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ARTICLE

Vesicle distribution in basalt lava flow units in the Mesozoic rift basins of northeast China and its application in gas reservoir prediction

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Abstract: The Mesozoic rift basins of northeast China are characterized by a significant proportion of basalt due to the progressive emplacement of basalt lava flows. The objective of this study was to construct vesicle distribution models of the basalt lava flow units, including conceptual geological models and thickness models, to understand the architecture of the basalt and the gas reservoir distribution. The conceptual geological models were constructed based on the characteristics of outcropping basalt lava flows, with supplemental seismic data used to extrapolate the lateral extents of large-scale basalt lava flows. The thickness models were constructed using data on the thicknesses of basalt lava flow units and vesicle zones. These data were obtained from 27 units in outcrop and 204 units interpreted from well logs in the basin. The conceptual geological models revealed that the shapes of the basalt lava flow units change from braided to tabular with increasing thickness and that their inner structures can be divided into three vesicle zones: the top vesicle zone, the massive core zone, and the base vesicle zone. The thickness models revealed that trends in the thickness of the top vesicle zone relative to the thickness of the basalt lava flow unit can be expressed using a piecewise function that can be separated into a linear function and a logarithmic function. Similarly, trends in the thickness of the massive core zone and the base vesicle zone relative to the basalt lava flow unit thickness can be expressed by a piecewise linear function. Vesicle distribution models provide an effective means of determining the proportion and distribution of vesicle zones in basalt with limited borehole data. We also constructed a reservoir model based on our vesicle distribution models, and this model revealed that suitable petroleum reservoirs are primarily located in the thinner braided lava flows.

Résumé : Les bassins d'effondrement (Mésozoïque) du nord-est de la Chine sont caractérisés par une proportion importante de basaltes en raison de la mise en place progressive de coulées de lave basaltique. L'objet de la présente étude est de construire des modèles de distribution des vacuoles des unités de coulées de lave basaltique, incluant des modèles conceptuels de la géologie et de l'épaisseur, afin de comprendre l'architecture des basaltes et la distribution des réservoirs de gaz. Les modèles géologiques conceptuels ont été construits en se basant sur les caractéristiques des affleurements de coulées de lave basaltique; des données sismiques additionnelles ont servi à extrapoler les étendues latérales des coulées de lave basaltique à grande échelle. Les modèles d'épaisseur ont été construits en utilisant des données sur les épaisseurs des unités de coulées de lave basaltique et des zones de vacuoles. Ces données ont été obtenues de 27 unités en affleurement et de 204 unités interprétées à partir de diagraphies de puits dans le bassin. Les modèles géologiques conceptuels révèlent que les formes des unités de coulées de lave basaltique changent d'anastomosées à tabulaires en fonction de l'augmentation de l'épaisseur et que leur structure interne peut être divisée en trois zones vacuolaires : une zone vacuolaire supérieure, une zone massive centrale et une zone vacuolaire basale. Les modèles d'épaisseur révèlent que les tendances dans l'épaisseur de la zone vacuolaire supérieure, par rapport à l'épaisseur de l'unité de coulée de lave basaltique, peuvent être exprimées au moyen d'une fonction par morceaux, laquelle peut être séparée en une fonction linéaire et une fonction logarithmique. De même, les tendances dans l'épaisseur de la zone massive centrale et dans la zone vacuolaire basale, par rapport à l'épaisseur de l'unité de coulée de lave basaltique, peuvent être exprimées par une fonction linéaire par morceaux. Les modèles de distribution des vacuoles fournissent un moyen efficace de déterminer la proportion et la distribution des zones de vacuoles dans les basaltes dont les données de forage sont limitées. Nous avons aussi construit un modèle de réservoir basé sur nos modèles de distribution des vacuoles et ce modèle a révélé que des réservoirs pétrolifères adéquats sont principalement situés dans les coulées de lave anastomosées plus minces. [Traduit par la Rédaction]

Introduction

Volcanic successions in the rift basins of northeast China have recently become a focus of geological research owing to the discovery of significant volcanic gas reservoirs in this region (Wang and Chen 2015). In these basins, basalt comprises a large proportion of the total volcanic succession and represents an important type of volcanic petroleum reservoir (Shan et al. 2012). Vesicles are the primary petroleum reservoir volume in basalt in this region (Huang et al. 2010*b*). Therefore, basalts function as petroleum reservoirs in these basins, demonstrating the importance of detailed basalt vesicle distribution estimates.

Previous studies of volcanic rocks in the basins of northeast China have been primarily limited to the description of lithology, facies, and reservoir volume (Feng et al. 2014). Elsewhere, Walker (1971) employed "lava flow units" as "fundamental building blocks" to understanding the emplacement of continental flood basalts (CFBs), which are typically composed of stacked basalt lava flow units. This approach has been extensively applied and refined in

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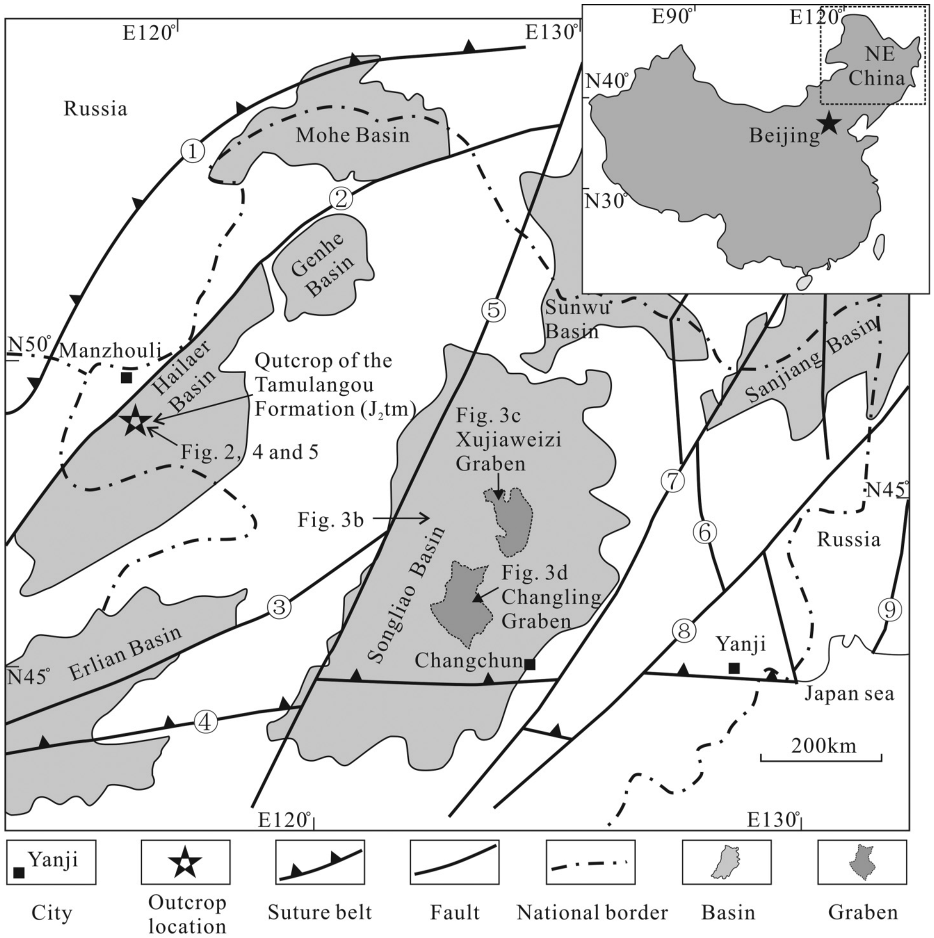
Fig. 1. Overview map of the study area in northern China. Locations of the outcrops and grabens used in this study are marked. Boreholes are indicated in Fig. 3. J_2tm, Tamulangou Formation.



1. Mongnia–Okhotsk suture zone; 2.Derbugan fault; 3.Hegenshan fault; 4.Xilamulunhe suture zone; 5.Nenjiang-Balihan fault; 6.Mudanjiang fault; 7. Yitong-Yilan fault; 8. Dunmi fault; 9. Xihuote-alin fault

many studies of CFBs throughout the world, including individual lava flow units (Lockwood and Lipan 1980; Planke et al. 1999*b*; Waichel et al. 2006), facies architecture and emplacement (Bull and McPhie 2006; Jerram et al. 2009; Vye-Brown et al. 2013), and seismic-scale facies (Planke and Cambray 1998; Planke et al. 1999*a*, 2000; Calvès et al. 2011; Jackson 2012). Therefore, basalt lava flow units represent a solid foundation for research on large-scale CFBs (Single and Jerram 2004; Waichel et al. 2012). Lava flow units also play a major role in vesicle distribution in basalt (Andersen and Boldreel 2009). Vesicles develop independently and accumulate to form vesicle zones in individual lava flow units (Cashman and Kauahikaua 1997). Complex vesicle distributions in CFBs are formed by the stacked flow units (Waichel et al. 2012). However, only few studies have quantitatively described the vesicle distribution in basalt lava flow units. For example, Single and Jerram (2004) investigated the thicknesses of vesicle zones in basalt lava flow units in the Skye lava field of tertiary igneous rock in Great Britain. The goals of our study are to complement previous studies regarding the distribution of vesicle zones in basalts by adding data from northeast China to the database and to present models that predict vesicle distributions.

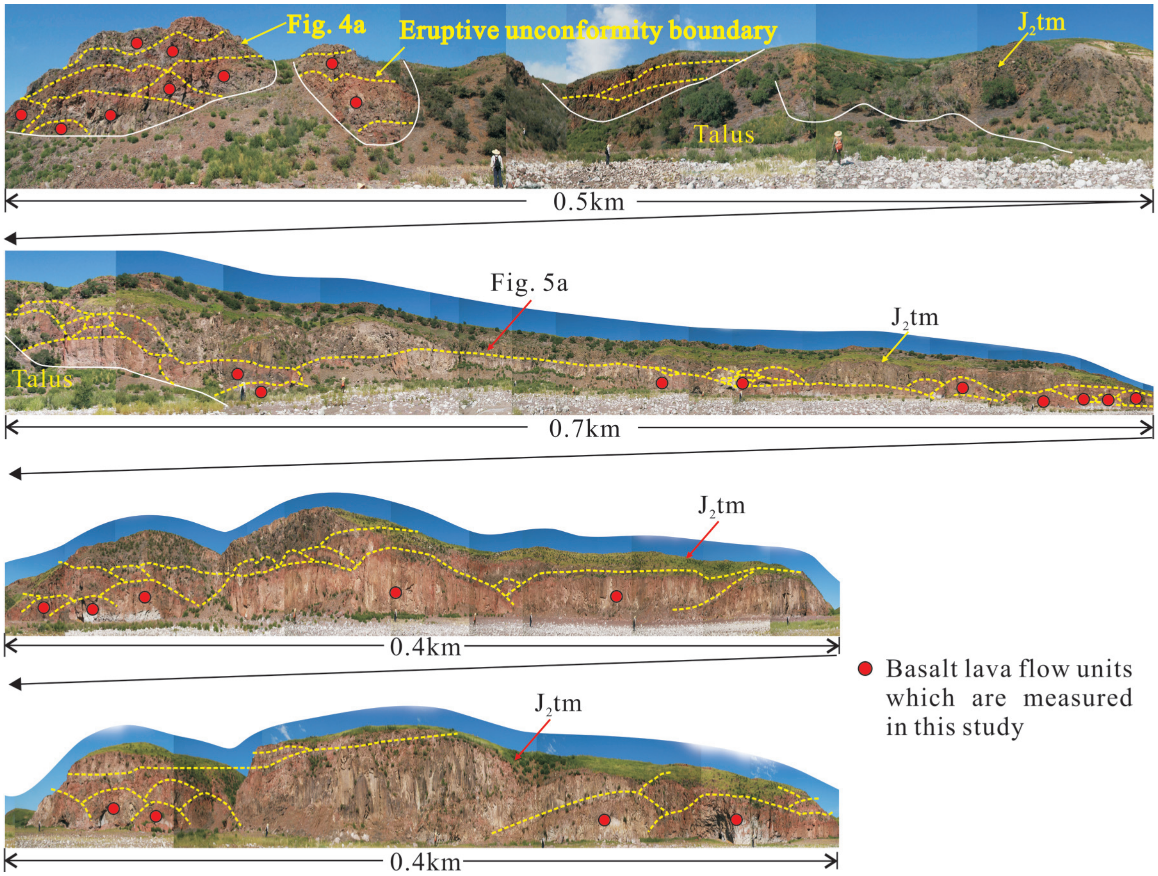
To explore the vesicle distribution in basalt lava flow units in the Mesozoic continental rift basins of northeast China, we selected the Songliao and Hailaer basins as representative study areas. Several deep boreholes and three-dimensional seismic surveys exist in the Songliao Basin, and the basalt at the margin of the Hailaer Basin is well exposed in outcrop. Vesicle distribution models were constructed by describing and measuring vesicle zones along profiles through the basalt lava flow units in the outcrop, and similar data were obtained from cores and petrophysical logs from boreholes. The interpretation of basin seismic data provided data on the lateral extent of basalts in the Songliao Basin.

Geological setting

The Songliao and Hailaer basins (Fig. 1) are situated in northeastern China between the North China plate and the Siberian plate and formed on continental crust (Feng 2008; Liu et al. 2010). Two important collisional belts exist in this area: the suturing of the Xilamulun belt in the south led the formation of the basement of the Songliao Basin (Wang and Fan 1997); and the Mongolia–Okhotsk belt in the north formed by the closure of the Mongolia–Okhotsk Ocean (Kravchinsky et al. 2002; Metelkin et al. 2007) (Fig. 1). The latter belt has the closest spatial and temporal relationships with the development and volcanism of the Songliao and Hailaer basins (Wang et al. 2002; Cai et al. 2010).

In the early Mesozoic, the Songliao Basin was a continental rift basin that was controlled by both the closure of the Mongolia–Okhotsk Ocean and the subduction of the Pacific plate (Wang et al. 2007). In this period, a series of independent grabens formed in the

Fig. 2. Erosional escarpments of the Tamulangou Formation (J_2tm) in Manchuria, northeast China (refer to Fig. 1 for location). A total of 27 basalt lava flow units were analyzed, and the measured parameters included the thicknesses of the lava flow units and the vesicle zones.



Songliao Basin (Feng et al. 2010). This basin subsequently entered the depression and structural inversion stage (Feng et al. 2011). The Hailaer Basin has a similar evolutionary history; however, the fault-depression transition times differed (Chen et al. 2007).

Three tectonostratigraphic sequences, which are separated by regional unconformities, developed in the Songliao Basin (Wang et al. 2007) and the Hailaer Basin (Zhang et al. 1994): (*i*) the fault-subsidence sequence; (*ii*) the depression sequence; and (*iii*) the structural inversion sequence. Volcanic successions developed during the fault-subsidence sequences of these two basins. In the Songliao Basin, volcanic successions developed in the Upper Jurassic Huoshiling Formation and in the Lower Cretaceous Ying Cheng Formation (Cheng et al. 2014). The Ying Cheng Formation is divided into three members: the first member is primarily composed of rhyolite and pyroclastic; the second member is derived from sedimentary sequences; and the third member primarily consists of basalt and pyroclastic deposits (Jia et al. 2007). In the Hailaer Basin, the volcanic sequences primarily developed in the Jurassic – Lower Cretaceous Xinganling Group in the fault-subsidence sequence (Chen et al. 2007). The Middle Jurassic Tamulangou Formation in the Xinganling Group, which primarily comprises olivine basalt, pyroxene basalt, and basaltic andesite (Zhao et al. 2011), was uplifted and exposed at the margin of the Hailaer Basin. This exhumation and related long-term water erosion resulted in a representative three-dimensional basalt outcrop at Hulun Lake in Manchuria that was employed in this study (Fig. 1).

Terminology

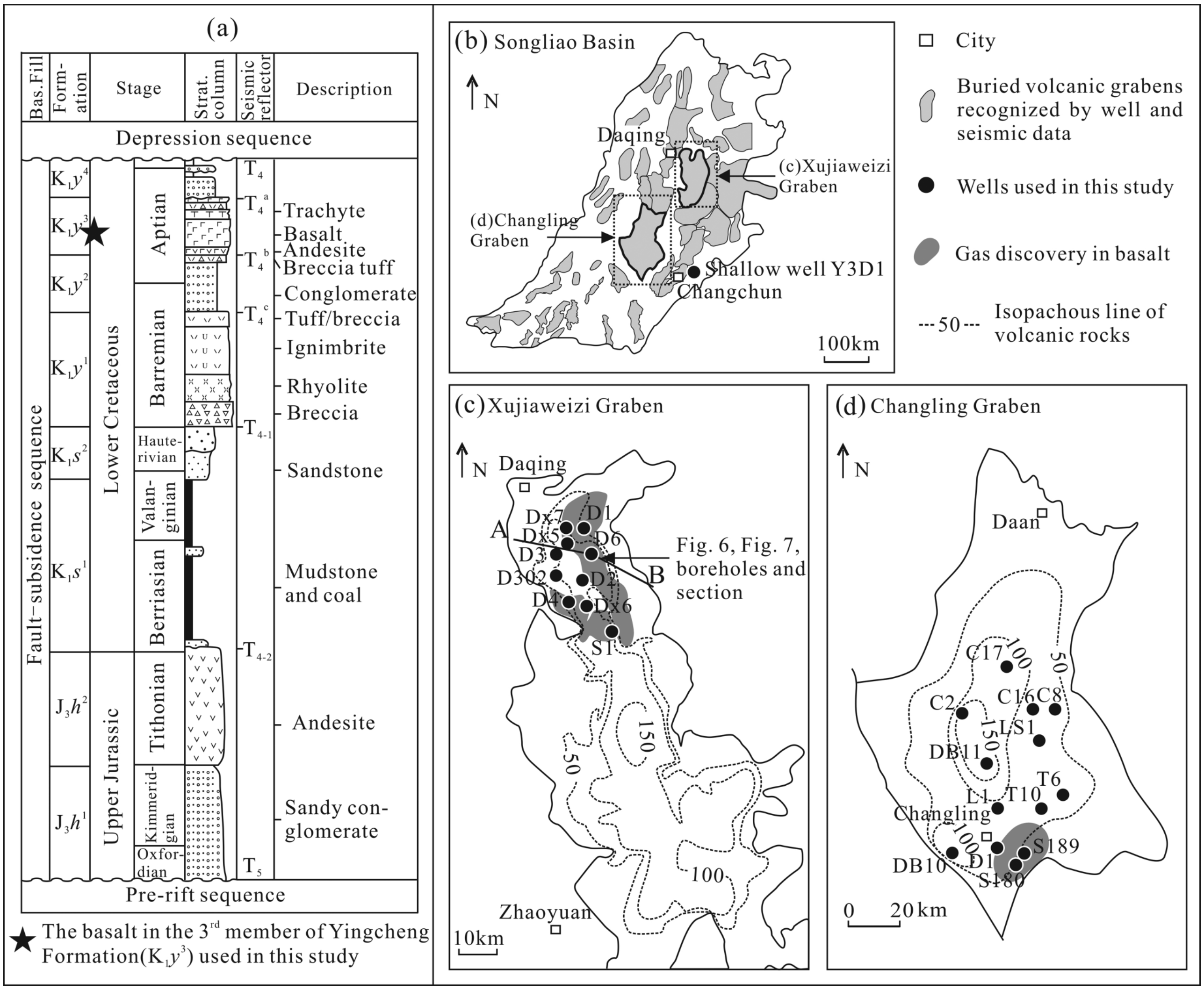
This paper uses the following terms: (*i*) "Eruptive unconformity boundaries": unconformity interfaces in volcanic rocks that formed during the short intervals of eruptions (De Rita et al. 1997). These boundaries can be identified by lithological and textural aspects, such as the presence of a cooling crust, a'a lava surface, or pahoehoe lava surface, etc. (Lockwood and Hazlett 2010). (*ii*) "Lava flow unit": a separate cooling unit that has a top that cooled significantly and solidified before another flow was superposed on it (Walker 1971; Self et al. 1997) or a lava flow unit that is enclosed by eruptive unconformity boundaries (Tang el al. 2015). (*iii*) "Braided lava flow unit": a thin, braided, channel-like lava flow unit (Jerram 2002). (*iv*) "Tabular lava flow unit": a thick, layer-like lava flow unit (Jerram 2002). (*v*) "Vesicle zones": based on the shapes and numbers of vesicles, the structure of a lava flow unit can be divided into three zones (Aubele et al. 1988). The "top vesicle zone" consists of the upper crust of a basalt lava flow unit, which is highly vesicular; the "massive core zone" includes the dense flow interior with few vesicles; and the "base vesicle zone" comprises the lower crust, which is characterized by the development of a few pipe vesicles (Cashman and Kauahikaua 1997; Self et al. 1998). According to outcrop observations, the top vesicle zone can be subdivided into the "upper layer" and the "lower layer". These features are described in the section "Basalt lava flow units in outcrop".

Database and methods

Both outcrop and borehole data were incorporated into the vesicle distribution models. The basalt of the Tamulangou Formation is exposed on the shores of Hulun Lake in continuous erosional escarpments that are approximately 1.9 km long. We measured profiles through 27 units to determine the thicknesses of the lava flow units and their vesicle zones (Fig. 2).

As a complement to the outcrop data, 204 basalt lava flow units were identified from a total of 116 m of core and 1885 m of petro-

Fig. 3. Borehole data and seismic sections used in this study. (*a*) Geology of columnar sections in the fault-subsidence sequence of the Songliao Basin, including the Upper Jurassic Huoshiling Formation (J_3h), the Lower Cretaceous Shahezi Formation (K_1s), and the Lower Cretaceous Yingcheng Formation (K_1y). The basalt analyzed in this study is the third member of the Yingcheng Formation. (*b*) Buried volcanic grabens in the Songliao Basin. (*c*) Locations of boreholes and seismic sections in the Xujiaweizi graben. (*d*) Locations of boreholes in the Changling graben. Numbers in the isopachous lines represent the thicknesses of the volcanic rocks in metres. Bas., basin; Strat., stratigraphic.



physical log data from 23 deep boreholes. These boreholes were drilled in the basalt of the third member of the Yingcheng Formation in the Xujiaweizi and Changling grabens of the Songliao Basin (Fig. 3). The thicknesses and vesicle distributions of the basalt lava flow units were determined. Additionally, seismic sections proved to be suitable for interpreting thick lava flow units, and the seismic data were used to determine the lateral extent of the tabular lava flow units in this basin (Fig. 3).

An image analysis was employed to count the surface porosity of the outcropping basalt (data are used in figures discussed in the subsection "Conceptual geological models"). Specimens were obtained from high-resolution photographs of the outcrops. The photographs were taken systematically at 50 cm intervals from the top to the base of flow units. The surface porosity was measured using the computer software CoreDBMS, which was designed by the Daqing Oilfield Company (Daqing, China). Porosimeter porosity and permeability measurements (data are used in the figure discussed in the subsection "Permeability of basalt reservoirs") were performed on a total of 223 samples from the 23 deep boreholes in the Songliao Basin (Figs. 3*c*, 3*d*), and one scientific shallow borehole Y3D1 at the southeast margin of the Songliao Basin (Fig. 3*b*), and the outcrop at the margin of Manchuria (Fig. 1). These analyses were performed in the laboratories of Jilin University and the Daqing Oilfield Company.

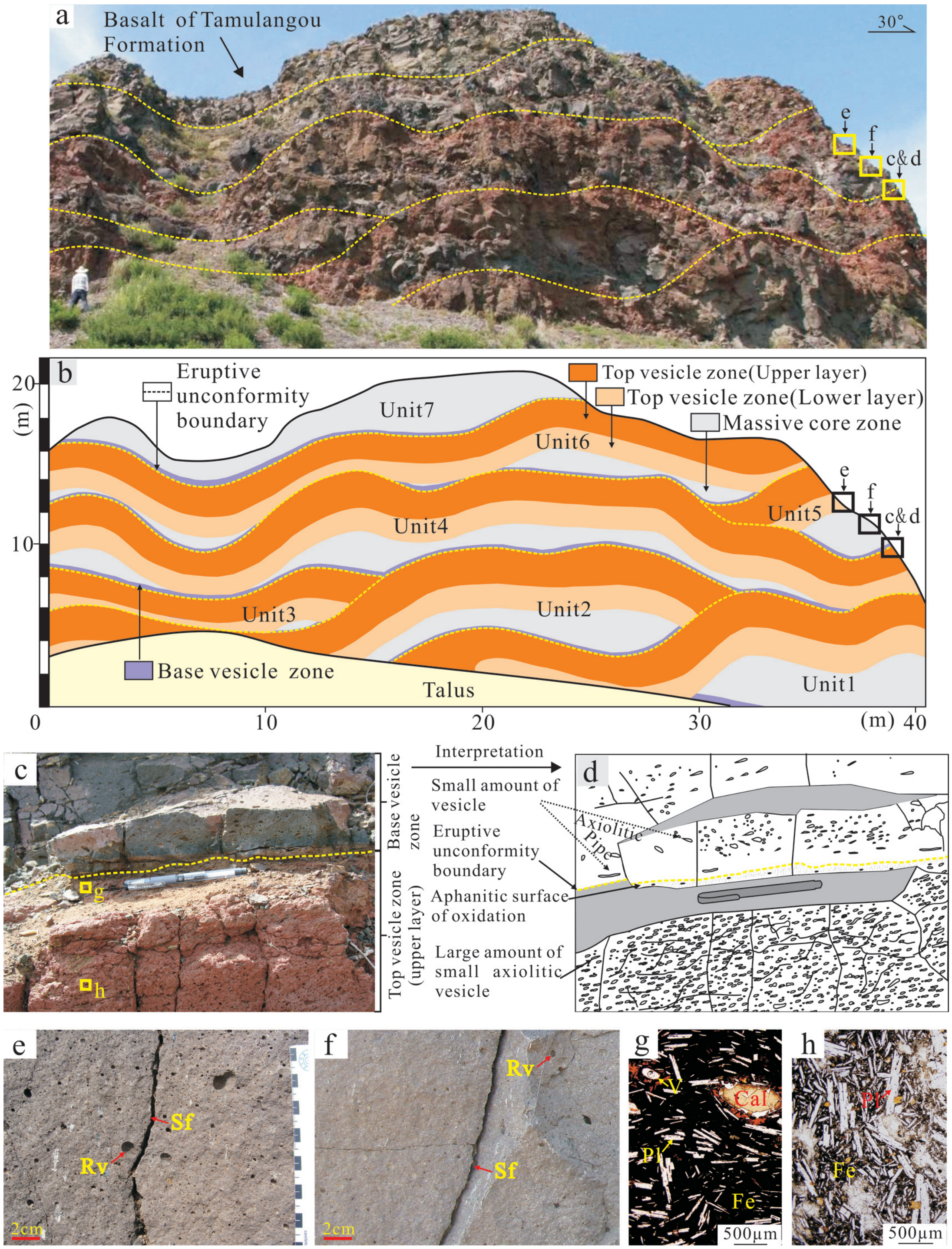
Basalt lava flow units in outcrop

Two representative escarpments were selected for this study, and their geological characteristics, including the shapes, inner structures, and stacking patterns of the braided and tabular lava flow units, were assessed to develop conceptual geological models. These data enabled the creation of identification standards for vesicle zones to ensure that the data from the 27 lava flow units assessed in the field had consistent benchmarks to enable clear identification.

Braided lava flow units

Figure 4 illustrates the characteristics of braided lava flow units. In the study escarpment, seven basalt lava flow units with thicknesses of 4–7 m were identified based on eruptive unconformity boundaries (Figs. 4*a*, 4*b*). These eruptive unconformity boundaries are characterized by the presence of a thin cooling crust (Fig. 4*c*), with a higher content of fine-grained secondary mafic minerals (Fig. 4*g*) compared with the underlying layers (Fig. 4*h*). Another

Fig. 4. (*a*) General view of braided lava flow units divided by eruptive unconformity boundaries. The basalt is a component of the Tamulangou Formation in Manchuria, northeast China. (*b*) Inner structures of the braided lava flow units. (*c*) Characteristics of the top vesicle zone (upper layer) and base vesicle zone, which are separated by an aphanitic surface abundant in fine-grained secondary mafic minerals (micrograph *g*, plane-polarized light; Cal, calcite; Fe, iron; Pl, plagioclase; V, vesicle) compared with the lower layers (micrograph *h*, plane-polarized light). (*d*) Interpretation of photograph *c*. (*e*) Characteristics of the top vesicle zone (lower layer), including the development of round vesicles (Rv) and straight fissures (Sf). (*f*) Characteristics of the massive core zone, including the development of a small round vesicle.



characteristic is the sudden change in pore quantities across the interface between two lava flow units (Figs. 4*c*, 4*d*). An individual braided lava flow unit can be divided into three vesicle zones (Fig. 4*b*): the top vesicle zone (which includes an upper layer, as shown in Figs. 4*c* and 4*d*, and a lower layer, as shown in Fig. 4*e*), the massive core zone (Fig. 4*f*), and the base vesicle zone (Figs. 4*c*, 4*d*).

Their characteristics are summarized in Table 1. The boundary between the top vesicle zone and the massive core zone is defined by the abrupt decrease in the abundance of vesicles. The boundary between the massive core zone and the base vesicle zone is defined by the abrupt increase in the abundance of vesicles or the change in pore shape to pipe-like or axiolitic shapes.

Table 1. Characteristics of vesicle zones in the basalt lava flow units.

Flow unit	Vesicle zone	Primary pore	Fissure	Surface porosity (%)
Braided lava flow units	Top vesicle zones (upper layer)	Directional, axiolitic, and small (diameter: 0.2–1 cm)	Microfissures	20–40
	Top vesicle zones (lower layer)	Round and larger than upper layer (diameter: 0.5–2 cm)	Straight fractures	8–20
	Massive core zones	Small round pores	Straight fractures	<5
	Base vesicle zones	Pipe and axiolitic, not highly directional	Straight fractures	10–15
Tabular lava flow units	Top vesicle zones (upper layer)	Directional, axiolitic, and small (diameter: 0.2–1 cm)	Microfissures	20–40
	Top vesicle zones (lower layer)	Large round pores (diameter: 10–15 cm)	Straight fractures	10–30
	Massive core zones	Few pores	Columnar joints and straight fractures	<1
	Base vesicle zones	Few round pores	Bedding joints	<5

Tabular lava flow units

Figure 5 illustrates the characteristics of tabular lava flow units. In the study escarpment, two tabular lava flow units (12 and 17 m thick) were identified based on eruptive unconformity boundaries (Figs. 5*a*, 5*b*). These units are thicker than the braided lava flow units, but their inner structures can also be divided into three vesicle zones (Fig. 5*c*; Table 1). In the tabular lava flow units, the upper layers of the top vesicle zones are generally similar to braided lava flow units (Fig. 4*c*, 5*e*); however, the lower layers of the top vesicle zones feature very large round vesicles (Fig. 5*d*). In addition, the massive core zones in the tabular lava flow units are much thicker and have lower porosities than the massive zones of the braided lava flows (Fig. 5*c*). The base vesicle zones are slightly thicker than the base vesicle zones in the braided lava flow units, and the tabular lava units show the development of bedding joints (Fig. 5*f*). Therefore, the boundary between the top vesicle zone and the massive core zone is defined by the sudden disappearance of the large round pores, and the boundary between the massive core zone and the base vesicle zone is defined by the occurrence of bedding joints and small round pores.

Basalt lava flow units in the Songliao Basin

The outcrop studies provided essential geological data to construct models regarding the distribution of vesicles in the two types of lava flows identified in the Hailaer Basin. In the Songliao Basin, petrophysical logs from the boreholes provided comparable data, however, only in one dimension. Seismic data can be used to identify large lava flow units and map their extent, which is a parameter that cannot be directly measured in the outcrop. In this section, we discuss the identification of the basalt lava flow units in boreholes and seismic sections.

Basalt lava flow units in boreholes

Basalt lava flow units and vesicle zones within lava flows can be identified by analyzing cores and logs (Boldreel 2006). An example of boreholes in the Xujiaweizi graben of the Songliao Basin is illustrated in Fig. 6. The basalt in this borehole can be divided into 12 lava flow units based on eruptive unconformity boundaries. These boundaries can be identified by sudden changes in the resistivity and acoustic curves, which are attributable to sudden changes in porosity across the interface between any two units. The finger-shaped gamma-ray curve in the lower gamma-ray background, which reflects an alteration zone, can also indicate the presence of eruptive unconformity boundaries (Huang et al. 2011). Based on the identification of lava flow units, we were able to measure the thicknesses of the lava flow units. In addition, the relative changes in the acoustic curve can help determine the boundaries between different vesicle zones in basalt lava flow units (Fig. 6). Porosity variations and the distribution of vesicles within flow units are reflected by the sonic log. The top vesicle zones are characterized by high sonic transit times (Fig. 6, p1), whereas the massive core zones are characterized by low sonic transit times (Fig. 6, p2). Therefore, the boundary between the top vesicle zone and the massive core zone in a lava flow unit can be identified as the midpoint of changes (high to low) in the acoustic curve. Because the base vesicle zones are thin and cannot be accurately identified by logs in some lava flow units, we identified the massive core zone and the base vesicle zone as a single entity in the boreholes.

Basalt lava flow units identified by seismic data

Previous studies on volcanostratigraphy and volcanic seismic reflection across the southeast Atlantic and western Australian margins have provided a reliable method for identifying basalt lava flows in buried basins (Planke and Eldholm 1994; Planke et al. 2000; Petersen et al. 2006, 2013). In this study, the lateral extents of tabular lava flow units were obtained from seismic interpretations in the Songliao Basin (Fig. 7). Based on correlations with well data, the tabular lava flow units exhibit continuous, high-amplitude, and parallel or subparallel seismic reflection features. The braided lava flow units are discontinuous, with low to moderate amplitudes and a hummocky configuration (Fig. 7*a*). Based on these characteristics, the tabular and braided lava flow units were interpreted as shown in Fig. 7*b*. This analysis revealed that a succession of tabular lava flow units may extend to 10–20 km in the study basin.

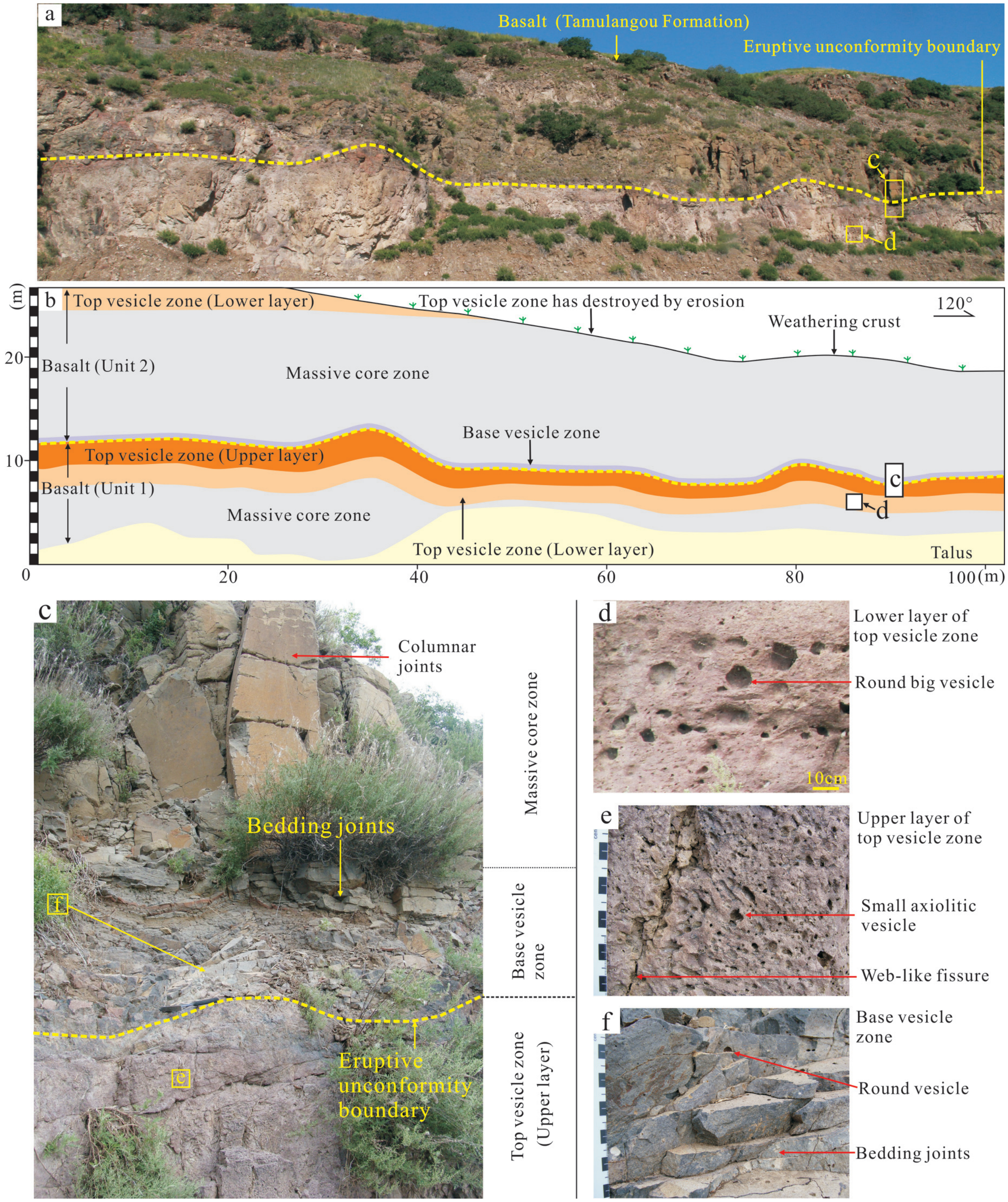
Vesicle distribution models

Vesicle distribution models of basalt lava flow units were established based on an analysis of outcrop and borehole data, including (*i*) conceptual geological models (Fig. 8) and (*ii*) vesicle distribution as a function of thickness models (Fig. 9).

Conceptual geological models

The conceptual geological models developed in this study describe the relationships among the shapes, scales, stacking patterns, and inner structures of the basalt lava flow units (Fig. 8). As the thicknesses increase, the shapes of the basalt lava flow units change from braided to tabular and the stacking patterns change from intersectional to vertical (Figs. 8*a* (I), 8*b* (I)). Two typical vertical sequences of braided lava flow units (Fig. 8*a* (II)) and tabular lava flow units (Fig. 8*b* (II)) were analyzed. The top vesicle zones in these two types of lava flow units are similar, with the exception of the size of round pores in the lower layers of the top vesicle zones. The massive core zones in the tabular lava flow units are much thicker than the massive core zones in the braided lava flow units and feature well-developed columnar joints. The base vesicle zones in the tabular lava flow units are thicker and feature numerous bedding joints.

Fig. 5. (*a*) General view of tabular lava flow units divided by an eruptive unconformity boundary. The basalt is a component of the Tamulangou Formation in Manchuria, northeast China. (*b*) Inner structures of the tabular lava flow units. (*c*) Partially enlarged photograph displaying the top vesicle zone (upper layer), the massive core zone, and the base vesicle zone. (*d*) Lower layer of the top vesicle zone with large round vesicles. (*e*) Upper layer of top vesicle zone with a large number of small axiolitic vesicles. (*f*) Base vesicle zone with bedding joints and several round vesicles.



Vesicle distribution as a function of thickness models

As indicated by the statistics in Fig. 9*a* (I), the measured thicknesses of the braided lava flow units in the Hailaer Basin are less than 8 m, whereas the minimum measured thickness of the tabular lava flow units is 8 m. In the Songliao Basin, the thicknesses of the basalt lava flow units range from 2 to 52 m; the majority of the thicknesses are between 2 and 15 m (Fig. 9*a* (II)). The thicknesses of the vesicle zones in the basalt lava flow units are indicated in Table 2. We compared the thicknesses of the vesicle zones estimated by this study with the thicknesses of the vesicle zones observed in the Skye lava field (Single and Jerram 2004). The two studies were broadly comparable with respect to this parameter.

As indicated in Fig. 9*b*, the thickness relationships between the top vesicle zones and the lava flow units were established from the outcrop and borehole data. The trends in the thicknesses of

Fig. 6. Example of basalt lava flow units in borehole D6. Based on the analysis of cores and logs, 12 lava flow units and their inner vesicle zones were identified. p1, core with a large number of vesicles (V); p2, core with few vesicles but several fissures (F). Refer to Fig. 3c for the location of borehole D6. A section of borehole D6 is also employed in Fig. 7. GR(API), natural gamma ray (American Petroleum Institute units); LLS/LLD, laterolog shallow / laterolog deep; AC, acoustic curve.

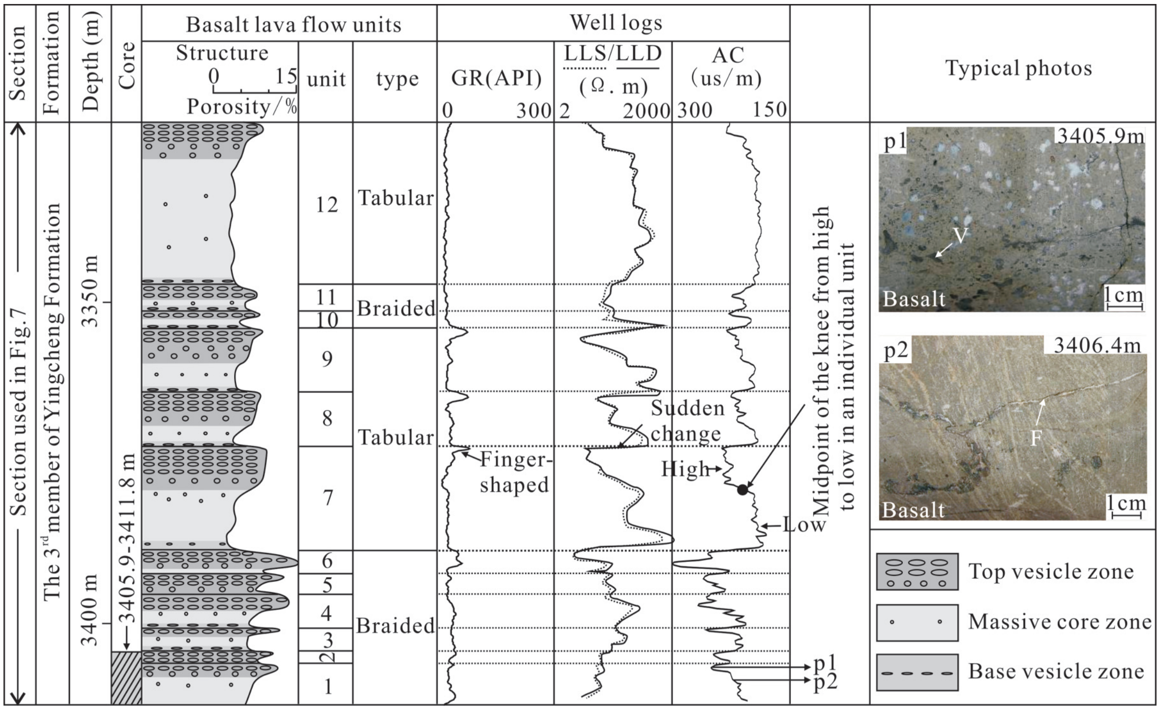
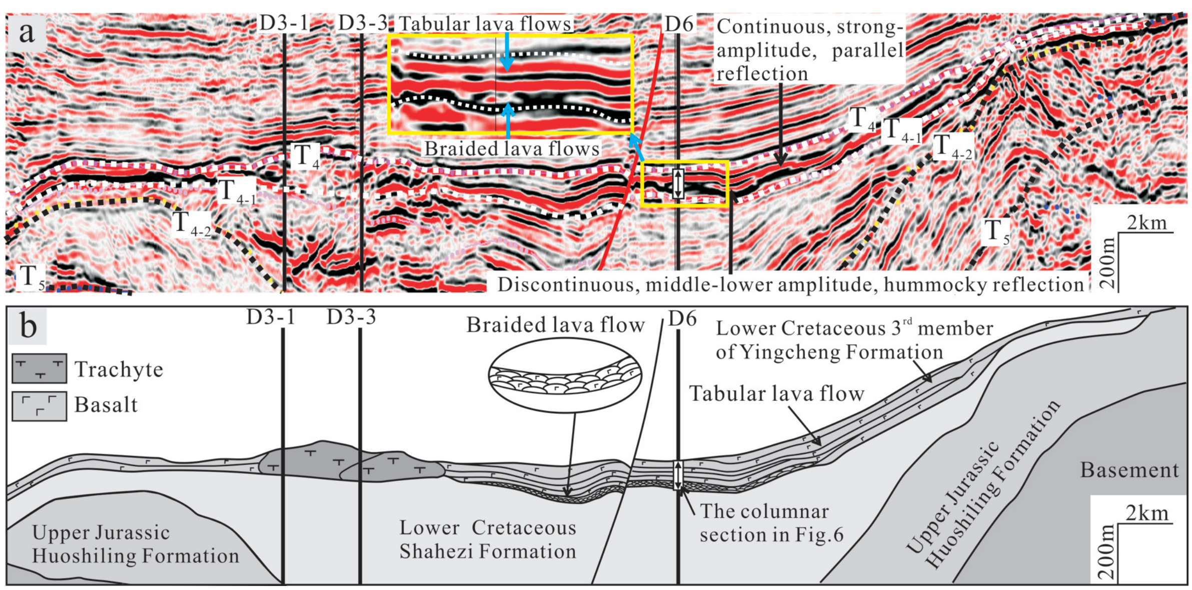
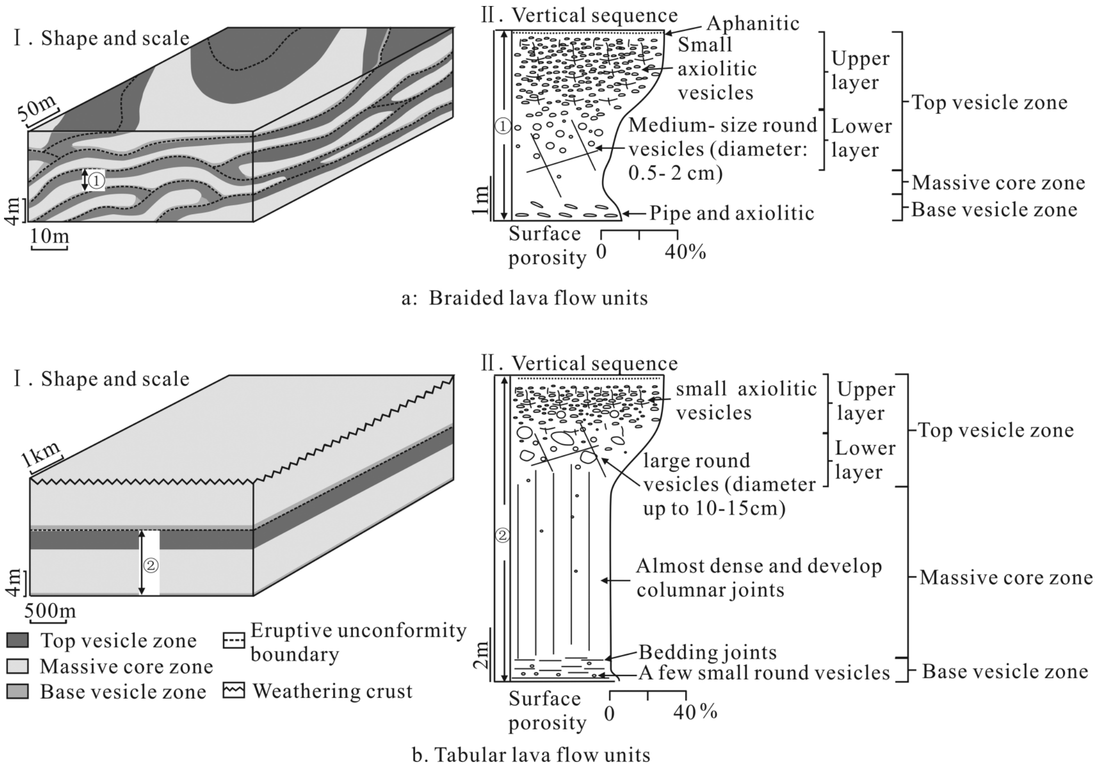


Fig. 7. Interpretation of basalt lava flow units using borehole and seismic data in the Xujiaweizi graben of the Songliao Basin. (*a*) Seismic section showing two typical configurations of basalt lava flow units; (*b*) interpretation of the seismic data. Seismic reflectors: T_4, top unconformity interface of the Yingcheng Formation; $T_{4\text{-}1}$, base unconformity interface of the Yingcheng Formation; $T_{4\text{-}2}$, base unconformity interface of the Shahezi Formation; T_5, subrift erosional surface overlying the Permo-Carboniferous basement. Refer to Fig. 3c for the location of the seismic section and Fig. 3a for the lithological placement of the seismic horizons.



the top vesicle zones versus the lava flow units can be expressed as a series of functions: (*i*) a linear function for thin (i.e., <2.6 and <2.8 m from outcrop data and borehole data, respectively) lava flow units and (*ii*) a logarithmical function for thicker lava flow units. This suggests that thin lava flow units commonly consist almost entirely of top vesicle zones, and the thicknesses of these top vesicle zones increase proportionally with the thicknesses of the basalt lava flow units within a certain range. Figure 9c illustrated that the trends in the thickness of the massive core zone and the base vesicle zone relative to the basalt lava flow unit thickness can be expressed by a piecewise linear function. It can be inferred that both the massive core zone and the base vesicle zone are absent in thin lava flow units, whereas the thicknesses of both zones linearly increase with the thicknesses of the lava flow units beyond a

Fig. 8. Conceptual geological models of (*a*) the braided lava flow units and (*b*) the tabular lava flow units.



certain thickness value. Because the base vesicle zone is typically thin and stable, the thicknesses of the massive core zone and the base vesicle zone can be approximated based on the thickness of the massive core zone. Therefore, the massive core zone comprises only a small or negligible proportion of a thin unit but constitutes a significant proportion of a thick lava flow unit.

Discussion

Distribution of reservoirs in basalt

Based on the understanding that the vesicle zone is the primary reservoir volume in basalt (Huang et al. 2010*b*), our findings suggest that (*i*) the distribution of the reservoirs follows an intersectional pattern in the braided lava flow units and is more stratified in the tabular lava flow units (as shown in Fig. 8) and (*ii*) the net reservoir thickness is a result of stacking of flow units (as illustrated in Fig. 10). In Fig. 10, we constructed a reservoir conceptual model to discuss the thicknesses of the reservoirs in basalt based on the assumption that the total basalt thickness is 40 m and is composed of different thicknesses of lava flow units. As the thicknesses of the lava flow units decrease, the proportion and total thicknesses of the reservoirs increase (Fig. 10). For example, when the basalt in this model comprises a single one unit 40 m thick, the vesicle zone accounted for only 16% of the total basalt. In contrast, the modeled basalt is entirely composed of vesicles when the thickness of the individual lava flow units is 2 m (Fig. 10). Therefore, a greater number of reservoirs develop in basalt derived from the stratification of thin lava flow units relative to basalt derived from thicker units. This inference is also supported by the observed porosity data. A greater number of high-porosity reservoirs develop in thin lava flow units relative to thicker units (Fig. 11).

Permeability of basalt reservoirs

Ólavsdóttir et al. (2015) observed very low permeability values in the basalt flow units in the North Atlantic region. In the Songliao Basin of northeast China, the permeability in the basalt flow units is generally low. The value of permeability ranges from 95 to 0.004 md (1 md = 0.001 μm^2), with a mean value of 0.08 md (Wang and Chen 2015). However, the permeability limitation for the nature gas reservoir is not very strict. The lower permeability limit of an effective gas reservoir in basalt is 0.005 md in this area (Huang 2010*a*). Figure 12 shows that permeability generally increases with porosity. Therefore, the vesicle zones in the basalt lava flows represent the primary effective gas reservoirs in this area.

Conclusions

(1) *Conceptual geological models:* The basalts in the Hailaer and Songliao basins comprise two types of lava flows: braided lava flows and tabular lava flows. Their inner structures can be divided into three vesicle zones: the top vesicle zone, the massive core zone, and the base vesicle zone.
(2) *Thickness characteristics and model applicability:* The thicknesses of the basalt lava flow units in this study range from 2 to 52 m, with most values in the range of 2–15 m. The thicknesses of the top vesicle zones, the massive core zones, and the base vesicle zones range from 1 to 7 m, 0 to 42.9 m, and 0 to 0.6 m, respectively. These results are generally comparable to the results obtained in the Skye lava field (Single and Jerram 2004), indicating that the quantitative models established in this study are not only suitable in the study area but also applicable to other regions.
(3) *Trends in the thicknesses of vesicle zones versus basalt lava flow units:* The trends in the thicknesses of the top vesicle zones versus the thicknesses of the basalt lava flow units can be expressed by a piecewise function that can be separated into a linear function and a logarithmic function. The trends in the thicknesses of the massive core zone and base vesicle zone versus the thicknesses of the basalt lava flow units can be expressed by a piecewise linear function.
(4) *Petroleum reservoir significance:* When basalt flows serve as petroleum reservoirs as in northeast China, the reservoirs primarily develop in the upper vesicle zone in an individual lava flow unit,

Fig. 9. Vesicle distribution as a function of thickness models: (*a*) thicknesses of basalt lava flow units; trends in thicknesses of (*b*) TVZ and (*c*) MCZ + BVZ versus basalt lava flow units. *N*, number of units; TVZ, top vesicle zone; MCZ, massive core zone; BVZ, base vesicle zone; R^2, coefficient of determination.

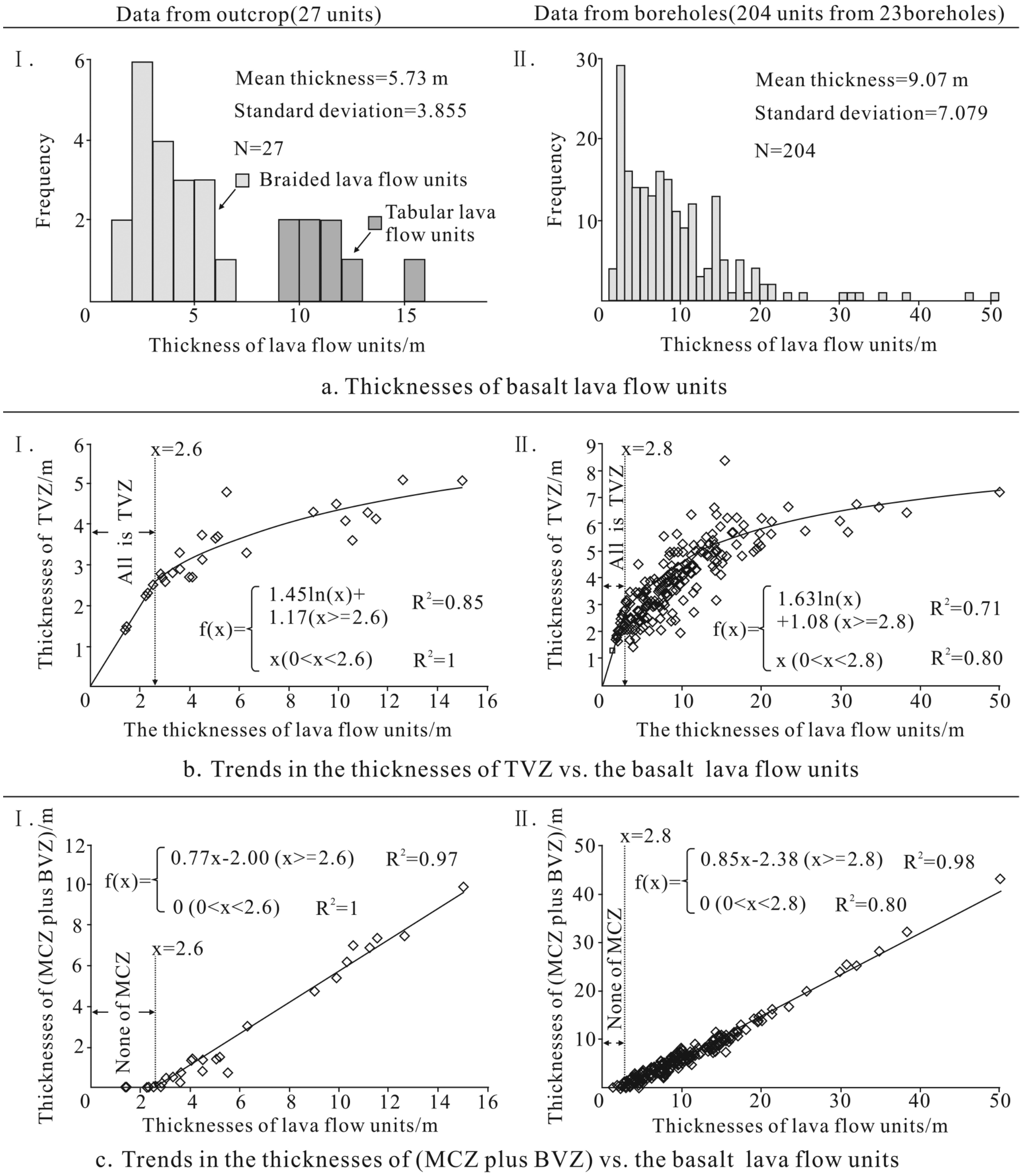


Table 2. Thicknesses of vesicle zones in the basalt lava flow units.

		Thickness of vesicle zone		
Lava flow unit	Vesicle zone	Outcrop at margin of Hailaer Basin minimum–maximum (mean) (m)	Boreholes in Songliao Basin minimum–maximum (mean) (m)	Data from Skye lava field (Single and Jerram 2004) (m)
Braided lava flows	Top vesicle zones	1.4–4.8 (2.8)	1.4–5.6 (2.8)	—
	Massive core zones	0–3 (0.7)	0–5.3 (1.7)	0.5–3
	Base vesicle zones	0–0.2	0–5.3 (1.7)	<0.4
Tabular lava flows	Top vesicle zones	4.3–5.1 (4.4)	2–8.5 (4.8)	<3
	Massive core zones	4.7–9.9 (6.9)	3.5–42.9 (9.9)	>5
	Base vesicle zones	0.2–0.6	3.5–42.9 (9.9)	<0.5

Fig. 10. Reservoir model developed in this study, which reveals that the number and proportion of vesicle zones exhibit an inversely proportional relationship with the thickness of the lava flow units. Thicknesses of vesicle zones are calculated using the function indicated in Fig. 9*b* (II).

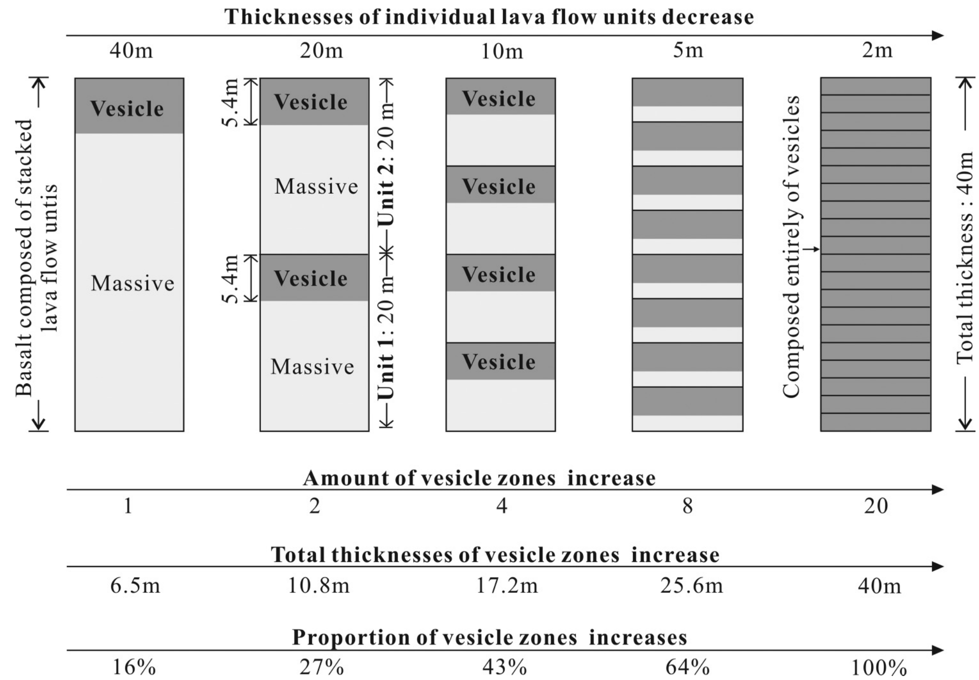


Fig. 11. Porosities of basalt lava flow units with different thicknesses (from borehole data): (*a*) thicknesses of lava flow units ≤10 m; (*b*) thicknesses of lava flow units >10 m. Std. dev., standard deviation.

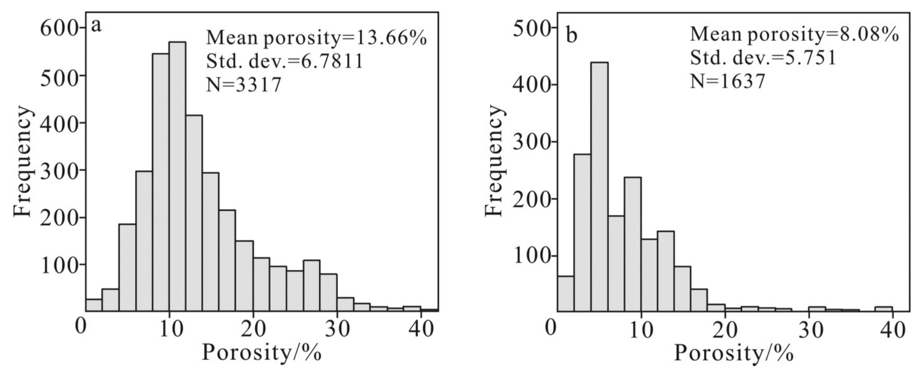
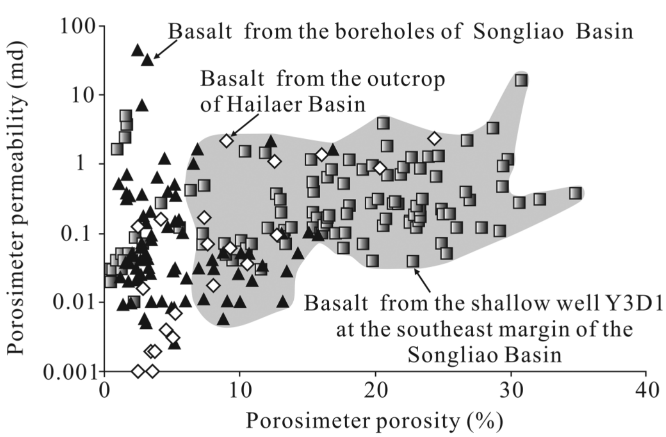


Fig. 12. Crossplot between the porosimeter porosity and permeability of the basalt. Gray area represents an effective gas reservoir. Lower permeability and porosity limits of an effective gas reservoir in basalt are 0.005 md and 6.2%, respectively, in this area.



and these processes are relatively independent among units. Owing to the stacking of lava flow units, the net-gross ratio of reservoir thickness is attributed to the stacking patterns. Reservoirs with high net-gross ratios are most common in stacks composed of stacked, thin braided lava flow units.

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