Types and Characteristics of Volcanostratigraphic Boundaries and Their Oil-Gas Reservoir Significance

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Abstract: Just like in sedimentary stratigraphy, the volcanostratigraphic boundary is an important factor for constructing volcanostratigraphic framework. The fundamental factor of volcanostratigraphic boundaries is to classify the types and define their characteristics. Based on field investigation and cross-wells section analysis of Mesozoic volcanostratigraphy in NE China, 5 types of volcanostratigraphic boundaries have been recognized, namely eruptive conformity boundary (ECB), eruptive unconformity boundary (EUB), eruptive interval unconformity boundary (EIUB), tectonic unconformity boundary (TUB) and intrusive contacts boundary (ICB). Except ICB, the unconformity boundaries can be divided into angular unconformity and paraconformity. The time spans and signs of these boundaries are analyzed by using age data of some volcanic fields that have been published. The time spans of ECB and EUB are from several minutes to years. In lava flows, cooling crust is distributed above and below ECB and EUB; in pyroclastic flows, airfalls and lahars, a fine layer below these boundaries has no discernable erosion at every part of the boundary. EUB may be curved or cross curved and jagged. The scale of ECB/EUB is dependent on the scale of lava flow or pyroclastic flows. The time span of EIUB is from decades to thousands of years. There is also weathered crust under EIUB and sedimentary rock beds overlie EIUB. In most instances, weathered crust and thin sedimentary beds are associated with each other laterally. The boundary is a smooth curved plane. The scale of EIUB is dependent on the scale of the volcano or volcano groups. The characteristics of TUB are similar to EIUB's. The time interval of TUB is from tens of thousands to millions of years. The scale of TUB depends on the scale of the basin or volcanic field. Both the lab data and logging data of wells in the Songliao Basin reveal that the porosity is greatly related to the boundaries in the lava flows. There is a high-porosity belt below ECB, EUB or EIUB, and the porosity decreases when it is apart from the boundary. The high-porosity belt below ECB and EUB is mainly contributed by primary porosity, such as vesicles. The high-porosity belt below EIUB is mainly contributed by primary and secondary porosity, such as association of vesicles and spongy pores, so the area near the boundary in lava flows is a very important target for reservoirs.

Key words: volcanostratigraphy, unconformity boundary, geological characteristics, northeast part of China, volcanic rocks

1 Introduction

The volcanostratigraphic sequence is composed mainly of pyroclastic lava, intrusive rock and lahar deposits, which vary laterally in thickness and distribution over short distances. This variability affects detailed comparison of volcanostratigraphy. Just like in sedimentary stratigraphy, the volcanostratigraphy boundary is the most important factor for constructing volcanostratigraphic framework.

Modern volcanoes have more advantages than paleo-volcanoes or deep-buried volcanoes in boundary identification because of historical documentation and less erosion (Gourgauda et al., 2000). For example, the Hoei eruption (AD 1707) of the Fuji volcano can be divided into 6 pulses and 3 stages on the basis of historical documentation, unconformity and hiatus in outcrops (Miyaji, et al., 2011). Unfortunately, most of the paleo-volcanoes have no historical documentation and hence geologic methods are very important in describing these boundaries. For instance, sedimentological and

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geochemical methods can sufficiently be used to define eruptive sequences in paleo-volcanoes (Jia and Zhang, 1996; Cai and Fu, 1997; Meng and Gao, 2004). Moreover, the occurrence of stratigraphic discontinuities, such as erosion unconformities and paleosols, can be used to delimit different eruptive sequences (Rita et al., 1997; Corsaro et al., 2002; Isaia et al., 2004). Also, measurements of gamma-ray and grain-size dependent magnetic susceptibility are helpful to unravel some uncertainties of volcanostratigraphy of the La Fossa deposits (Gehring, 2004). On the other hand, the data of well logging and high-resolution seismic data are very important to interpret deeply buried volcanostratigraphy. For example, the volcanic feature of the North Rockall Trough is delineated by using visualization techniques on 3D seismic reflection data (Thomson, 2005). In the Songliao Basin, the sequence of deep-buried volcanoes is ascertained by seismic and logging data (Tang et al., 2011, 2012a, 2012b).

The above discussion shows that the fundamental factor of volcanostratigraphic research is to recognize volcanostratigraphic boundaries. In fact, the classification of volcanostratigraphic boundaries is not adequately explained. Eruptive interval boundaries, such as paleosols or erosional unconformities, have obtained the most attention. Boundaries which are formed during pulses or phases are ignored, but are very meaningful to construct high-resolution framework that is very important to volcanic gas and oil pool analysis. This paper attempts to discuss the types and geologic attributes of the

volcanostratigraphic boundary. We will pay attention to various types of volcanostratigraphic boundary and give detailed description and discussion in the study with focus especially on boundaries of paleovolcano lava flows.

2 Types of Volcanostratigraphic Boundary

Volcanostratigraphic boundaries can be classified according to the time span and dynamics of boundary formation. They are eruptive conformity boundary (ECB), eruptive unconformity boundary (EUB), eruptive interval unconformity boundary (EIUB) (Fig. 1a), tectonic unconformity boundary (TUB) (Fig. 1b) and intrusive contacts (IC) (Fig. 1a). Furthermore, the EUB is subdivided into eruptive angular unconformity boundary (EAUB) and eruptive paraconformity boundary (EPB). The EIUB is subdivided into eruptive interval paraconformity boundary (EIPB) and eruptive interval angular unconformity boundary (EIAUB), and the TUB into tectonic paraconformity boundary (TPB) and tectonic angular unconformity boundary (TAUB) (Table 1).

2.1 Eruptive conformity boundary (ECB) and eruptive unconformity boundary (EUB)

Boundaries exist between lava flows, pyroclastic flows, airfalls and lahars, which are formed during eruptive pulses or phases with time intervals ranging from seconds to years (Fisher and Schmincke, 1984; Salvador, 1987; Jerram, 2002; Single and Jerram, 2004). Fig. 1a shows characteristics of the volcanostratigraphical boundary of
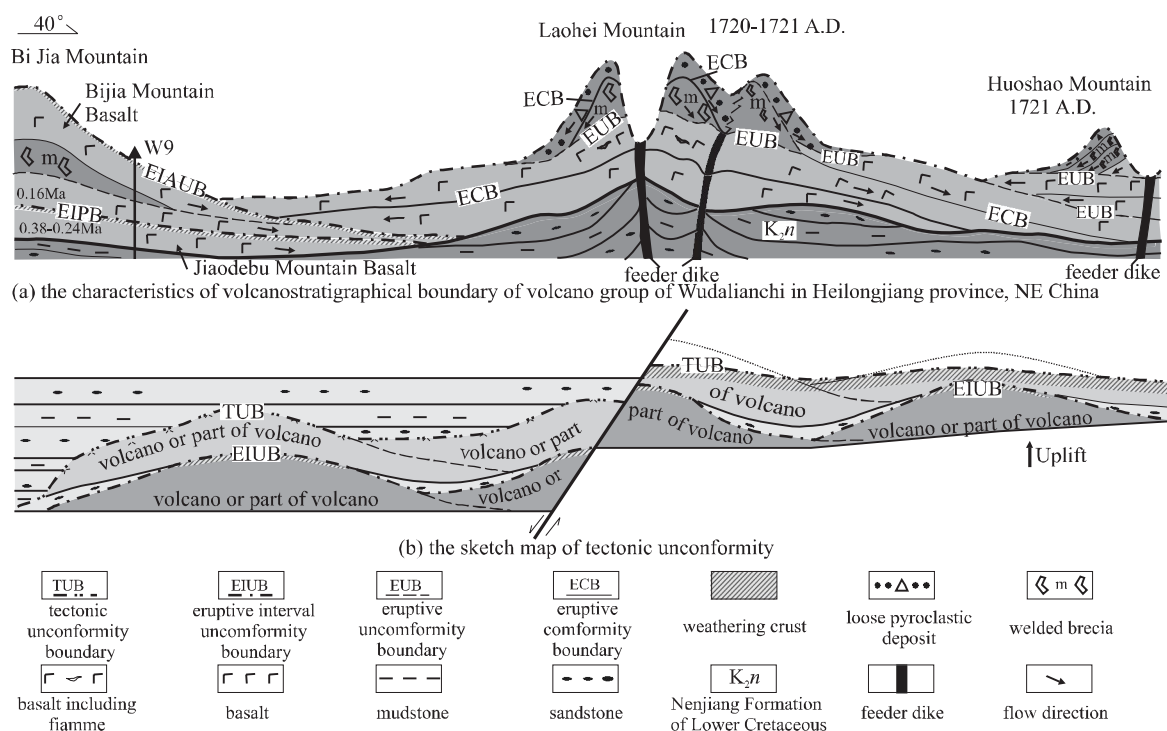

(a) the characteristics of volcanostratigraphical boundary of volcano group of Wudalianchi in Heilongjiang province, NE China

(b) the sketch map of tectonic unconformity

Fig. 1. A sketch map of characteristics of the volcanostratigraphic boundary.

Table1 Characteristics of volcanostratigraphic boundaries

Boundary type	Sign	Time span	Location	Lithology
Eruptive conformity boundary (ECB)	Lag breccia (see Figs. 3, 12 in Lindsay et al., 2001)	Hours to days?	Between Atana and Toconao ignimbrite	Rhyolitic rocks and andesitic rocks
	Relic spherulite horizon/ lithophysal horizon/ intensely perliticvitrophyre (see Figs. 3, 5, 6 in Andrews et al., 2008)	Minutes to days?	Between Jackpot 5 and Jackpot 4 in Jackpot rhyolite member/ inner rabbit spring ignimbrite member / brown's view member	Rhyolitic rocks, graben basin
	Pumice train, accretionary lapilli layer, oxidized layer (see Fig. 3 in Giannetti and Casa, 2000)	Minutes to days?	Between the flow unit which is inner of the unit B, D and E of Lower white trachytic tuff	Trachytic tuff
	Historic document, lithology facies during eruptive plus or stage (see Fig. 3 and Table 2 in Miyaji et al., 2011)	No hiatus to days?	Most of units	Rhyolitic rock of Hoei of Fuji volcano
Eruptive unconformity boundary (EUB), including paraconformity and angler unconformity	Historic document, facies during eruptive plus or stage (see Fig. 3 and Table 2 in Miyaji et al., 2011)	21.5 hours	Between unit J and K	Rhyolitic rock of Hoei of Fuji volcano
	Unconformity surfaces,amalgamation surface, by-pass or nondepositional surfaces during eruptive plus (see Fig. 1 in Rita et al., 1997)	Seconds to years	Between phases geological insignificant	
Eruptive interval unconformity boundary (EIUB), including paraconformity and angler unconformity	Truncation or erosion caused by tectonic collapse (see Fig. 2 in Lucchi et al., 2008)	Event, years to Ka?	Among intervals of erupitve activity (eruptive epochs)	Trachydacite-trachyte tuff
	Pebble gravel caused by erosion or reword (see Fig. 9 in Sohn et al., 2002)	Tens to hundreds of years	Most of boundaries between the units of Hamori Formation of Songaksan tuff ring, Jeju Island	Wet pyroclastic surge deposits and rework
	Paleosols,erosional structure, dipiric structure caused by erosion (see Figs. 3, 16 in Giannetti and Casa, 2000)	Several to tens of Ka	Between the units of the lower white trachytic tuff	Trachytic tuff
	Paleosols/ calcified rootlet/block weathered rock caused by buried landscape /erosion (see Fig. 2 in Andrews et al., 2008)	?	Among Jackpot member, Rabbit Springs member and Backwater member of Rogerson Formation	Rhyoliticrocks, graben basin
	Soils, caldera collapse, sector collapse and sedimentary rocks caused by erosion or rework during interval of eruptive period (see Fig. 1 in Rita et al., 1997)	Tectonic events (thousands to millions of years)	Between eruptions of significant duration of soils or erosional breaks to occur	
Tectonic unconformity boundary (TUB), including paraconformity and angler unconformity	Angular unconformity caused by transgression/tectonic subsidence (see Figs. 3, 4 and Table 2 in Khalaf et al., 2010)	Several Ma	Among the Fatira Ei Beida sequences, between Fatira Ei Zaraqa sequence and Gabal Fatira sequence	Submarine volcanic rocks, tholeiitic mafic and felsic volcaniclastic rocks, extensional back-arc tectonic setting
	Truncation/paleosols caused by tectonic uplift -subsidence / eustatic sea-level fall (see Figs. 3, 4 and Table 2 in Khalaf et al., 2010)	Several Ma	Inner of Fatira Ei Zaraqa sequence	
	Erosion conformity/ contact , which caused by intrusions and uplift/marine erosion, between intrusive rock and extrusive rock (see Figs. 10, 11 in Madeira et al., 2010)	Ca. 1.75 Ma (from 2.0 Ma to 0.25 Ma)	Between lower unit and upper unit, middle unite ant upper unite	Foidite, tephrite / basanite, phonotephrite, phonolite
	Paleosols, paleoweathered crust caused by marine erosion /subaerial erosion (see Fig. 2 in Lucchi et al., 2008)	Several to tens of Ka	Among the intervals of erupitve activity(eruptive epochs)	Trachydacite-trachyte tuff
	Gravel layer caused by erosion (see Fig. 3 in Lindsay et al., 2001), cooling crust	Ca. 1.5 Ma (4.0–5.5 Ma)	Between upper Tara and loweer Tara ignibrite	Rhyolitic rocks and andesitic rocks
Intrusive contact (IC) including con concordant and discordant	Baked contact (Guillou et al., 1996)	?	dike in volcanic island of El Hierro(hot pot)	Basalt?
	Metamorphism effect (Khalaf et al., 2010)	Tens of Ma	Between the sequences and granitic rocks	Granitic rocks
	Intrusions and uplift (see Figs. 10, 11 in Madeira et al., 2010)	Ca. 0.1–0.7 Ma (2.0–1.9 or 1.3 Ma)	Between lower unit and middle unit	Foidite, tephrite / basanite, phonotephrite, phonolite

the Wudalianchi volcano group. There are three volcanoes, namely the Bi Jia Mountain volcano (BJM), Lao Hei Mountain volcano (LHM) and Huo Shao Mountain volcano (HSM). The LHM includes tens of lava flows that erupted from January 14, 1720 to March 18, 1721 according to the historical documentations (Chen and Wu, 2003). The HSM includes several lava flows that erupted following the LHM from April 26 to May 28, 1721. The BJM includes several lava flows that erupted from 0.38 to 0.24 Ma and at 0.16 Ma (Li et al., 1999).

ECB can be formed by repeated eruption with very short life span (Table 1). Depending on velocity and

viscosity of magma eruption (Lockwood and Hazkett, 2010), different lava flows may occur. The ECB due to such eruption is thought to be conformable when its occurrence is concordant with adjacent volcanic flow units in the lower part of LHM and HSM (Fig. 1a) and when no hiatus or short hiatus is discernable. EUB may correspond to local hiatus for a specific eruptive phase. Unconformity might have developed due to a shift in eruptive focus during growth of the cone of LHM such as the cinder cone in northern California, USA (Lockwood and Hazkett, 2010). Furthermore, the boundary can be identified as EAUB when the modes of occurrence of the flow are different between the lower part and the cone of LHM and HSM (Fig. 1a). Such a boundary resulted from transition from subtle eruption to violent eruption. In addition, the EAUB is Formed by overlap flow units which come from different directions of LHM and HSM. On the other hand, the EUB can also be called EPB when young pyroclastic flows or lahars erode the older's and their occurrences are concordant.

2.2 Eruptive interval unconformity boundary (EIUB)

There are some boundaries existing between volcanoes or part of volcanoes, which were formed during the eruption phase or epoch with time intervals from years to thousands of years. The EIUB can be subdivided into the EIPB and EIAUB. The difference between the EIPB and EIAUB is the occurrence of the underlying and overlying volcanoes or part of volcanoes. A boundary is called EIPB when the occurrence is concordant between adjacent volcanoes, such as the weathering crust of the lower part of BJM, otherwise it is called EIAUB, such as the weathering crust of the upper part of BJM that borders with LHM.

Both of the above volcanostratigraphic boundaries have hiatus and discernable erosion (Table 1). At least, some parts of cooled crust of lava flow or fine layers in the upper part of a volcano are not visible. Weathering crust, such as BJM, is usually developed in such places (Fig. 1a). Sometimes, there are sedimentary rocks above the lower part of a volcano.

2.3 Tectonic unconformity boundary (TUB)

TUBs are also volcanostratigraphic boundaries among volcanoes or volcanic fields and regions that were formed during an eruptive period or epoch with time intervals from tens of thousands to millions of years (Table 1). The TUB is often an unconformity between two members or formations whose bedding planes are discordant. There are two boundary relationships. One is presented as contact between the overlying sedimentary rocks (ca. hundreds of meters thick) and the underlying volcanic rocks (left in Fig. 1b), and the other is presented as a boundary formed

due to long-term exposure and erosion of the underlying volcanic rocks(Xu et al, 2013a).

2.4 Intrusive contact (IC)

ICs are boundaries of intrusive rocks and subvolcanic rocks accompanied with volcanic rocks and sedimentary rocks such as sills, dikes, laccolites or stocks (Gu et al., 2002; Wu et al., 2006; Rohrman, 2007; Rey et al., 2008; Guo et al, 2013). There are two types of such boundaries, namely concordant and discordant ones (Table 1). Intrusive rocks can form any occurrence in any time after eruption. Sills are concord to the country rocks, while dikes and laccolites intrude the host rock layers (Lee et al., 2006; Cukur et al., 2010). Subvolcanic rocks can form dikes during volcanic eruption along magma feeder conduits that cut the older country rocks (Fig. 1a).

3 Characteristics of Volcanostratigraphic Boundaries

Many classic marks of EUB and EIUB can be identified in volcanic fields and buried volcanic rocks. Also, TUB can be identified in buried volcanic rocks by using cores, cuts, logging and seismic data. Such places are shown in Fig. 2. This paper introduces the characteristics of volcanostratigraphic boundaries based on typical volcanic rocks of the Mesozoic in the northeast part of China, including basaltic and rhyolitic rocks of the early Cretaceous Yingcheng Formation, trachyte-andesite rocks of the Late Jurassic Maoersan Formation in the Songliao Basin and Late Jurassic Tamunagou Formation in the Hailar Basin (Li et al., 2010) formed with the subduction of the Paleo-Pacific plate beneath the Eurasian continent and of the Mongolia-Okhotsk oceanic plate beneath the Erguna massif (Xu et al., 2013b), respectively.

3.1 Eruptive uncomformity boundary (EUB)

Lithologies and textures are some of the signs of eruptive boundaries, such as AA lava, blocky lava, pahoehoe lava, toothpaste lava (Lockwood and Hazlett, 2010) and the fore stepping-back stepping stacking pattern (Rita et al., 1997). If any of theses lithologies and textures or assemblies is found, the eruptive boundary could be identified. Furthermore, the occurrence of flow units below and above the boundary is the main principle evidence of unconformity or conformity.

Fig. 3a shows boundary characteristics of basaltic compound lava flow. Compound lava flows are divided into 7 units according to the red oxidation zone that represents original surface of lava flow (Fig. 3a/I, II). The red oxidation zone is characterized by short hiatus between lava flows. This zone has an amount of small and
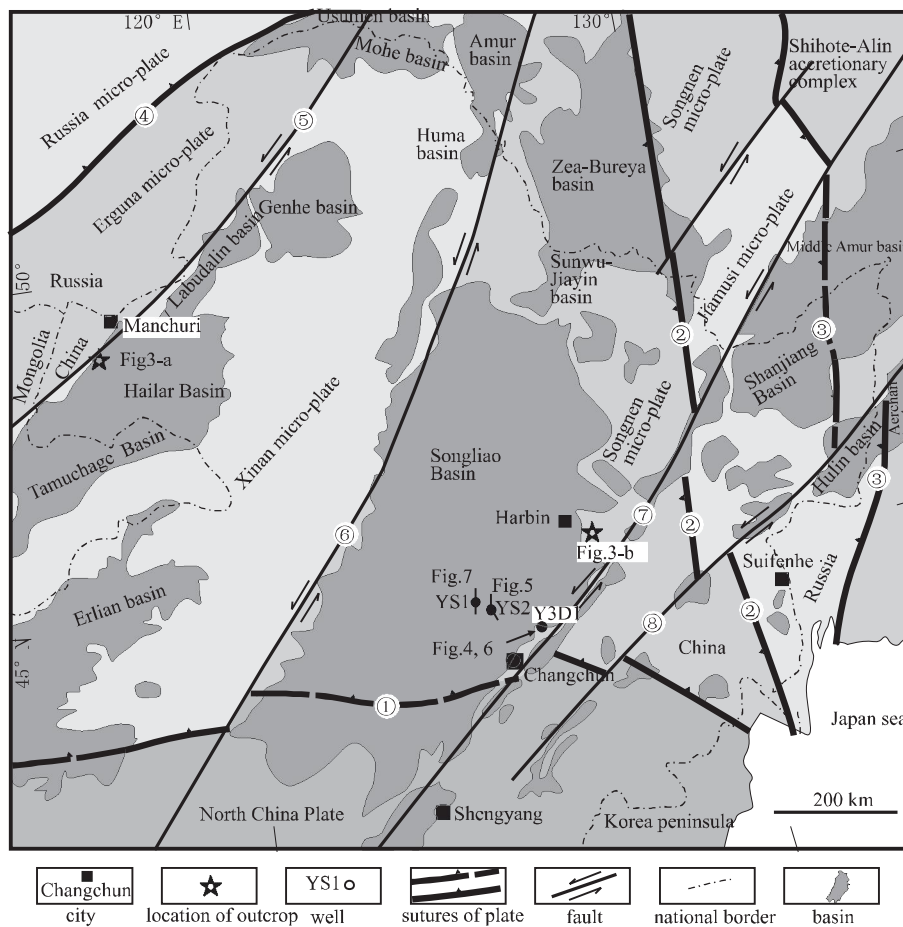
Fig. 2. A pilot map of the study area, showing tectonic elements and fault systems (after Zhang et al., 1999; Wang et al., 2007; Liu et al., 2011; Sun et al., 2011).
①Xilamulunhe-Chuangchun-Yanji suture zone;②Mudanjiang suture zone; ③Tongjian-Yuejishan suture zone; ④Mongolia-Okhotsk suture zone; ⑤ Derbugan fault; ⑥Nenjiang-Kailu fault; ⑦Jiamusi-Yitong fault; ⑧Dunhua-Mishan fault.

round vesicles, about centimeters thick Fig. 3a/IV). A zone of relatively large and round pores is next to the oxidation zone (Fig. 3a/IV). The middle part of lava flow is characterized by 15% plagioclase phenocryst (Fig. 3a/V), which is more than that in the upper part. Pipe-like pores are developed in the lower part of lava flow (Fig. 3a/III). Among lava flows the occurrence is discordant. Therefore, this boundary is regarded to be a EAUB. A typical feature of this boundary system is jagged, crosswise curved surface (Fig. 3a/I, II). The scale of such boundaries is dependent on the scale of lava flow.
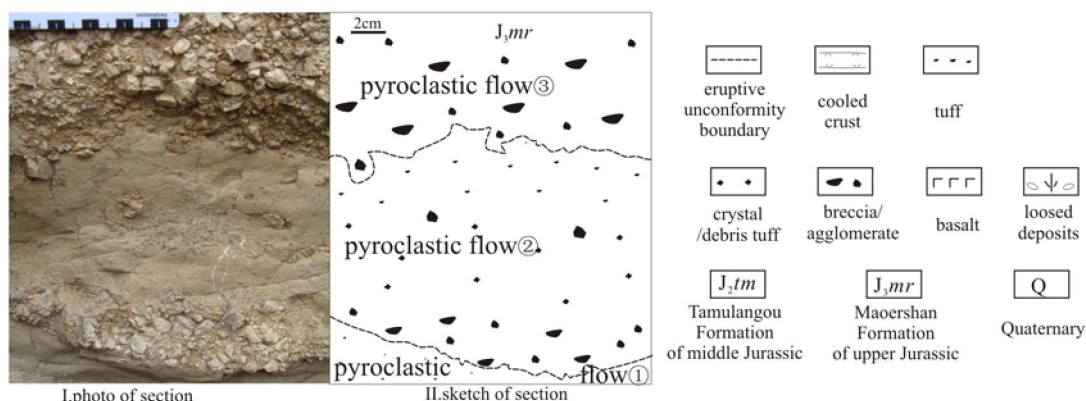
Fig. 3b shows boundary characteristics of pyroclastic flow. The boundary is jagged and curved as a result of younger coarse flow eroding the top fine part of older flow. The scale of the boundary depends on the scale of pyroclastic flow. The boundary is therefore classified as EUB because of its discontinuous record and the absence of hiatus. In case the mode of occurrence of those flow units cannot be measured, it is difficult to determine whether a boundary belongs to EPB or EAUB.

3.2 Eruptive interval unconformity boundary (EIUB)

Fig. 4a shows that the weathered crust is about 0.5 m thick, and consists of two parts, namely paleosol and survival beds. The rocks, both under and over the weathered crust, are gray basalt including breccia and vesicles (Fig. 4a/P1, P2). In Fig. 4, the paleosol consists of red clay (Ca. 60%), angular fragment of quartz (Ca.5%) and feldspar (Ca.15%), round-angular rock debris (Ca.17%) and calcareous layer (Ca.3%) (Figs. 4b, 4c). The angular debris (Ca.15%) in the upper part of the weathered crust is autoclastic basalt of younger lava flow that mixed with clay (Fig. 4b/P3, P4). The round debris (5%) in the lower part of the weathered crust was derived from erosion and reworking of older lava flow (Fig. 4b/P5). The clay is red and thick (Fig. 4b/P3, P5 and Fig. 4c/P6, P7), while the calcareous layer is yellowish-green and thin (Fig. 4c/P6, P8). Fig. 4d/P9, P10 shows that younger basalt lava flow injects paleosol, which is called injection structure, indicating there was loose deposit before the upper lava flow erupted. The weathered crust suggests that the volcanic

I. photo of quarry wall

II. sketch of quarry wall
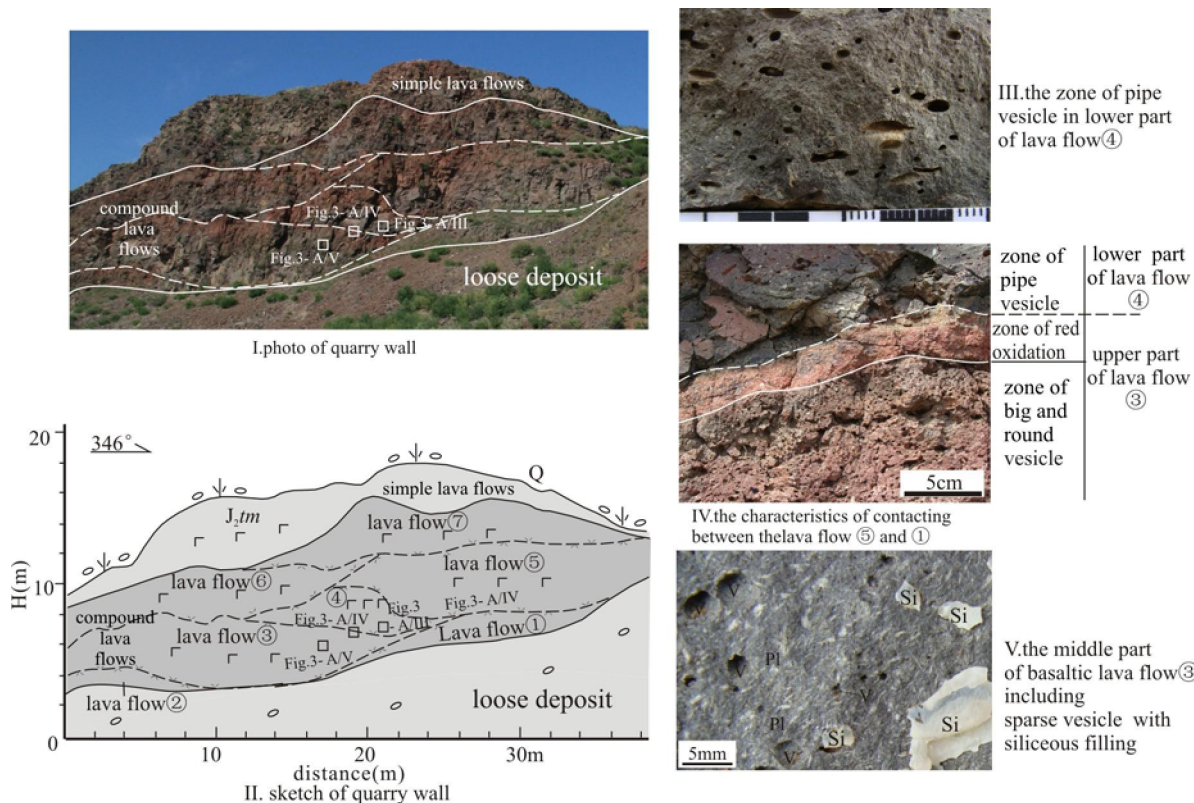
A. boundary characteristics of compound lava flow Tianrandong of Manchuri in Inner Mongolia, China

III. the zone of pipe vesicle in lower part of lava flow④

IV. the characteristics of contacting between the lava flow ⑤ and ①

V. the middle part of basaltic lava flow③ including sparse vesicle with siliceous filling

I. photo of section

II. sketch of section

B. boundary characteristics of pyroclastic flows of Shangzhi city of Helongjiang province, China

Fig. 3. Characteristics of the eruptive unconformity boundary.
Pl-plagioclase; Si-siliceous; V-vesicle.

eruption interval and the older volcanic rocks underwent erosion or reworking, and that the boundary is an EIUB. The typical feature of EIUB is smoothly curved surface. The scale of the boundary is dependent on the scale of volcano or volcano group. When the mode of occurrence of volcanic rocks cannot be measured, it is difficult to determine whether a boundary is EIPB or EIAUB.

3.3 Tectonic unconformity boundary (TUB)

TUB can be illustrated by volcanostratigraphic characteristics of the Yingcheng Formation in the Songliao Basin (Fig. 5). The relationship between well depth and reflection time of seismic wave is built by using sonic logging data. The contact between the frontier of older volcanic rocks of the 1st member of the Yingcheng Formation (K_1yc^1) and young sedimentary rocks of the 2nd member of the Yingcheng Formation (K_1yc^2). The top of K_1yc^1 is abruptly terminated in lateral direction and the most common pattern is onlap at the base of K_1yc^2. The bottom of the 3rd member of the Yingcheng Formation (K_1yc^3) shows a downlap pattern. K_1yc^2 is absent in Well YS201, whose time span is about 5 Ma (Wang et al., 2002,
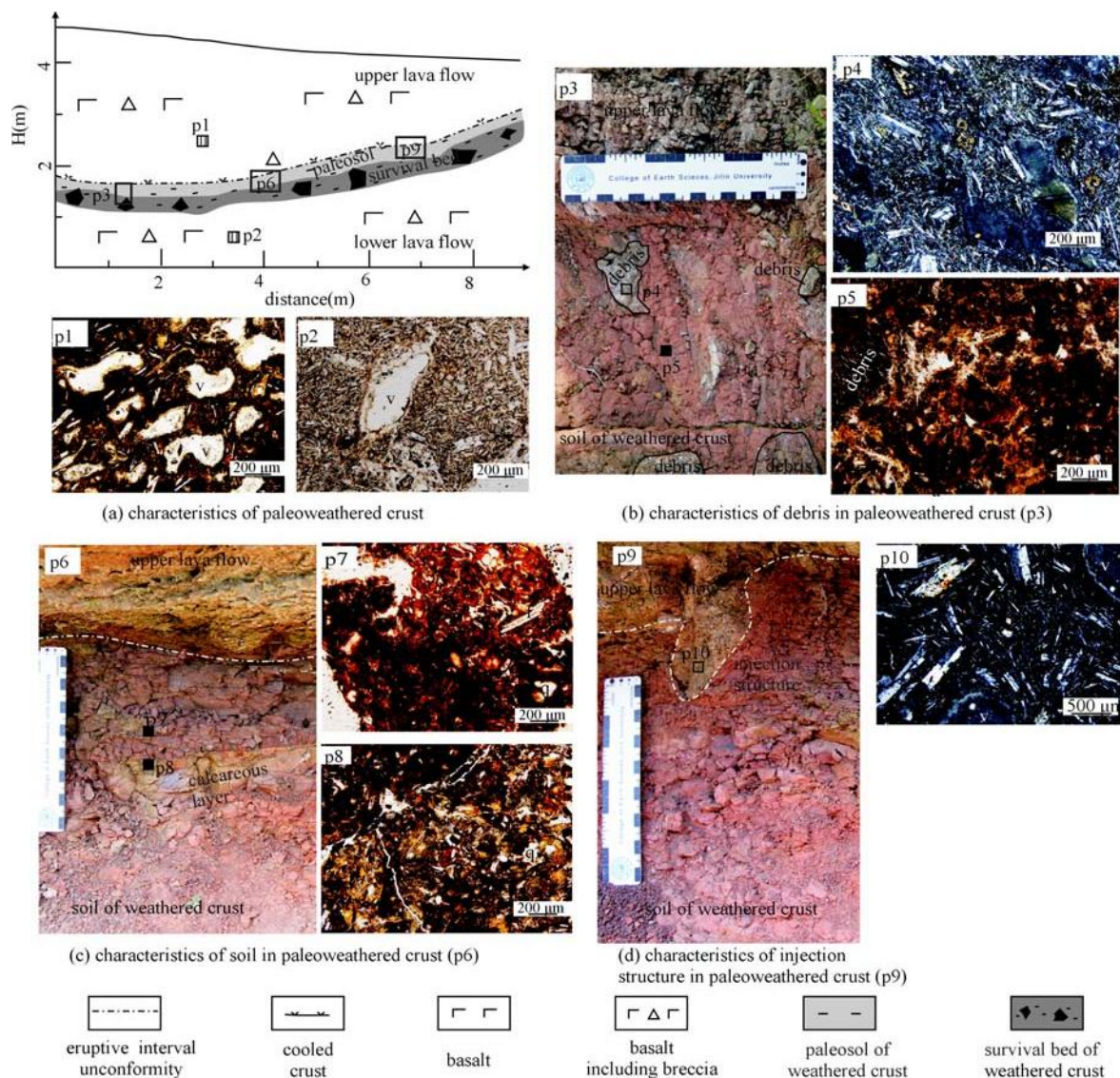
Fig. 4. Characteristics of the eruptive interval unconformity boundary of the 1st member of the Yingcheng Formation (K_1yc^1) in the Songliao basin, NE China.

F-felderspar; Q-quartz; Cal-calcite; V-vesicle. The samples at P3, P6 and P9 are loose. P1, P2, P5 and P8 are plane-polarized light. P4 and P10 are cross-polarized light.

1995). Therefore, the top boundary of K_1yc^1 in this area is tectonic unconformity. This type of boundary has two shapes at least. The first is strong-amplitude curved plane that follows the original landscape of volcanic field, and the second is weak-amplitude curved plane resulting from planation process. The scale of this type of boundary depends on the scale of basin or volcanic field.

4 Discussions

4.1 Porosity related to volcanostratigraphic boundaries
4.1.1 Porosity characteristics of ECB and EUB in lava flows

Fig. 6 shows four basaltic lava flow units. There is no discernable erosion among flow units and its occurrence cannot be measured. Pores are developed below ECB or EUB. The porosity of a single lava flow decreases when it is apart from the top boundary. The pores can be divided into two parts: one is the top part with high porosity, permeability and big throat radius because of abundant vesicles and amygdales (Fig. 6 P1 and P3), and the other is the middle and lower part with small porosity, permeability and throat radius because of sparse or none vesicles and amygdales (Fig. 6 P2 and P4). The porosity, permeability and throat radius decrease gently in each part and changes rapidly in the transitional zone between the two parts, especially in the simple lava flow. Good reservoirs are usually related to locations of ECB or EUB in lava flows. However, porosity characteristics related to boundaries in compound lava flows are different from
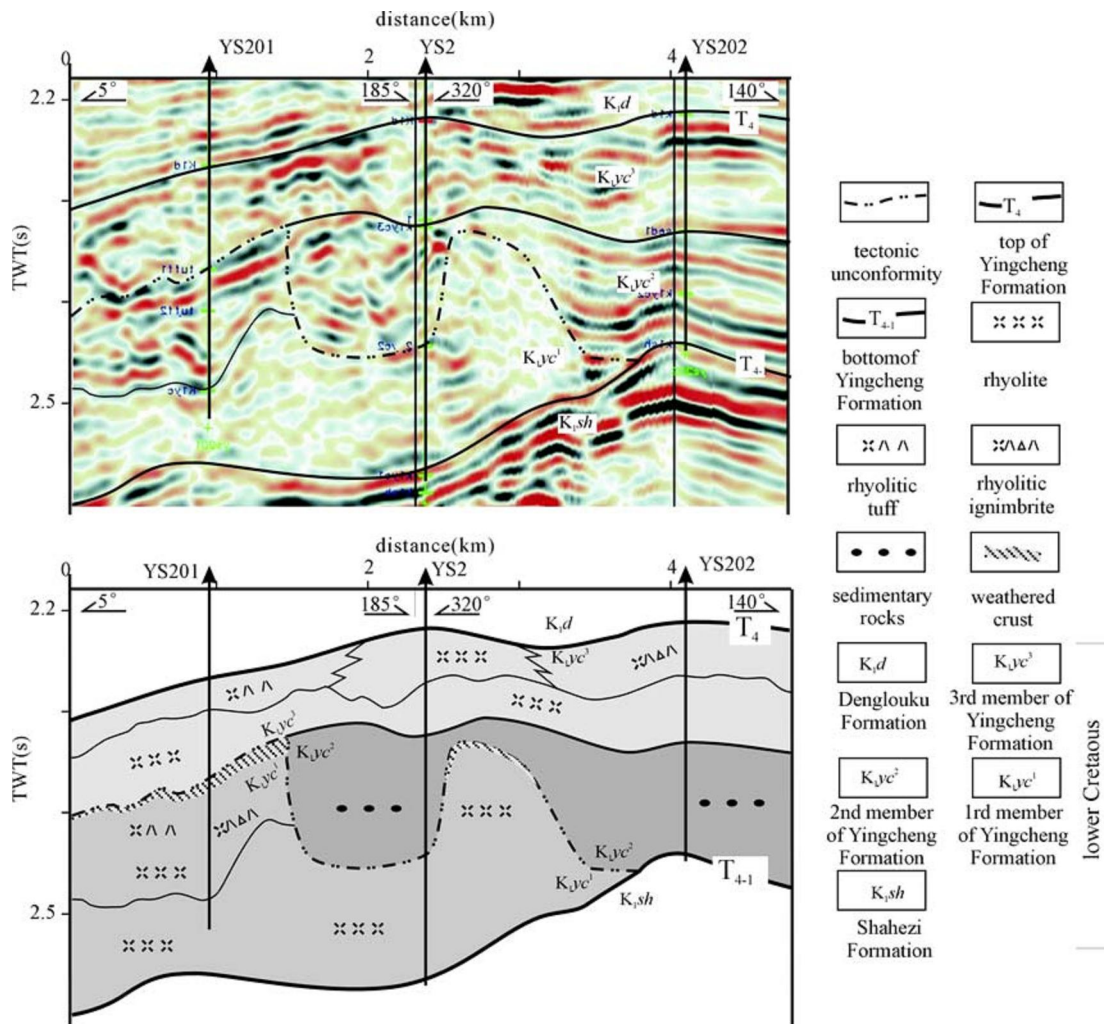
Fig. 5. Characteristics of the tectonic unconformity boundary of the Yingcheng Formation in the Songliao Basin, NE China.
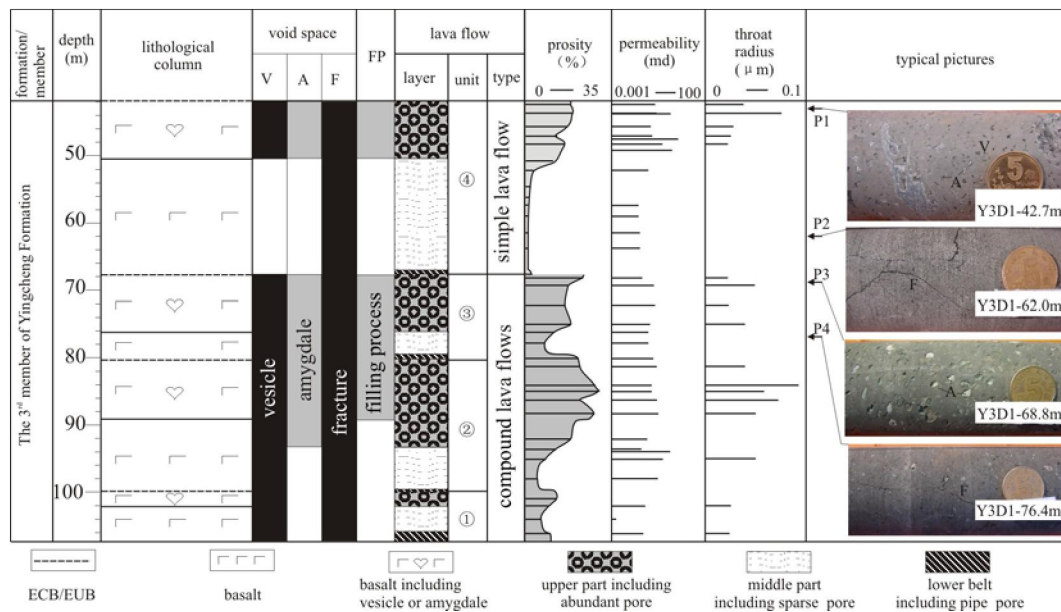

Fig. 6. Porosity correlates with ECB or EUB in basaltic lava flows of the 3rd member of the Yingcheng Formation of well Y3D1 in the Songliao Basin, NE China.
V-vesicle; A-amygdale; F-fracture; FP-filling process. The porosity, permeability and throat radius were measured in a constant-volume cell employing He and mercury (Hg) porosimeter.

those in simple lava flows. Firstly, the eruptive unconformity boundary of compound lava flows appears as a crosswise curve (Fig. 3a), but it is almost a plane in the case of simple lava flows (Tang et al., 2013). This means that good reservoirs in compound lava flows are probably connected each other laterally, which is different form simple lava flows, where no lateral connection is distinguishable. Secondly, the thickness ratio of the pores/vesicles belt to the sparse pore belt in compound lava flows is higher than that in simple lava flows.

4.1.2 Porosity characteristics of EIUB in lava flows

The relationship between well depth and reflection time can be described by using sonic logging data. The seismic reflection profile presents a continuous boundary in the Yingcheng Formation (Fig. 7a). This boundary has the following characteristics. First, the rock above the boundary is tuffaceous mudstone at wells YS101 and YS102, which is located on the flank of volcanoYS1. The boundary is very clear in the FMI image (Fig. 7b, 7d). Second, there is weathered crust below the boundary at well YS1, which is located on the top of volcanoYS1. It is characterized by high gamma and low density and resistance in the static FMI image (Fig. 7c). From the above it can be concluded that the boundary belongs to EIUB, and furthermore it is regarded to be a EIAUB according to the occurrence which is measured by FMI logging.

Below the EIUB of wells YS101 and 102 is compound rhyolitic lava flow. Core sample and cuts show that it is rich in primary and secondary porosity, such as vesicles (Fig. 7-P1) and spongy pores (Fig. 7-P2/3). The characteristics of porosity in well YS101 and YS102 are the same as those of the eruptive unconformity boundary of compound lava flow in Fig. 6. The characteristics of porosity in well YS1 is different from those of wells YS101 and YS102. The porosity of well YS1 changes rapidly when it is further apart from the boundary, ranging from a low-porosity belt about tens of centimeters thick to a high-porosity belt of about 4 m thick with rapid porosity decrease subsequently. Thus, the characteristics of reservoirs of EIUB are different from those of EUB and ECB, especially in weathered crust. The distribution characteristics of porosity correlated to EIUB is similar to tectonic unconformity boundary, which is a large-scale volcanic weathered crust of the Carboniferous in northern Xinjiang, China, but the thickness of the high-porosity layer of EIUB is smaller than that of TUB (Wang et al., 2011; Zou et al., 2011; Hou et al., 2012).

4.2 Filling units related to volcanostratigraphic boundaries

Volcanostratigraphic filling units are divided into the

following geologic bodies: lava flow unit/pyroclastic deposit unit, cooling unit, volcanic edifice, member and formation (Tang et al., 2012b). The lava flow unit/pyroclastic deposit unit is the basic unit defined by individual lava flow/pyroclastic flow from one eruptive center and disperses along a given direction. It is characterized by continuous change of dipping directions and angles. The cooling unit is characterized by the same cooling history and generally is overlapped by lava flow unit/pyroclastic deposit unit with similar dip and direction. The volcanic edifice is overlapped by cooling units mainly around the eruptive center. The dip angle and thickness of volcanic rock decrease from the central part to the distal parts along a given edifice limb.

Fig. 1a shows that a lava flow unit/pyroclastic deposit unit and cooling unit confined by ECB and/or EUB are generally tens of meters thick and thousands of meters in extent, and characterized by continuous change of dip directions and angles. This means that ECB and/or EUB is related to the lava flow unit/pyroclastic deposit unit or cooling unit. This figure also illustrates that volcanic edifices confined by EIUB are generally hundreds of meters thick and several kilometers in extent, and is characterized by continuous change of dip directions and angles. This means that EIUB is related to volcanic edifices. Stratigraphic members or formations confined by the TUB are generally hundreds of meters thick and tens of kilometers in extent. This means that TUB is related to members or formations of strata. In one word, volcanostratigraphic boundaries are related to the type of filling units.

5 Conclusions

According to time span and dynamic features of the formation of boundaries, volcanostratigraphic boundaries can be divided into ECB (eruptive conformity boundary), EUB (eruptive unconformity boundary), EIUB (eruptive interval unconformity boundary), TUB (tectonic unconformity boundary) and IC (intrusive contacts). Furthermore, the EUB includes EAUB (eruptive angular unconformity boundary) and EPB (eruptive paraconformity boundary). The EIUB includes EIPB (eruptive interval paraconformity boundary) and EIAUB (eruptive interval angler unconformity boundary). The TUB includes (TPB) tectonic paraconformity boundary and (TAUB) tectonic angular unconformity boundary.

Time intervals of ECB and EUB are from several minutes to years. There is cooling crust above and below these surfaces in lava flows, or there is no discernable erosion in all the boundaries in pyroclastic flows, airfalls and lahar. These two types of boundaries may be curved

(a) seismic reflection characteristics of volcanostratigraphy

(b) characteristics of eruptive interval unconformity boundary of well YS101

(c) characteristics of eruptive interval unconformity boundary of well YS1

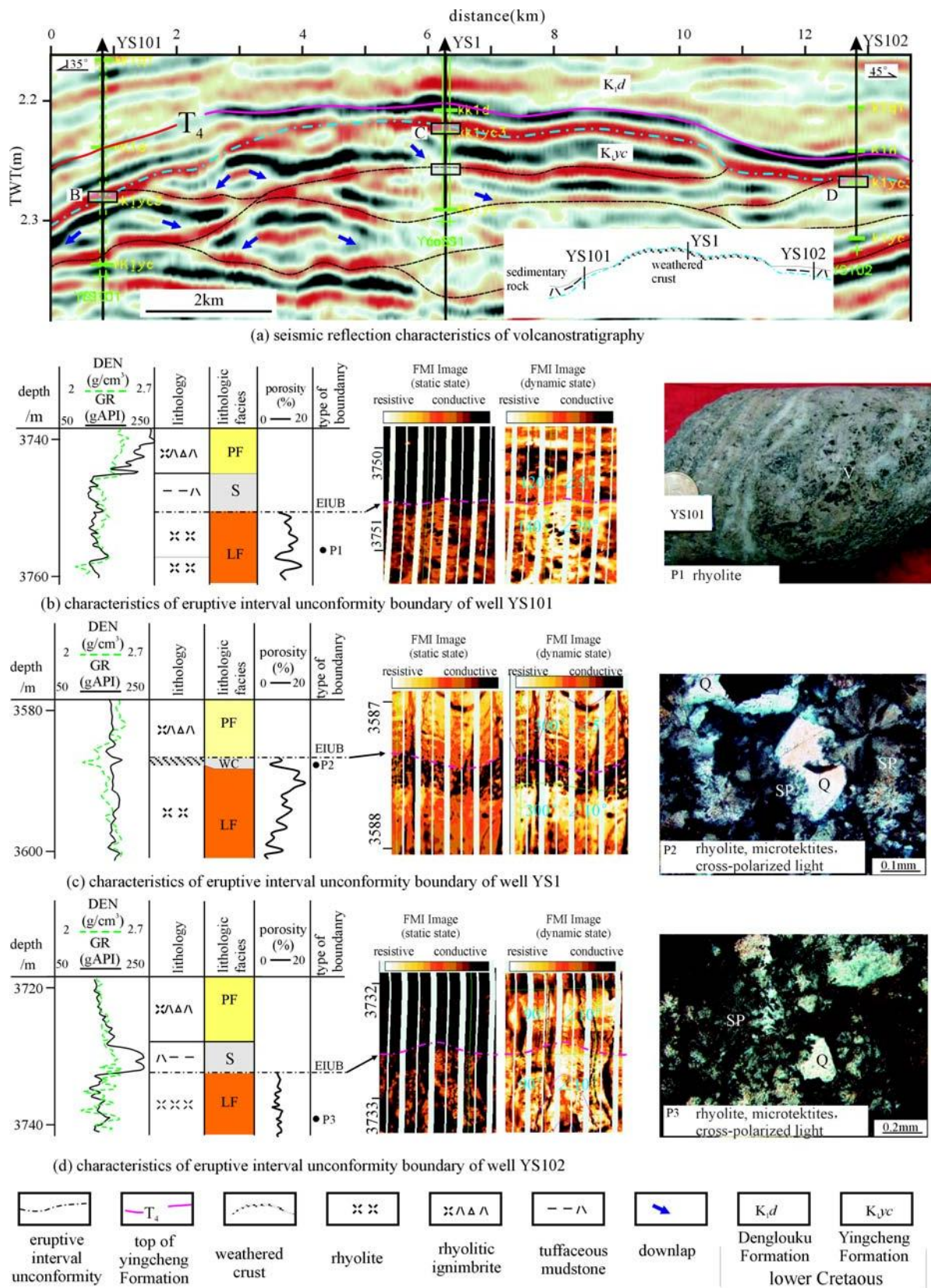(d) characteristics of eruptive interval unconformity boundary of well YS102

Fig. 7. Porosity characteristics correlate with the eruptive interval unconformity boundary of the 3rd member of the Yingcheng Formation in the Songliao Basin, NE China.

LF-lava flow; PF-pyroclastic flow; WC-weathered crust; EIUB-eruptive interval unconformity boundary; S-sedimentary rocks; V-vesicles; SP-spongy pore; Q-quartz.

or cross-curved and jagged and are distributed in relatively small areas. The EUB is related to primary porosity. Pores are developed below ECB or EUB. The porosity of a single lava flow decreases when it is further apart from the top boundary. Porosity, permeability and throat radius change rapidly in the transitional zone between the upper and the middle-lower part of lava flow.

Time intervals of EIUB are from decades to thousands of years. There is weathered crust under the EIUB, and sedimentary rocks overlie EIUB. In most cases, weathered crust and thin sedimentary bed are associated with each other laterally. The boundary is a smooth curve plane. Characteristics of TUB are similar to those of EIUB. The time interval of the tectonic unconformity boundary is from tens of thousands to millions of years, and the distribution scale is larger than that of EIUB. EIUB and TUB are likely related to secondary porosity, especially below weathered crust. High-porosity zones are probably developed below EIUB and TUB of lava flows.

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