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1 **The characteristics and formation mechanism of a regional fault in shale strata:**

2 **Insights from the Middle-Upper Yangtze, China**

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17 **Abstract**

18 Shale is a type of fracture-prone rock, but few regional faults are observed in shale
19 strata. Here, we investigate a regional detachment fault in the Middle-Upper Yangtze
20 (MUY) to understand the formation mechanism of a special regional fault in shale strata.
21 Based on a lithological, mineralogical, and mechanical study as well as semi-

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quantitative model of displacement, we found that the formation of this detachment fault is closely related to the lithological association and flexural slip processes. The lithological association of this detachment fault is characterized by two thick competent layers separated by a thin weak interlayer at both the macroscopic and microscopic scales. When these layers are folded, the detachment fault zone is commonly present in a thin weak interlayer, namely, the Wufeng Formation at the macroscopic scale, and primarily along interfaces in laminar siliceous shales (LSS) and secondarily in K-bentonite interlayers within the LSS at the microscopic scale. The regional fault zone is characterized by parallel to strata surfaces and abrupt contacts with the protolith. The fabric of the fault core is obviously controlled by the flexural slip intensity and the number of slip events, as well as their direction and structural position. The natural shale gas obtained from Well HD-1 has proven that this regional detachment fault in shale strata is not only a migration pathway for hydrocarbons but also acts as an adsorption state reservoir for free gas from other areas. This regional detachment fault in shale strata is likely to advance the shale gas industry and to expand the exploration of conventional gas.

Key words:

Detachment fault, Shale gas, Natural fracture, Sichuan Basin, Hydrocarbon migration

1. Introduction

Shale gas is defined as natural gas that occurs in organic-rich shale formations (Curtis, 2002; Zou et al., 2010). Shale formations are commonly so tight that shale gas

is commonly treated as one in situ enriched unconventional gas (self-generation and self-storage) that does not migrate or has a relatively short hydrocarbon migration distance (Curtis, 2002; Zou et al., 2010). However, practices show that the tectonic condition is the key factor for shale gas enrichment and prolific production in China (Guo and Zhang, 2014; Liu et al., 2018). As of November 28th, 2019, Well JY1-HF in Fuling county, Chongqing Municipality, had produced more than $1.13 \times 10^8 \text{ m}^3$ shale gas, which is approximately thrice the reserves ($4024.8 \times 10^4 \text{ m}^3$) connected by this borehole and its hydraulic fractures (He et al., 2018b). These results indicate that the shale gas is likely partially composed of gas that has undergone long-distance migration, which has commonly been ignored by previous studies. With the development of the shale gas industry, shale gas exploitation around the world has become increasingly restricted by certain issues, such as pollution (Zeng et al., 2013), expenses (Yu and Sepehrnoori, 2013), and the possibility of inducing earthquakes (Schultz et al., 2018) as a result of hydraulic fracturing. Until now, little shale gas buried deeper than 4,000 m has been extracted, given the restrictions on hydraulic fracturing technology and high cost. Hence, if shale gas can be obtained without hydraulic fracturing treatment, the industry exploiting shale gas could receive a significant boost.

In 2013, basing on the core samples and outcrop data from Chongqing Municipality, we found one naturally fractured layer in the Wufeng Formation. After a field survey lasting more than two years, we recognized that this fractured layer is a regional detachment fault that is merely 0.3-1.5 m thick but stable over 1000 km in the Middle-Upper Yangtze (MUY) (Fig. 1a). It is particular that this layer is located at the bottom

of a shale gas target layer (Wufeng-Longmaxi Formation) in the Sichuan Basin (He et al., 2018a; Potter, 2017; Qiu and Zou, 2019) (Fig. 1b, Fig. 2), which not only affects the regional stress field with its frictional instabilities but also likely acts as a regional hydrocarbon migration pathway in the shale gas reservoir formation. Guided by this deduction, we obtained the natural shale gas flow in Well HD-1 (Fig. 1b, Fig. 2). Well HD-1 is 1386 m deep and has a daily production of more than $0.3 \times 10^4 \text{ m}^3$ shale gas without hydraulic fracturing treatment (a conservative value that has been tested under a serious gas blow-by due to a defect in the well cementation). The shale gas is mainly from the detachment fault at depths of 1331.8-1333.0 m (He et al., 2018b). The investment return period of Well HD-1 is comparable to that of the shale gas exploration Well JY-1 (Fig. 1b). Therefore, if the detachment faults in the shale strata are well studied, the detachment-related shale gas can hopefully be exploited without hydraulic fracturing treatment, by using pinnate horizontal well technology (He et al., 2018a).

The faults and fractures are often regarded as effective channels for hydrocarbon migration and entrapment (Aydin, 2000; Smart et al., 2009b; Xu et al., 2019). Particularly, regional faults likely dominate the entrapment of hydrocarbons and the enrichment of shale gas. Shale is known to be a fracture-prone rock (Gale et al., 2014; Ma et al., 2020), but few regional faults have been observed in shale strata. Meanwhile, more than 99% of shale gas in China is produced in the MUY now. In this study, we took the detachment fault in the Wufeng Formation in MUY as an example, to investigate the formation mechanism of a regional detachment fault in shale stratum and its implications for hydrocarbon exploration. Outcrops, core samples, rock sections,

X-ray diffraction (XRD), scanning electron microscopy (SEM), microscopic computed tomography (Micro-CT), mechanical behavior tests and a semiquantitative study of flexural slip displacement were integrated to discuss the formation mechanism. Some experiences (e.g. Well HD-1) are applied to discuss the implications for hydrocarbon exploration in order to provide a preliminary insight into a way to boost shale gas industry these days.

2. Geological setting

MUY is more than 1200 km long in west to east direction and is located in the northwest of the Yangtze Block (YB) (Li et al., 2018a; Zhang et al., 2013). The MUY is a relatively stable quasicraton (Zhang et al., 2013) that is mainly composed of the Sichuan Basin and surrounded by the Qianzhong Uplift, the Xuefeng Mountains, and the Huaiyang Uplift (Fig. 1a). The MUY has experienced a complex tectonic and sedimentary history since the breakup of Rodinia at approximately 750 Ma BP (Zhao et al., 2018). It consists of the four main stages: (1) Neoproterozoic rift stage (approximately 750-635 Ma), in which the rift movement was mainly located in the northern, western and southeastern edge of the YB. (2) Passive continental margin stage (approximately 635-488 Ma), in which a large marine transgression had started in the Ediacaran period and caused the maximum flooding during the early Cambrian period. The marine transgression then progressed to marine regression. The YB was gradually growing from several local shallow carbonate platforms during the Ediacaran period to the full Yangtze carbonate platform at the end of the Cambrian period. (3) Proto-Tethys Ocean closure stage (approximately 488-420 Ma), in which the YB was transferred

from a passive continental margin to a compressional foreland basin. A new marine transgression sequence overlapped during the Cambrian at the beginning of the Ordovician period and the maximum flooding surface was reached at the end of the Ordovician period. A large marine regression was then initiated at the beginning of the Silurian period and regression from the YB was completed at the end of the Silurian period. (4) Orogeny stage (approximately 420 Ma to present). At the end of the Silurian period, the late Caledonian orogeny led to the formation of the northeast-trending central uplift. After the Caledonian orogeny and the Yunnan orogenic movements, all Devonian and Carboniferous systems were eroded in the MUY (Liang et al., 2016). A major regression occurred across the MUY from the late Early Triassic to Middle Triassic periods. By the end of the Triassic period, the depositional environment of the MUY transformed into a fluvial–lacustrine setting after the seawater had totally regressed. At present, the MUY is a prominent Mesozoic NE-trending fold-and-thrust belt (Li et al., 2018a). The thin-skinned and thick-skinned deformations (Fig.1) are dominated by the NW-directed thrust shearing deformation at 243–226 Ma (Chu et al., 2012). Three detachment faults developed above the Sinian in the Eastern Sichuan Basin (Fig.1 and Fig.3), such as the Middle-Lower Cambrian gypsum-salt rocks (ϵ_1), the Silurian shale (S_1l), and the gypsum-salt rocks in the Jialingjiang Formation–Leikoupo Formation (T_{1j} – T_{2l}) (Gu et al., 2015). Dominated by the detachment faults, the MUY can be divided in three structural layers. The upper structural layer is shallower than the detachment fault in the Jialingjiang Formation–Leikoupo Formation (T_{1j} – T_{2l}). In the shallower section of this structural layer, folds are dominated by the

NW-directed and NE-directed tectonic superposition. The folds are mainly characterized by wide centrocinal folds. The faults in these folds commonly disappear downward to the detachment fault (T_{1j} - T_{2l}). The middle structural layer is the section from the Silurian upward to the Jianlingjiang Formation (Fig.3). The structural trend of this structural layer is mainly NE-directed. The deformation is stronger and characterized by thrust faults, recoil faults, and the folds between them (Fig.1, Fig.3). The lower structural layer is the strata underlying the Silurian. This layer is commonly deeper than 6000 m and dominated by a gentle structure. The basement is not involved in the deformations. The strata underlying the Cambrian is deeper than the detection range of the seismic profile resolution and is assumed as one part of the lower structural layer (Li, 2005). Based on numerous outcrops and core samples (He et al., 2018a), it was recognized that the detachment faults in Silurian shale (S_{1l}) are located at the middle-upper Wufeng formation (O_{3w}) (Fig.2) and are stable over the MUY (Fig.1b). Since the Late Ordovician period, the Yangtze carbonate platform has gradually evolved into a siliciclastic-dominated inner shelf basin (Fig. 1a). In the MUY, the pagoda limestone (Baota Formation, O_{3b}) gradually evolved into siliceous shale (Wufeng Formation, O_{3w}). At the end of the Ordovician period, the MUY evolved into a shallow restricted basin with a barrier from the Xuefeng Mountains in the east and experienced a glacio-eustatic sea-level fall in the Hirnantian Stage (Creveling et al., 2018; Zou et al., 2018), recorded by the Guanyinqiao Formation (O_{3g}). As temperatures increased and sea levels rose starting in the Silurian period, the MUY returned to a deep inner shelf basin (Zou et al., 2018), as recorded by the Longmaxi Formation (S_{1l}). A

large marine regression was then initiated at the beginning of the Silurian period, and seawater retreated entirely out of the YB at the end of the Silurian period. The Wufeng-Longmaxi formations is the key production layer of shale gas in China, now.

3. Methodological approaches

Since 2005, a large number of shale gas wells have been drilled in the MUY and have provided considerable lithological, mineralogical, and petrophysical information (Dai et al., 2016; Hao et al., 2013; Li et al., 2018b; Yan et al., 2018). Based on this information, classical fieldwork combined with core sample tests was performed to guarantee broad coverage of the data. Fieldwork included lithological and structural analysis of the outcrops located in different structural positions and sedimentary facies. The analysis of seismic profiles, outcrops and core sample images are used to revealing the macroscopic features of the detachment fault. The core sample tests included rock slicing and processing, XRD, SEM, Micro-CT, and mechanical behavior testing. Combined with a semiquantitative study of flexural slip displacement in Well HD-1 and the petrophysical tests reported, all the tests were used to analyze the microscopic features and the kinematics of the detachment fault. In detail, the analytical and experimental methods were as follows:

A total of 354 samples from each lithological unit were ground to obtain a <200 mesh shale powder (i.e., <75 μm) so as to determine their mineral content by using XRD analysis. The XRD analysis was performed according to the two independent 2010 procedures of the China Petroleum Standardization Committee (CPSC) with a Bruker D8 DISCOVER diffractometer (Co K α -radiation, 45 kV, 35 mA). The diffracted

beam was measured with scintillation and 0.02° 2θ step size as well as 20 s step time.

The diffractogram was derived from 2° to 76° 2θ (Xiong et al., 2017).

The samples used for SEM mapping were first milled with an argon ion beam. SEM mapping was performed by inserting the vertically sectioned samples, coated with carbon, into a FEI Helios NanoLabTM 650 DualBeam FIB-SEM. The images were taken at distance of 4 mm with backscattered electrons at 5 kV acceleration voltage (Ma et al., 2016b). SEM imaging aimed to observe the microfracture distributions at high resolution.

The samples used for computed micro tomography (μ CT) were prepared in cylindrical shape with a length of 50 mm. The samples were scanned over 360° in large field view mode. The exposure time was 120 s and 1600 slices were collected during scanning for each sample. Afterwards, a 3D model of the respective sample was generated by importing the slices into Avizo Fire 8.1. From Avizo, the rendered volumes statistically yield the pore lengths and widths by assigning different grayscale values to the microstructural features of interest. Ultimately, the pore throat connectivity was qualitatively determined according to the grayscale values of different segmentations (Rist and Günes, 2008).

The core samples were drilled and cut to a size of 25.4 mm in diameter and 50.8 mm in length for the mechanical tests. The stress-strain correlations of the samples were measured with a triaxial rock mechanics testing system (RTR-1000 type) at a static constant speed (2 kN/min) during cyclic loading at a confining pressure of 20 MPa (Li et al., 2015). The shear strength was measured with an MTS-810 servohydraulic

materials testing system (MTS, USA). The shear stress was increased at a constant speed (2 kN/min) parallel to the bedding and the constant normal stress was 10 MPa (Ye et al., 2016).

4. Lithological characteristics

4.1. Lithological association

The lithological association is composed of five formations: the Baota Formation (O_3b), Linxiang Formation (O_3l), Wufeng Formation (O_3w), Guanyinqiao Formation (O_3g) and Longmaxi Formation (S_1l). The petrological features of these formations are as follows (Fig. 4a):

The Baota Formation (O_3b) is mainly composed of thick massive Pagoda limestone, which is characterized by a particular network structure with an unusually large spatiotemporal scale of homogeneity. This unit is up to 90 m thick in the stratigraphic section and extends almost continuously across the Yangtze Platform for over 2000 km in WE-direction (from Shanghai to Kunming) and approximately 800 km in NS-direction (from southern Shanxi to the southeastern Guizhou province), covering about $150 \times 10^4 \text{ km}^2$. Petrographically, the pagoda limestone is usually ranging from carbonate mudstone to wackestone (Zhuo et al., 2017) and typically consists of light gray to purplish red, medium- to thick-bedded, and pure to slightly argillaceous limestone (93%-97% CaCO_3). The network structure is predominantly meandering (Fig. 4a) and is filled with argillaceous limestone. The skeletons of benthic organisms are in the mm- to cm-size range and scatter in the limestone by less than 2%, with brachiopods and ostracodes showing common articulated preservation whereas crinoid ossicles are

220 usually disarticulated (Zhan et al., 2016).

221 The Linxiang Formation (O_3l) is scattered across the MUY and has a thickness of
222 2-5 m. The formation is absent around the northern part of the Longmenshan fault (Nie
223 et al., 2017) and is thickest at 180 m in the west of the MUY (Yanyuan County, Sichuan
224 Province). Furthermore, the Linxiang Formation is separated from the underlying Baota
225 Formation by a para-unconformity in the Northern Yangtze Uplift but is generally in
226 conformable contact with the underlying Baota Formation elsewhere. The Linxiang
227 Formation typically consists of medium- to thick-bedded nodular limestone (Fig. 4a).
228 In the middle and southwest of the MUY, the Linxiang Formation consists of
229 interlayered yellow shale, sandy shale, calcareous shale or banded limestone in the
230 upper section.

231 The Wufeng Formation (O_3w) was deposited at the end of the Ordovician period
232 during the height of the marine transgression, corresponding to the maximum flooding
233 surface. Although this formation is only 5-12 m thick, roughly increasing
234 southwestward, its distribution is much broader than that of the Baota Formation (Han
235 et al., 2016). From bottom to top, the Wufeng Formation typically consists of calcareous
236 mudstone, siliceous shale, Laminar Siliceous Shale (LSS), calcareous mudstone.
237 Although the calcium content in the Wufeng Formation gradually increases westward
238 in the MUY, and a lamellar structure is commonly observed in the siliceous shale. The
239 lamellar structure in the siliceous shale is produced by interfaces and K-bentonite layers,
240 with a single lamella thickness of 2-8 cm (Fig. 4a). There are more than 10 K-bentonite
241 layers in the Wufeng Formation, and these layers have a single layer thickness from 1

to 20 mm (Su et al., 2009). The ratio of K-bentonite layers is less than 10% in the Wufeng Formation. Additionally, the Wufeng black shales contain many well-preserved graptolite specimens (Liu et al., 2017c), which is organic rich shale (TOC > 2.0%) too.

The contact between the Guanyinqiao Formation (O_3g) and the underlying Wufeng Formation is generally conformable in the Sichuan Basin and unconformable (or nonexistent) outside of the Sichuan Basin (Wang et al., 2016). In the Sichuan Basin, the Guanyinqiao Formation is usually composed of siliceous shale and calcareous siliceous shale. However, outside of the Sichuan Basin, the Guanyinqiao Formation consists of argillaceous limestone and dolomite limestone with abundant bioclasts associated with the *Hirnantia* fauna (Fig. 4a) (Chen et al., 2017). Although the Guanyinqiao Formation is thicker locally along the southern margins of the MUY, its average thickness is 0.3-0.6 m in the MUY. Only in some very restricted areas, it reaches a greater thickness, such as 7 m in Fenggang County in Guizhou Province and 5.33 m in Chuxian County in Anhui Province (Xu et al., 2004).

The Longmaxi Formation (S_{1l}) is widespread in the MUY, exhibits two sedimentary centers (Fig. 1a) located in the south and southeast of Sichuan Basin, and pinches out toward the uplifts in and around the MUY (Huang et al., 2018; Ma et al., 2016a). In the MUY, this formation covers the underlying formation with thicknesses of 229-673 m and 20-300 m inside and outside the Sichuan Basin, respectively (Ma et al., 2016a). The Longmaxi Formation consists of black organic-rich shale (Fig. 4a), black carbonaceous shale, silty shales, locally siliceous mudstones, siltstone and fine

sandstone (Yan et al., 2010). In the Sichuan Basin, it mainly consists of shale in the lower and middle sections and gradually evolves to fine sandstone in the upper section. Outside of the Sichuan Basin, the Longmaxi Formation is much thinner than it is inside the basin and mainly consists of siltstone and fine sandstone interlayered with shale. There are more than 10 K-bentonite layers in the Longmaxi Formation too. Although it is unknown where the K-bentonite originated from (Su et al., 2009), their sedimentary centers roughly correspond with each other during the Wufeng and Longmaxi Formation deposition period (Huang et al., 2018). It is implied that this paleogeomorphologic pattern was not obviously deformed by volcanic activities.

4.2. Mineral characteristics

The Baota Formation is almost entirely composed of calcite and small amounts of clay (Zhuo et al., 2017). The upper stratum contains quartz, clay minerals, calcite, dolomite, feldspar (K-feldspar and plagioclase) and pyrite (including marcasite). The mineral composition of the Guanyinqiao Formation varies widely throughout the MUY, which corresponds to the diversity of the depositional environments in which it was deposited. Both the Wufeng and Longmaxi Formations show large variations in mineral composition. Compared with the Longmaxi Formation, the Wufeng Formation is significantly more enriched in quartz (up to 89.6% quartz content) (Fig. 4b). Although some samples of the Longmaxi Formation contain abundant quartz (up to 70%), the quartz-rich layers are merely scattered in some local areas. The LSS, whose quartz content is commonly larger than 50% (Fig. 2, Appendix A), are the most quartz-rich layers in the stratigraphic assemblage that is stable across the MUY.

4.3. Mechanical behavior

Previous studies showed that the mechanical behavior of shale is obviously different among locations due to many factors, such as the test conditions, mineral composition, and microstructure (Rybacki et al., 2016; VanLandingham et al., 2005). Under the same test conditions, the mechanical behavior is dominated by the lithology of the strata. Test results have shown that a single layer of siliceous shale is the strongest lithological unit in the lithological association, given its compressive strength (Fig. 4c), shear strength (Fig. 4d), and tensile strength, as shown in Table 1. The siliceous shale with interfaces in the LSS is the weakest lithological unit in the lithological association, with a shear strength of approximately 6.12 MPa, which is less than half the values of the other lithological units, such as the Baota Formation (O_3b), Linxiang Formation (O_3l), Longmaxi Formation (S_1l), and the siliceous shale single layer in Wufeng Formation (O_3w) (Table 1). This result indicates that the mechanical behavior of the siliceous shale is dominated by its interfaces, which results in the LSS being the weakest layers in the lithological association.

5. Structural characteristics

5.1 Outcrop scale

The detachment fault in the Wufeng Formation is commonly observed within the LSS (Fig. 5a) in both the core and limbs of a fold in the MUY. The detachment fault is mainly composed of a fractured zone that is commonly parallel to the strata and stable throughout all outcrops with a thickness of 0.3-1.5 m (Fig. 5a). This detachment fault is far wider than the local fault in the Longmaxi Formation (Guo and Zhang, 2014). The

local faults are commonly shorter than 10 km and cannot be traced regionally. On both the upper and lower surfaces, the fault zone is in abrupt contact with protolith (Fig. 5a). The protolith above and below the fault zone layer is parallel to each other and feature the same lithology because they are part of the same stratum. Thus, these characteristics are obviously different from those of common faults (Fig. 5b) and fractures (Fig. 5c) in shale strata. Although some deformed layers (Fig. 5d) are observed in addition to the fault zone, these deformed layers are only occasionally observed locally and cannot be traced regionally. Hence, the deformed layers are commonly not considered as part of the detachment fault. Around the fault zone, the protolith is occasionally deformed by a fault as part of the fault zone (Fig. 5b). Due to the influence of faulting, parts of the detachment fault are occasionally observed at the bottom of the Longmaxi Formation.

The fault zone of the detachment fault is commonly composed of fault breccia and fault gouge (Fig. 5a, d, e, f, g). In some areas, the bedding in the LSS is obviously deformed by shear stress and exhibits C or S cleavages (Fig. 6d, e). In some areas, the bedding in the LSS cannot be easily identified in the fractured zone (Fig. 5e, f). The cleavage patterns in the fault gouge reveal that the gouge was obviously deformed by shear stress. The fabric of the fault zone is very complex and obviously differs according to structural position. In general, the fault zone is mainly composed of fault gouge in the limb of the fold, where the LSS are mainly composed of calcareous siliceous shale. In the core of the fold, where the LSS are mainly composed of siliceous shale, the fractured zone is composed of fault breccia and decoupled shale layers. This unit features tension vertical fractures and numerous decoupled layers. The fault zone

is commonly composed of one fractured zone in the southeast of the Sichuan Basin, where the folds are dominated by multistage coaxial folding (Fig. 1b). In the southwestern Sichuan Basin, where the folds are dominated by multistage noncoaxial folding, the fault zone is occasionally composed of two or more fractures zones (Fig. 6a).

5.2 Core sample scale

The recovery of core samples from the detachment fault is commonly less than that from intact strata. The core samples are mainly composed of fault breccia (Fig. 6a). Some of the fault gouge has likely been removed by the drill mud. Additionally, in the fault zone composed of two fracture zones, cementation is mainly observed in the lower fracture zone. Although the lower fracture zone is mainly cemented by calcite or quartz veins, some of the high-angle fractures are open at depth. The fractures in upper fracture zone are commonly open and have intersected some veins, indicating that some fractures were cemented by calcite or quartz veins before the detachment fault formed (Fig. 6a). In areas where the detachment fault is composed of two fractured zones, the fracture zones are occasionally separated by a layer of undamaged shale (Fig. 6b). The fault zones may be composed of fault breccia cemented by calcite or quartz or of fault gouge. The fractures are parallel or perpendicular to the slip plane and are partly cemented by calcite or quartz veins (Fig. 6b). The fault gouge can exhibit shearing along sharp shear planes composed of nanoscale grains (Fig. 6d). In the core of the fold, the shale bedding is commonly decoupled, and the fractures in the fold are mainly parallel to the strata and, to a lesser degree, orthogonal to the strata (Fig. 6c, Fig. 6e).

The fractures parallel to the strata are commonly cemented by veins, whereas the fractures orthogonal to the strata are only partly cemented by veins (Fig. 6c) and may partly remain open at depth (Fig. 6e). The inner faces of the fractures commonly have slickensides (Fig. 6f) and sharp shear planes (Fig. 6g). On the upper or lower surfaces of the veins, fiber steps and lineations are commonly observed (Fig. 6h), indicating that some detachments and movements have occurred along these fractures. On the other hand, some movement marks can be observed in the K-bentonite layer. Rounded pyrite crystals on the surface of the K-bentonite layer (Fig. 6i) indicates that slip movement mainly has occurred along the interfaces in the LSS and secondarily along the K-bentonite interlayers.

5.3 Microscale

The syntectonic veins in the fractured zones display at least two stages (Fig. 7a), which indicates that the detachment fault formed by episodic tectonic activity. Additionally, many microfractures were observed at the base of the bedding in the upper section that were obviously formed by an action of shear stress (Fig. 7b). The deformation texture of the clay minerals showed that the deformation was dominated by shear stress, that induced a large number of directional fractures (Fig. 7c, Fig. 7d). In the 2-dimensional images, the fractures are arranged according to the direction of shear stress. In the 3-dimensional images, the fractures are connected to both and beaded pores (Fig. 7e, Fig. 7f). With the shale strata, the hydrocarbon migration pathways are mainly defined by the directional fractures and the pores connected by them. The permeability of the fractured zone may be higher than 220 mD (Guo and

Zhang, 2014), which is much larger than the permeability of the key shale gas layer (i.e. generally <0.1 mD) (Guo, 2014). These are indicating that the directional fractures and the associated hydrocarbon migration pathways formed through shear movement within the detachment fault.

6. Displacement

According to the field observations, the fabric of the fault zone is commonly different among different structural positions, even in the same limb. The fabric of a fault zone is known to be dominated by several key factors, such as the lithological association, confining pressure and relative displacement (Geoff Tanner, 1989; Scuderi et al., 2017). The regional differences in lithological association and confining pressure are so obvious that they cannot be universally concluded. Hence, we conducted a semiquantitative study of the displacement at different structural positions of the fold to show the formation mechanism of the detachment fault.

Based on the premise that the length of the top surface is constant during tectonic activity, the relative displacement at interfaces can be quantitatively calculated as follows:

(1) Angular fold

In an angular fold, the relative displacement of the detachment fault changes sharply in the core of the fold but is the same in the limbs (Fig. 8). The displacement is positively correlated with the thickness of the overlying stratum and the dip angle of the strata. The displacement of the detachment fault can then be calculated as:

$$\Delta L(x) = H \cdot \tan(\alpha) \quad (1)$$

396 where $\Delta L(x)$ is the displacement of a point in the detachment fault (m),

397 H is the thickness of the stratum overlying the detachment fault (m),

398 α is the dip angle of the strata in which the detachment fault is located ($^\circ$),

399 counted in the range of (0° to 90°).

400 (2) Isopach fold

401 In a certain section of an isopach fold, all the strata exhibit the same curvature (Fig.

402 8). Hence, the displacement can be calculated as follows:

403
$$\widehat{AD} = \widehat{BK'} \Rightarrow r_1 \alpha_1 \frac{\pi}{180^\circ} = r_2 \alpha_2 \frac{\pi}{180^\circ} \Rightarrow \alpha_2 = \alpha_1 + \alpha_1 \cdot \frac{H}{r_2} \quad (2)$$

404
$$\Delta L(x) = \widehat{BK'} - \widehat{BK} = r_2 \alpha_2 \frac{\pi}{180^\circ} - r_2 \alpha_1 \frac{\pi}{180^\circ} = H \cdot \alpha_1 \frac{\pi}{180^\circ} \quad (3)$$

405
$$\tan \alpha_1 = f'(x_k) \Rightarrow \alpha_1 = \arctan(f'(x_k)) \quad (4)$$

406
$$\therefore \Delta L(x) = H \cdot \frac{\pi}{180^\circ} \cdot \arctan(f'(x)) \quad (5)$$

407 where H is the thickness of the strata overlying the detachment fault (m),

408 $f(x)$ is a function of the detachment layer surface (m) and can be obtained from

409 the seismic profile,

410 $f'(x)$ is the slope of the tangent line at point $(x, f(x))$,

411 Point A is the peak of the curve $f_1(x)$,

412 Point B is the peak of the curve $f_2(x)$,

413 Line KD is the normal to the curve $f_2(x)$ at Point K, and

414 $\Delta L(x)$ is the displacement of a point in the detachment fault (m).

415 According to Eq. 5, the displacement in the isopach fold is positively correlated with

416 the thickness of the strata overlying the detachment fault and the tangent of the dip

417 angle of the detachment fault surface. The displacement increases from the core to the

edge of the limb. When the horizontal distance from the core is close to the radius of the fold, the displacement increases progressively.

(3) Common fold

In a common fold, the top and bottom surfaces of the strata are commonly not parallel to each other (Fig. 8). The displacement can be calculated as follows:

$$f'_1(x_a) = 0 \Rightarrow A(x_a, y_a) \quad (6)$$

$$f'_2(x_b) = 0 \Rightarrow B(x_b, y_b) \quad (7)$$

$$\frac{-(x_d - x_k)}{f'_2(x_k)} + f_2(x_k) = f_1(x_d) \Rightarrow D(x_d, y_d) \quad (8)$$

$$\therefore \widehat{AD} = \widehat{BK'} \Rightarrow \int_{x_a}^{x_d} \sqrt{1 + f'_1(x)^2} dx = \int_{x_b}^{x_k} \sqrt{1 + f'_2(x)^2} dx \quad (9)$$

$$\therefore \Delta L(x) = \widehat{BK'} - \widehat{BK} = \widehat{AD} - \widehat{BK} = \int_{x_a}^{x_d} \sqrt{1 + f'_1(x)^2} dx - \int_{x_b}^{x_k} \sqrt{1 + f'_2(x)^2} dx$$

$$\Delta L(x) = \int_{x_a}^{x_d} \sqrt{1 + f'_1(x)^2} dx - \int_{x_b}^{x_k} \sqrt{1 + f'_2(x)^2} dx \quad (10)$$

where

$f_1(x)$ is a function of the top surface of the stratum overlying the detachment layer (m) and can be obtained from the seismic profile,

$f_2(x)$ is a function of the detachment fault surface (m) and can be obtained from the seismic profile,

Based on the seismic profile of the Huayingshan anticline (Fig. 9a), the calculations result shows that the displacement increases from the core to the limb. The displacement increases more slowly as the dip angle of the limb gradually increases. The largest displacement in the southeast limb is 719.7 m, which is slightly smaller than the value (i.e., 752.99 m) calculated with Eq. (1) (with $H=489$ m, $\alpha=57^\circ$). The

discrepancy may arise because the thickness of the formation changed during the folding process. Although the displacement of the detachment fault is not linearly correlated with the thickness of the strata overlying the detachment fault, the displacement is at least positively correlated with the thickness of the strata overlying the detachment layer (Fig. 8).

In summary, the displacement in the detachment fault is smallest in the core of the fold. In the arc section (i.e., the core of the fold), the displacement commonly increases from the core to the limb (such as in the isopach fold shown in Fig. 8). If the limb is straight and has a certain dip angle, the largest displacement is in the limb and is stable across the whole width of the limb. The displacement in the limb is positively correlated with the thickness of the strata overlying the detachment layer and the dip angle of the limb, such as in the angular fold shown in Fig. 8.

7. Formation mechanism

Faults and fractures are commonly observed in shale and mudstone strata (Gale et al., 2014). However, most of them are distributed locally. Few of natural faults and fractures are distributed regionally as the detachment fault in the Wufeng Formation in MUY. As mentioned above, the Wufeng Formation is not only overlain by massive strata (Longmaxi Formation, S_1l) but also acts as a thin weak interlayer between two thick competent formations (Fig. 2, Fig. 9a). The shear strength of the LSS is the weakest in the lithological association composed of the Baota, Linxiang, Wufeng, Guanyinqiao and Longmaxi Formations (Table 1, Fig. 4). Additionally, the displacement is positively correlated with to the thickness of the strata overlying the

detachment fault and the dip angle of the limb (Fig. 8). Flexural slip commonly occurs between beds and along competent-incompetent contacts (Damasceno et al., 2017; Fagereng and Byrnes, 2015; Geoff Tanner, 1989). Hence, at the macroscopic level, the flexural slip occurred readily in the interlayer section containing folded strata. At the microscopic level, the interfaces and the K-bentonite layers also act as thin weak interlayers between the two thicker competent layers (Fig. 9a). The interfaces in the LSS are so straight and glazed that their frictional resistance is much smaller than that of the K-bentonite. Sharp shear planes (Scuderi et al., 2017) are commonly observed on the interfaces (Fig. 6f, g), indicating that the LSS section readily accommodated slippage chiefly along its interfaces and also partly along the K-bentonite interlayers (Fig. 6f, g, i, Fig. 9a).

Once the shear planes (Scuderi et al., 2017) had formed, the permeability of the fault zones increased drastically. Depending on its frictional stability, a shear plane may be partly or completely cemented. During the later folding process, the shear planes may have been activated and may have disturbed the neighboring layers that were weakened during the previous slip process (Fig. 6b). Hence, the fractured zone likely increased in thickness as coaxial folding proceeded. Within the multistage noncoaxial folding zone, the shear stress was noncoaxial. A pre-existing shear plane may not have been active during the later folding process because of cementation or anisotropy in rheological properties. Thus, new shear planes formed during subsequent folding, which resulted in two fractured zones within the multistage noncoaxial folding zone, such as in the southwestern Sichuan Basin (Fig.6a).

Shear stress is known to be positively correlated with displacement before a rock is fractured (Jafari et al., 2003). The displacement of the detachment fault commonly increases from the core to the limb of a fold (Fig. 8) and dominates the flexural slip intensity as it increases from the core to the limb. The fabric of the detachment fault gradually changes from breccia with decoupled shale layers in the core section to fault gouge and breccia with S cleavages in the limb of the fold (Damasceno et al., 2017; Geoff Tanner, 1989; Smart et al., 2009a).

8. Implications

8.1 Tracing regional detachment faults

Fractures in low porosity and low permeability shale reservoirs often form ‘super highways’ for fluid flow in the subsurface (Crandall et al., 2017). The connected natural fracture systems are crucial for the exploration and exploitation of shale gas (Gale et al., 2014; Liu et al., 2017a). However, given the limitations of applicable method, regional fault zones are not well distinguishable from local fault zones prior to drilling. Additionally, some thinner fault zones are commonly ignored. In contrast, many local fractures are mistaken as fractures with regional extent. In fact, many fractures in outcrops and core samples most likely do not exist in the subsurface. The distribution of local fractures is commonly not homogeneous across larger areas. Furthermore, permeability test results in the laboratory are commonly smaller than those at the field scale because of the postulated existence of undetected fractures acting as flow conduits (Bredehoeft et al., 1983). There is little agreement on whether and where natural fractures independently contribute to production of hydrocarbons. In other cases, open

natural fractures may capture hydraulic fracturing fluids, preventing new fracture growth and reducing the effectiveness of hydraulic fracturing treatments, as observed in Well WX2 in the southeastern Sichuan Basin (Wu et al., 2017). In this well, core samples are enriched of gas with a field desorption gas content of 3.52 m³/t , but no commercial gas flow was obtained after hydraulic fracturing (Wu et al., 2017).

As mentioned before, the formation of a regional fault zone in the MUY (i.e. the detachment fault in the LSS) is closely related to the lithological association of the Wufeng Formation and a flexural slip process. Both at the macroscopic and microscopic levels, the lithological association is characterized by two thicker competent layers containing with a thin weak interlayer. When the layers were folded, a fractured layer of regional extent formed within this thin weak interlayer. The fabric of the fractured layer is correlated with multistage folding and the differences in displacement at different structural positions. Hence, attention should be paid to distinguish regional fault zones from local fault zones in areas with similar lithological associations. In the MUY, the seismic impedance contrast of the Silurian-Ordovician interface is so strong that the detachment fault can be easily traced in the seismic profile (Huang et al., 2018). Therefore, the detachment fault could be traced by seismic impedance contrasts in seismic profiles in conjunction with core sample images or FMI logging (Fullbore Formation Microimage logging) at other locations. In the other areas with a similar lithological association, more attention should be paid to conclude on the correlation between the fabric of the fault zone and its tectonic position within the fold. Whether or not this fault is a regional detachment fault can be further concluded with core

samples, FMI logging, seismic profiling, a semiquantitative evaluation of the displacement, and the fluid potential distribution of the fold.

8.2 Influences on shale gas enrichment

There are many similarities between the enrichment of shale gas and entrapment of hydrocarbons in China. Tectonic conditions are the key factor for shale gas enrichment and prolific production (Guo and Zhang, 2014). However, so far the correlation between shale gas enrichment and hydrocarbon entrapment has not been effectively characterized. Moreover, there are debates about the concept that the per well output of shale gas may be larger than the reserves of the shale strata associated with the borehole and its hydraulic fractures (He et al., 2018b).

The permeability of the fracture zone may exceed 220 mD (Guo and Zhang, 2014), which is significantly larger than that of the target shale gas layer (i.e., generally <0.1 mD). A regional fault zone in shale strata may act as a hydrocarbon migration pathway in a tectonic unit, such as a fold or a fault block. Considering Well HD-1 as an example, observed in the center of Huayingshan anticline without hydraulic fracturing treatment (Fig. 9c). The field desorption gas content in the Longmaxi Formation exceeds 1.0 m³/t at 1313.8-1321.5 m depth, which is larger than that in the detachment fault (i.e., 0.64-0.89 m³/t, at depths of 1331.8-1333.0 m) (He et al., 2018b). During the gas desorption process, the gas is mainly in the form of needle-shaped bubbles in the black shale containing no fractures (Fig. 9d). However, the gas is in the form of both needle-shaped and free bubbles in the core samples from the fracture zone (Fig. 9e), which indicates that the fracture zone traps both adsorbed and free gas. In the Longmaxi Formation, the

total hydrocarbon content in the drill mud was observed to be much smaller (on average 0.1% at 1280-1332 m depth) than in the detachment fault (on average 3.8% at 1331.8-1333.0 m depth) (He et al., 2018b). When drilling into the fault zone, a well kick was observed in the wellhead. The mud pit was rich in bubbles (Fig. 9f) as the conventional gas reservoir was drilled, which indicates that the fractured zone is rich in free gas. Therefore, the fault zone acts as a reservoir layer that not only adsorbs large amounts of shale gas generated in situ but also traps large amounts of free gas that was generated both in situ and at greater distances exceeding the km-scale. Additionally, the fault zone acts as a high-permeability pathway for free gas migrating from areas nearby or being desorbed from the adjacent shale strata. Hence, by applying a thorough search for regional fault zones, shale gas may hopefully be exploited without the need to apply hydraulic fracturing measures.

8.3 Implications for hydrocarbon exploration

A regional detachment fault zone is commonly connected with local faults that constitute a regional migration pathway system (Fig. 1b). The regional fault in organic rich shale strata is a special type of a hydrocarbon-source fault that dominates hydrocarbon migration in the source rock. For example, the detachment fault in LSS is located within the source rock of the Sichuan Basin, i.e. the Wufeng-Longmaxi Formation (Guo and Zhang, 2014; He et al., 2018a; Liu et al., 2017b; Ma et al., 2007) and is a particular fault within the fault system of the MUY (Fig. 1b). The giant gas fields are commonly closely related to this fault system (Hao et al., 2018; Ma et al., 2007). Hence, studies of regional faults in shale strata are of benefit for the

characterization of gas migration systems, which serves to expand the exploration strategies for both shale gas and conventional gas.

9. Conclusions

(1) Regional detachment faults in shale strata are closely related to the lithological associations of the strata and flexural slip processes. In the MUY, the lithological association of the detachment fault in the Wufeng Formation is characterized by two thicker competent layers separated by a thin weak interlayer at both the macroscopic and microscopic scales. During folding of these units, a detachment fault formed in the thin weak interlayer. At the macroscopic scale, the thin weak interlayer is the Wufeng Formation, in which the regional shear stress is localized. At the microscopic scale, the thin weak interlayer is represented primarily by interfaces within the LSS and secondarily by K-bentonite interlayers therein.

(2) Although the fabric of the detachment fault zone is very complex and obviously different between structural positions, it is evidently controlled by the flexural slip intensity, the number of slip events, as well as their orientation and structural position. The fault zone is mainly composed of one fracture zone within the multistage coaxial folding zone and two or more fracture zones in the multistage noncoaxial folding zone. The displacement commonly increases from the core to the limb of the fold and is related to the thickness of the strata overlying the detachment fault and the dip angle of the limb. The fault zone is mainly composed of fault gouge in the limb of the fold and fault breccia and decoupled shale layers in the core of the fold. The fault zone is in direct contact with protolith and is obviously different from the faults

commonly observed within shale strata.

(3) Flexural slip not only induced a fractured layer but also controlled the distribution of directional fractures within this regional fault zone. The regional detachment fault may not only act as a migration pathway for hydrocarbons within the shale strata but also as a reservoir for adsorbed free gas that migrated from other areas. The regional fault zone probably connects with the local faults, which constitute a regional migration pathway system. A search for regional detachment faults in shale strata will not only benefit to study the enrichment mechanism of shale gas but will also expand exploration strategies for both shale gas and conventional gas.

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Figure captions

Fig. 1. (a) Lithofacies paleogeographic map of the Yangzi craton during the Late Ordovician Wufeng period, (Guo and Zhang, 2014; Nie et al., 2017; Tang et al., 2016; Wang et al., 2016; Wang and Sun, 2014; Xu et al., 2004; Yan et al., 2010; Zou et al., 2015). (b) Geomorphological map of the Sichuan Basin and regional fault system in the MUY, (modified from (Feng et al., 2008)

Fig. 2. Lithological association of the detachment fault in the MUY (Guo, 2014; Liu and Wang, 2016; Zhao et al., 2016)

Fig. 3. Generalized stratigraphy and tectonic history of the MUY, (Ma et al., 2007).

Fig. 4. (a) Petrofabric of the formations related to the respective lithological association. (b) Ternary diagram of the mineral composition of the Baota and Longmaxi Formations in the MUY (Guo, 2014; Li et al., 2018b; Wang et al., 2016; Yan et al., 2018). (c) The Stress-strain curves of the samples listed in Table 1. (d) The shear stress-shear displacement curves of the samples listed in Table 1.

Fig. 5. Characteristics of the detachment fault observed in the outcrops: (a) the slip layer is mainly composed of fault gouge with S cleavage in the limb of the Hauangyang syncline, Guizhou Province. (b) Common fault in shale strata, which is obviously different from the detachment fault showing an angle between the bedding and fault planes. (c) Fractures in shale strata can only be traced over short distances. (d) Detachment fault zone composed of fault breccia (Xiushan County, Chongqing municipality). (e) Detachment fault zone composed of fault breccia (Heyuanbao County, Chongqing municipality). (f) Detachment fault zone mainly

composed of fault gouge with S cleavage in the limb of the Anchang syncline, Guizhou Province. (g) Detachment fault zone mainly composed of fault gouge with S cleavage in the limb of the Zhuoheba syncline, Chongqing municipality.

Fig. 6. Detachment fault in core samples. (a) The detachment fault zone recovered from Well XD-1 is composed of two fractured layers with fault breccia and fault gouge. (b) Fractured fault zone is occasionally interlayered with unfractured shale. (c) Shale bedding is commonly decoupled in the core of the fold. (d) Narrow shear planes are occasionally observed in the fractured zone. (e) Vertical fractures are commonly observed in the core of the fold. (f) Slickensides in the slip layer. (g) Narrow shear planes in the fault zone. (f) Fiber steps and lineations are commonly observed on the upper or lower surfaces of veins within the fault zone. (i) Rounded pyrite crystals are occasionally observed within the K-bentonite layer.

Fig. 7. Distribution of fractures in the fault zone at the microscale. (a) Syntectonic veins in the fracture zone. (b) Microfractures are dominated by shear stress. (c) Directional fractures formed by deformation. (d) Directional fractures commonly remain open. (e) Fractures in the fracture zone connect the isolated and beaded pores. (f) Narrow shear plane acting as high permeability pathway connecting isolated pores.

Fig. 8. Flexural slip displacement at different structural positions within the fold. The upper part of the figure shows the geometric shape of the strata before folding, the central part shows the present geometric shape of the fold, and the lower part shows the correlation between displacement (ΔL) and horizontal distance from

the fold core (x).

Fig. 9. Formation mechanism of the detachment fault drilled at Well HD-1 and its contribution to the concentration of shale gas. (a) Formation mechanism of the detachment fault in the Huayingshan anticline. (b) Correlations between shale gas enrichment and trapping of natural gas. (c) Natural shale gas flow obtained without hydraulic fracturing treatment at Well HD-1. (d) Shale gas in shale strata is commonly desorbed as needle-shaped bubbles, which indicates that the shale rock is the reservoir and that the natural shale gas flow does not emanate from a conventional fractured gas reservoir. (e) Shale gas desorbs rapidly as free bubbles from macrofractures and more slowly from microfractures, which shows that the fractures are the ‘super highways’ for gas flow in this shale stratum. (f) When drilling the slip layer, the drill mud contained abundant free bubbles, which demonstrate the natural yield potential of shale gas reservoirs drilled in well HD-1.

ERA	SYSTEM	SERIES	GROUP/FORMA-TION	SYM-BOL	LITHOLOGY	THICKNESS (m)	AGE (Ma)	TECTONIC CYCLE	TECTONIC MOVEMENT
Cenozoic	Quaternary			Q		0-380		Himalayan	
	Tertiary	upper		N		0-300	3		Later Himalayan
		lower		E		0-800	25		Early Himalayan
Mesozoic	Cretaceous			K		0-2000	80	Yanshanian	
	Jurassic	Upper	Penglaizhen	J _{3p}		650-1400	140		Late Yanshan
		Middle	Suining	J _{2sn}		340-500			
			Shaximiao	J _{2s}		600-2800			
		Middle-lower	Ziliujing	J _{1z}		200-900			
	Triassic	Upper	Xujiahe	T _{3x} *		250-3000	195		Late Indosinian
		Middle	Leikoupo	T _{2l} *			205		Early Indosinian
		Lower	Jialingjiang	T _{1j} *		900-1700			
			Feixianguan	T _{1f} *
Paleozoic	Permian	Upper	Changxing	P _{2c} *		200-500	230	Hercynian	
		Lower	Longtan	P _{2l}					Dongwu
			Maokou	P _{2m}		200-500	270		Yunnan
	Carboniferous	Mississippian	Guo-Liangshan	P _{1g-P1l}		0-500	320	Caledonian	Caledonian
	Silurian					0-1500			
				S
	Ordovician			O		0-600			
Proterozoic	Sinian	Upper	Xixiangchi			0-2500		Caledonian	
		Lower	Yuxiansi						
	Pre-Sinian		Jiulaodong	C				Yangtze	Tongwan
									Chengjiang
									Jinning

Angular fold

$$\Delta L_{J1} = H_1 \tan \alpha$$

$$\Delta L_{J2} = H_2 \tan \alpha$$

$$\Delta L_{K1} = H_1 \tan \beta$$

$$\Delta L_{K2} = H_2 \tan \beta$$

Isopach fold

Concave fold

Free bubble

Free gas content

Detachment fault in Wufeng

Adsorbed gas content

Zhenzhuchong Formation Bottom

Xujiahe Formation Bottom

Leikoupo Formation Bottom

Longtan Formation Bottom

Permian Bottom

Ordovician Bottom

Middle-upper Ordovician Bottom

Needle bubble

Fault

Table 1. The mechanical characteristic of the formations

Location	Formation	Shear strength (MPa)	Tensile strength (MPa)	Compressive strength (MPa)	Young's modulus (GPa)	Poisson's ratio	Lithology	References/ Sample Number
Well HD-1	O _{3b}	29.44	5.24	122.00	23.47	0.258	Pagoda limestone	L1
Well HD-1	O _{3b}	32.29	4.62	122.50	26.11	0.281	Pagoda limestone	L2
Well HD-1	O _{3l}	44.50	4.38	162.50	29.68	0.283	Nodular limestone	L3
Well HD-1	O _{3w}	44.09	7.51	140.10	25.52	0.241	Siliceous shale single layer	L4
Well HD-1	O _{3w}	53.30	18.34	142.90	14.80	0.105	Siliceous shale single layer	L5
Well HD-1	O _{3w}	6.12	2.59	85.70	5.96	0.105	Siliceous shale with interface	L6
Well HD-1	O _{3w}	6.13	-	38.50	6.13	0.175	Siliceous shale with interface	L7
Well HD-1	S _{1l}	20.37	2.02	76.00	17.87	0.418	Black shale	L8
Well HD-1	S _{1l}	38.57	8.84	171.90	21.26	0.344	Silty mudstone	L9
Well HD-1	S _{1l}	26.91	5.55	136.10	19.90	0.146	Mudstone interlayered with siltstone	L10
Changning, China	O _{3w}	-	-	111.41	35.09	0.120	Calcareous siliceous shale	(Wang et al., 2014)
	S _{1l}	-	-	29.9-105.9	10.15-33.11	0.19-0.28	Calcareous shale	Wang et al., 2014)
Chongqing, China	S _{1l}	33.64-46.85	-	90.0-137.0	17.9-35.0		Shale	(Dou et al., 2016; He et al., 2017b; Yang et al., 2013)
Wei yuan, China	S _{1l}	-	-	189.1-228.7	20.26-33.37	0.174-0.198	Shale	(Liu and Wang, 2016)
Fengxiang, China	S _{1l}	-	-	-	33.7-41.3	0.170	Shale	(Dou et al., 2016)
Woodford, West Texas	-	12.51	-	-	9.25-23.47	-	Shale	(He et al., 2017a)
Alum, Southern Sweden	-	-	4.7-10.1	21.3-94.5	8-29	-	Shale	(Rybacki et al., 2015)
Barnett, Texas, USA	-	-	4.1-4.2	35.8-105.7	12-25	-	Shale	(Rybacki et al., 2015)
Dotternhausen, Germany	-	-	1.4-3.3	64.8-78.4	9-10	-	Shale	(Rybacki et al., 2015)
Wickensen, NW-Germany	-	-	7.1-11.4	78.8	11	-	Shale	(Rybacki et al., 2015)
Harderode, Germany	-	-	8-10	68-85	15-20	-	Shale	(Rybacki et al., 2015)
Haddessen, Germany	-	-	3.8-4.8	48-106	8-15	-	Shale	(Rybacki et al., 2015)