_1yc^1$ and $K_1yc^3$ have similar origins, and are attributable to the partial melting of enriched asthenosphere, which has a similar source as OIB.

- The rhyolite in $K_1^h$ originates from the re-melting of granite in the crust. The acidic volcanic rocks in $K1yc1-S2$, $K1yc3-S2$ and $K1yc3-S4$ originates from the partial melting of newly formed basic lower crust rocks. $K_1yc^3-S3$ originated from fractional crystallization of the basic magma.

- Different types of faults controlled the distribution regularity of the volcanic rocks in the Changling fault depression. In the beginning of the rift period, the activity of boundary faults controlled the circularly distributed volcanic rocks in $K1h$; In the period of the Yingcheng Formation, the volcanic rocks were controlled by the major syngenetic fault systems.
Thanks for your attention!