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**Analysis of the charging process of the lacustrine
tight oil reservoir in the Triassic Chang 6 Member in
the southwest Ordos Basin, China**

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30 Abstract

31 With the success of Bakken tight oil (tight sandstone oil and shale oil) and Eagle
32 Ford tight oil in North America, tight oil has become a research focus in petroleum
33 geology. In China, tight oil reservoirs are predominantly distributed in lacustrine
34 basins. The Triassic Chang 6 Member is the main production layer of tight oil in the
35 Ordos Basin, in which the episodes, timing, and drive of tight oil charging have been
36 analyzed through the petrography, fluorescence micro-spectrometry,
37 micro-thermometry, and trapping pressure simulations of fluid inclusions in the
38 reservoir beds. Several conclusions have been reached in this paper. First, aqueous
39 inclusions with five peaks of homogenization temperatures and oil inclusions with
40 three peaks of homogenization temperatures occurred in the Chang 6 reservoir beds.
41 The oil inclusions are mostly distributed in fractures that cut across and occur within
42 the quartz grains, in the quartz overgrowth and calcite cements, and the fractures that
43 occur within the feldspar grains, with blue-green, green, and yellow-green
44 fluorescence colors. Second, the peak wavelength, $Q_{650/500}$, and Q_{F535} of the
45 fluorescence micro-spectrometry indicate three charging episodes of tight oil with
46 different oil maturities. The charging timing (141–136 Ma, 126–118 Ma, and 112–103
47 Ma) have been ascertained by projecting the homogenization temperatures of aqueous
48 inclusions onto the geological time axis. Third, excess pressure differences up to 10
49 MPa between the Chang 7 source rocks and the Chang 6 reservoir beds were the main
50 driving mechanism supporting the process of non-buoyancy migration.

- 51 **Keywords:** Lacustrine tight oil reservoir; Fluid inclusion; Charging episode;
- 52 **Charging timing; Charging drive**

Draft

53 Introduction

54 The term ‘tight oil’ first appeared in the 1940s when it was used to describe
55 oil-bearing tight sandstones (Ledingham 1947). Tight oil is defined as ‘oil produced
56 from tight sandstones or carbonates that are adjacent to or interbedded with source
57 rocks, based on the application of horizontal drilling and multistage hydraulic
58 fracturing technology’ (National Energy Board 2011; IEA 2011; EIA 2012; Zou et al.
59 2013, 2015). With the success of Bakken tight oil (Williston Basin) (Miller et al. 2008)
60 and Eagle Ford tight oil (South Texas, US) (Mullen 2010) in North America, tight oil
61 has become a research focus in petroleum geology (Johnstone 2007; Jia et al. 2012),
62 and was considered as the practical unconventional resources like shale gas (USGS
63 2008; BP 2011). In this study, tight oil refers to ‘oil produced from tight sandstones
64 that are adjacent to or interbedded with source rocks, utilizing horizontal drilling and
65 multistage hydraulic fracturing technology’. Previous research that studied tight
66 sandstone oil reservoirs predominantly focused on marine basins worldwide. However,
67 in China, tight sandstone oil reservoirs are generally distributed in lacustrine basins
68 (Cao et al. 2016; Ma et al. 2016), such as Ordos, Sichuan, Junggar, Santanghu, and
69 Songliao basins. The Chang 6 Member (Chang 6) has been the main production layer
70 of tight sandstone oil in the Ordos Basin (Fig. 1).

71 Previous research on the formation and distribution of tight oil reservoirs has
72 commonly focused on tight oil charging processes (Jiang et al. 2000; Zou et al. 2013,
73 2015). Tight oil reservoirs are considered to be characterized by non-buoyancy

74 migration, primary migration, secondary migration over a short distance, and
75 proximal-source accumulation (Zou et al. 2013, 2015). It is important to analyze the
76 charging processes of tight oil to guide exploration and exploitation. Petroleum
77 inclusions are the intact and original oil and gas samples trapped in minerals during
78 the geological evolution of basins, which preserve geological, physical, and
79 geochemical information (Aplin et al. 2000; Goldstein 2001). This information serves
80 as reliable and assertive evidence to determine the episodes, timing, temperatures,
81 pressures, and intensities of fluid charging (McLimans 1987; Goldstein and Reynolds
82 1994; Aplin et al. 2000; Goldstein 2001; Liu et al. 2003). In this paper, several
83 principal objectives we focusing on are as follows: 1) describing the charging
84 episodes of the Chang 6 tight oil reservoirs in the southwest Ordos Basin; 2)
85 analyzing the charging timing of the Chang 6 tight oil reservoirs in the study area; and
86 3) discussing the charging drive that charged the Chang 6 tight oil reservoirs in the
87 study area. These studies can provide useful data for understanding and predicting
88 tight oil reservoirs of the Chang 6 in the southwest Ordos Basin. Furthermore, the
89 results of this investigation could be meaningful for researchers in other parts of the
90 world where the oils are produced from lacustrine tight sandstones.

91 **Geological Settings**

92 **Regional Geological Setting**

93 The Ordos Basin, with an area of 370 000 km², is located in the western part of
94 the North China Plate. The basement consists of Archean and Lower Proterozoic
95 metamorphic crystalline rocks which are overlain by Mid-Upper Proterozoic,

96 Paleozoic, Mesozoic, and Cenozoic sedimentary strata (Yang et al. 2005b). The
97 evolution of the Ordos Basin during the Paleozoic-Mesozoic is divided in three stages:
98 1) a Cambrian to Early Ordovician craton basin with divergent margins; 2) a Middle
99 Ordovician to Middle Triassic craton basin with convergent margins, and 3) a Late
100 Triassic to Early Cretaceous intraplate remnant craton basin (Yang et al. 2005b).
101 Tectonically, the basin is divided into six structural units: the Yimeng Uplift, the
102 Western Edge Fold-Thrust Belt, the Tianhuan Depression, the Yishan Slope, the
103 Weibei Uplift, and the Jinxi Flexural-Fold Belt (Fig. 1). The study area is located in
104 the southwest Ordos Basin, which mainly stretch across the Tianhuan Depression and
105 the Yishan Slope (Fig. 1). The Yishan Slope has a 1°–2° dip and includes some of the
106 main locations for petroleum exploration and development in the Ordos Basin. In the
107 Mesozoic, four episodes of exhumation occurred in the Ordos Basin, including the
108 exhumations that occurred during the Late Triassic, the Middle Jurassic, the Late
109 Jurassic, and the Late Cretaceous–Quaternary, respectively (Chen et al. 2006). The
110 last exhumation during the Late Cretaceous–Quaternary created the contemporary
111 geomorphology in the Ordos Basin (Chen et al. 2006). As shown in Fig. 1c, the
112 denudation thickness of the Mesozoic strata increases from northwest to southeast in
113 the study area.

114 As a consequence of regional collisional tectonism and related intra-plate
115 deformation in the Middle–Late Triassic (Indosinian Movement), the southern Ordos
116 Basin evolved into a foreland basin, and was dominated by lacustrine environments in

its center during most of the Late Triassic. Orogenic highlands, such as the Yin Mountains in the north and the Qinling Orogen in the south, were the main sediment source areas around the basin (He et al. 2016), gradually forming some fluvial-lacustrine-deltaic sediments, including sandstones, siltstones, mudstones, oil shales (commonly defined as a fine-grained sedimentary rock with fissility containing organic matter that yields substantial amounts of oil and combustible gas upon destructive distillation), and tuff interlayers, named the Yanchang Formation. The Yanchang Formation is subdivided into ten members: Chang 10 Member to Chang 1 Member from the bottom to the top of the formation (Yang et al. 2005b), which records a complete cycle of lake development (Li et al. 2009): initial formation and development stage (Chang 10–Chang 8), peaking stage (Chang 7–Chang 4+5), and declining stage (Chang 3–Chang 1). The Chang 9, Chang 7, and Chang 4+5 are composed predominantly of dark mudstones, shales, and oil shales. The Chang 6 consists of fine sandstones and siltstones interbedded with dark mudstones (Fig. 2).

Characteristics of Source Rocks and Crude Oils

The shales and mudstones developed in the Chang 7 are the main source rocks of the crude oil in the Chang 6 reservoir beds, and are mainly distributed in the southern Ordos Basin, with a mean thickness of 15–30 m (Lu et al. 2006; Zhang et al. 2006). The values of total organic carbon content (TOC) range from 0.74% to 26.69%, with a mean of 11.36%. Kerogen types vary from predominantly Type II₁–II₂. As for the thermal-maturity, vitrinite reflectance (R_o), ranges from 0.65% to 1.15%, with an average value of 0.85%, which indicates that the organic matter has entered the

mature stage of hydrocarbon generation (Yang et al. 2005a; Zhang et al. 2006; Hanson et al. 2007). The color of crude oil in the Chang 6 is dark brown. The oil density ranges from 21.31 °API to 45.11 °API, with a mean value of 35.91 °API. The dynamic viscosity of the Chang 6 oil is 2.10×10^{-3} – 17.44×10^{-3} Pa · s, with a mean value of 5.76×10^{-3} Pa · s. The mean freezing point of the oil ranges from 0 °C to 34.00 °C, with a mean value of 19.61 °C. The wax content of the oil ranges from 11% to 20%, with an average value of 15% (Zhang et al. 2006; Hanson et al. 2007).

Characters of Reservoir Beds

Fine sandstones and siltstones are the predominant reservoir beds for the Chang 6 tight oil reservoirs (Fig. 2). The porosity of the reservoir beds of the Chang 6 tight oil mainly ranges from 6.0% to 12.0%, with a mean value of 9.03%. The permeability of the reservoir beds is mainly 0.01–2.03 mD, with an average value of 1.16 mD (Bai et al. 2013). According to the definition of tight reservoir beds in China (porosity of sandstone < 12% and permeability of sandstone < 2.00 mD) (Zou et al. 2013, 2015), the reservoir bed of the Chang 6 can be classified as tight reservoir beds, and is an important exploration target for tight oil reservoirs in the Ordos Basin.

Diagenesis of Tight Sandstones

The mineralogy and petrophysical properties of the Chang 6 reservoir sandstones have undergone diagenetic modification. The major diagenetic alternations are mechanical compaction, chemical pressolution, quartz cementation, growth of carbonates and authigenic clay minerals and the dissolution of unstable grains (Zheng et al. 2007; Dou et al. 2009; Zhao et al. 2009).

Based on the previous research on the diagenesis of the Chang 6 tight sandstones (Zheng et al. 2007; Dou et al. 2009; Zhao et al. 2009), four diagenetic stages can be identified in the Chang 6 tight sandstones (Fig. 3). 1) Syndiagenetic stage. This period is mainly characterized by hydrolysis of volcanic materials and detrital mica. 2) Eodiagenetic A stage. Diagenetic alternations include mechanical compaction, alteration of volcanic materials and detrital mica and chlorite during this stage. 3) Eodiagenetic B stage. This stage is characterized by intensive mechanical compaction, calcite cementation, quartz replacement by carbonate cement, illitization of smectite and precipitation of authigenic chlorite. 4) Mesodiagenetic A stage. Diagenetic alternations consist of chemical pressolution, dissolution of feldspars, rock fragments and carbonate cements, albitization and formation of authigenic quartz and illite.

Samples and Methods

Samples and Instruments

In this study, fluid inclusion samples were collected from 13 core samples of sandstones from 6 wells in the Chang 6 (Table 1). The lithology of the samples are mainly lithic arkose and feldspathic litharenite. 135 aqueous inclusions and 109 hydrocarbon (oil and gas) inclusions have been analyzed in these core samples.

Fluorescence and conventional optical microscopic analyses of the fluid inclusions were conducted with an Olympus Microscope that was equipped with an 8-mm telephoto lens with 100x magnification and Lucia fluorescence micro-spectrometry ($\leq 2 \mu\text{m}$). A Zeiss Ultraviolet G 365 nm excitation filter (395 nm beam splitter; 420 nm barrier filter) was used for sample illumination. A black body

correction was used to correct spectra for background effects, which include the spectral characters of the light source, optical imaging system, photomultiplier and monochromator. A standard tungsten lamp (3100 K) was used as a reference radiator. The micro-thermometry microscope was a Linkam (THMS 600G), which had an analysis precision of ± 0.1 °C. The initial heating rate was 10 °C/min, and the heating rate changed to 2 °C/min when the fluid inclusions approached a uniform state. The gas-liquid ratio (G/L) of single oil inclusion was measured by Confocal Laser Scanning Microscopy (CLSM).

Methodology

Analyses of fluid inclusions included petrography, fluorescence micro-spectrometry, micro-thermometry, and trapping pressure simulations.

Fluid Inclusion Petrography

The analyses of petrography of fluid inclusion includes dividing the inclusions into distinct types based on their setting, fluorescence colors, and phase character at room temperature. The setting of fluid inclusions can be ascertained by their distribution in the host minerals, the distribution type (individual or group), and the size and shape of the individual inclusion. Generally, oil inclusions, which are irradiated by ultraviolet light, produced fluorescence colors in the visible light range (wavelength of 400–700 nm), while gas and aqueous inclusions exhibited no fluorescence color. The shift of fluorescence colors (red–orange–yellow–green–blue–colorless) indicates increasing oil thermal maturities (Liu and Eadington 2005). The phase type of fluid inclusions mainly contains gas-phase, liquid-phase, solid-phase,

205 and gas-liquid phase. Generally, the phase types are the same for each episode of fluid
206 inclusion formation. Fluid inclusions have different gas-liquid ratios associated with
207 the fluid composition and density. Based on the petrographic characters, the time
208 relationship between hydrocarbon charging and diagenetic evolution can be
209 established.

210 ***Fluid Inclusion Assemblage Approach***

211 To minimize the emphasis on the inherited, primary, secondary, and
212 pseudosecondary classification of inclusions, Goldstein and Reynolds (1994)
213 introduced the concept of the fluid inclusion assemblage (FIA) to describe a group of
214 fluid inclusions that were all trapped at the same time. An FIA defines the most finely
215 discriminated fluid inclusion trapping event that can be identified based on
216 petrography. An FIA could be composed of all of the inclusions trapped along a single
217 healed fracture, or all of the inclusions trapped in the most finely discriminated
218 growth zone in a single crystal (Goldstein 2001). This requirement further implies that
219 the inclusions in the FIA were all trapped at approximately the same temperature and
220 pressure, and all trapped a fluid of approximately the same composition. The
221 requirement that the inclusions within an FIA were all trapped ‘at the same time’ is
222 relative and the absolute amount of time of the event will vary according to the
223 environment of formation (Bodnar 2003). The FIA approach is one in which the
224 researcher is forced to identify a single event of fluid inclusion entrapment, resolved
225 to as close to an instant of geologic time as will the petrographic relationship allow
226 (Goldstein 2001), which is the preferred method to be applied to sedimentary rocks

and other rocks containing fluid inclusions.

Fluorescence Micro-spectrometry of Fluid Inclusion

Fluorescence micro-spectra of single oil inclusion can be recoded, corrected and averaged by Lucia fluorescence micro-spectrometry ($\leq 2 \mu\text{m}$), utilizing the Zeiss Ultraviolet G 365 nm excitation filter. The spectra characters of oil inclusions can be used to assess the origin, differentiation, and thermal-maturity of crude oil (Hagemann and Hollerbach 1986). The peak wavelength (λ_{max}) and intensity (I) of fluorescence spectra can be used to recognize the differences between different properties of oil inclusions (McLimans 1987; Stasiuk and Snowdon 1997; Si et al. 2013). A larger peak wavelength value indicates lower oil thermal-maturity, and vice versa.

$Q_{650/500}$ is defined as the fluorescence intensity ratio between the fluorescence intensity of a wavelength of 650 nm (corresponding to the fluorescence color of red) (I_{650}) and the fluorescence intensity of a wavelength of 500 nm (corresponding to the fluorescence color of green) (I_{500}) (Hagemann and Hollerbach 1986; Burruss 1991; Li et al. 1998). Larger I_{650} values indicate that the oils contain more large-molecular compounds and that the oil thermal-maturity is lower, while larger I_{500} values indicate the converse results (Burruss 1991). So larger $Q_{650/500}$ values suggest lower oil thermal-maturity, while smaller values suggest higher oil thermal-maturity.

Q_{F535} is defined as the ratio between the area of wavelengths within 720–535 nm and the area of wavelengths within 535–420 nm (Si et al. 2013). Smaller Q_{F535} values indicate the oils in the inclusions contain more small-molecular compounds and that

the oil thermal-maturity is higher, while larger Q_{F535} values suggest that the oil thermal-maturity is lower.

Fluid Inclusions Micro-thermometry

Fluid inclusion petrography, micro-thermometry, transmitted light and micro-fluorescence observation methods were employed to systematically obtain information on homogenization temperatures of oil inclusions and their coeval aqueous inclusions. Combined with the burial history curves, the results of micro-thermometry can be used to determine the charging timing. By projecting the average homogenization temperatures ranges onto the burial history curves, the timing of each hydrocarbon charging event is determined (Goldstein 2001; Munz 2001; Chen 2007).

Trapping Pressure Simulation of Oil Inclusion

Based on the following assumptions, the pressure-temperature (P-T) path of oil trapped in the inclusions will obey the isometric change on the P-T phase diagram. 1) The fluid trapped upon sealing of the inclusion was a single, homogenization phase. 2) The cavity in which the fluid is trapped does not change in volume after sealing. 3) Nothing is added or lost from the inclusion after sealing. 4) The effects of pressure are insignificant, or are known. 5) The origin of the inclusion (inherited, primary, secondary, or pseudosecondary) should be known (Roedder and Bodnar 1980).

The physical trapping conditions (pressures and temperatures) for oil inclusions and their coeval aqueous inclusions are the same when these oil and aqueous inclusions are trapped in the same FIA and have not been stretched, leaked, and

271 refilled (Goldstein and Reynolds 1994; Munz 2001; Chen 2007). Due to the
272 differences of the physical and chemical stabilities of hydrocarbon and aqueous
273 inclusions, the variation in the homogenization temperatures of the aqueous inclusions
274 is less than those of the oil inclusions or other fluid inclusions (CO₂ inclusions, etc.)
275 (Goldstein 2001; Liu et al. 2003). Generally, the homogenization temperatures of the
276 oil inclusions are lower than those of the coeval aqueous inclusions (Nedkvitne et al.
277 1993; Liu et al. 2003). The analyzed homogenization of aqueous inclusions represents
278 the final homogenization. However, the homogenization of petroleum inclusions
279 represents only a partial homogenization.

280 The pressure and temperature conditions for trapping of petroleum inclusions
281 and coexisting aqueous inclusions can be estimated by the intersecting isochore
282 principle (Roedder and Bondnar 1980). In this study, we employed the method that
283 introduced by Aplin et al. (2000), namely, using the point at which the isochore of a
284 petroleum inclusion intersection with a vertical line of the homogenization
285 temperature of a coeval aqueous inclusion to deduce the true trapping pressure and
286 trapping temperature (Fig. 4). The aqueous and oil inclusions measured in the
287 experiment should be small and regular-shape (Liu et al. 2003). The inclusions we
288 have measured are elliptical or near circular with diameters of 5 µm. In the study, the
289 trapping pressure of the oil inclusions were calculated by PVT-simulations, using the
290 modelling software of VTFLINC, which is based on the state equation of
291 Soave-Redlich-Kwong (Aplin et al. 1999, 2000; Liu et al. 2003).

292 Three pieces of information are required to conduct the PVT simulations: 1) the
293 homogenization temperature of inclusion; 2) the G/L ratio at room temperature; 3) the
294 composition of the included petroleum, or at least a composition which is sufficiently
295 detailed to enable the accurate prediction of its physical behavior (Aplin et al. 1999).
296 The most problematic point of the PVT modelling is characterization of the
297 composition of the included petroleum (Munz 2001). A method that a model
298 composition of the inclusions is calculated by using the present-day reservoir fluid
299 composition as a regression parameter was introduced by Aplin et al. (1999). The
300 necessary data from fluid inclusion analyses are: 1) the molar volume of the
301 petroleum at room and homogenization temperature; 2) the G/L ratio at room
302 temperature determined by confocal laser scanning microscopy (CLSM) (Aplin et al.
303 1999). The calculations are done as a series of iterations, titrating gas components
304 (C_1 – C_5) into or out of the fluid composition, until a composition is found that matches
305 the volumetric constraints at room temperature (experimental) and at the
306 homogenization temperature (calculated). The accuracy of this method is dependent
307 on the initial composition. Aplin et al. (1999) assume that the inclusion fluid is most
308 accurately modelled if the fluid, which is used as input for the calculations, is
309 generally related.

310 The detailed steps to calculate the trapped pressure are as follows: 1) measuring
311 the G/L of single oil inclusion accurately by using CLSM; 2) calculating the
312 composition of oil inclusion accurately by VTFLINC; 3) establishing the P-T phase

diagrams and isochores of the oil inclusions; 4) drawing the intersection point of trapping temperature and isochore of oil inclusion, and ascertaining the trapping pressure at the intersection point (Roedder and Bondnar 1980; Aplin et al. 1999; Liu et al. 2003). According to the error analyses on the calculating method in the research made by Xu et al. (2017b), the deviation is always less than 5.0 MPa, with a mean of 2.5 MPa, which is acceptable.

Analysis of Quantitative Grain Fluorescence (QGF) and Quantitative Grain Fluorescence on Extract (QGF-E)

The samples (cores) were disaggregated into individual grains by physical crushing and gentle agitation. The grains are then sieved to select the sand fraction (60-80 meshes). A pre-cleaning procedure was developed to remove potential contaminants and soluble and reactive hydrocarbons, aiming to ensure that fluorescence is only yielded from either inclusion oils or from surface adsorbed hydrocarbons. To remove soluble hydrocarbons or additives, the QGF cleaning processes comprise cleaning the grains in dichloromethane (DCM) in an ultrasound bath for 10 min. Samples are then oven dried at 60 °C. The dried sample was digested in 10% H₂O₂ at room temperature for 1 h with the initial and final 10 min in an ultrasonic bath to degrade and remove reactive organic compounds and clay particles adhering to the grain surfaces. The sand grains were decanted and then digested in 3.6% hydrochloric acid (1 M HCl) at room temperature, with periodic agitation, to remove carbonate minerals and coatings that might produce mineral fluorescence, as well as iron oxides and hydroxides, which may coat grain surfaces. The remaining grains,

comprising predominantly quartz and feldspar, were washed a second time with HPLC (high performance liquid chromatography) grade DCM in an ultrasonic bath for 10 min to extract hydrocarbon compounds adhering to the grain surface. The grains are dried for QGF analysis (Liu and Eadington 2005).

The wavelengths of QGF spectra of ancient and modern oil reservoirs typically range from 400 nm to 600 nm (Liu et al. 2007). The QGF index is defined as the fluorescence intensity ratio between the average fluorescence intensity of a wavelength of 375-475 nm and the fluorescence intensity of a wavelength of 300 nm (Liu and Eadington 2005). A QGF index greater than 4 generally indicates an ancient oil reservoir, while values that range from 0 to 4 generally correspond to a carrier bed (Liu and Eadington 2005). Residual and current oil reservoirs have strong quantitative grain fluorescence on extract (QGF-E) spectra. Generally, the intensity of the QGF-E is over 20 *a.u.* (*arbitrary units*), and the peak wavelength ($\lambda_{\max}$) is approximately 370 nm. However, the intensity of the QGF-E is rarely over 40 *a.u.* in aqueous layers, and the peak wavelength ($\lambda_{\max}$) is 300-500 nm (Liu and Eadington 2005).

Formation Pressure Calculation of Shale-mudstone

Acoustic log-based pore pressure detection using Eaton's (1975) method yielded accurate estimates with the overpressures generated by disequilibrium compaction, combined with the measured pressure obtained by drilling and well logging. Based on the rule of porosity-effective stress, the effective stresses are equal while the porosities of media are the same (Bowers 2002; Ruth et al. 2004). According to the principle of Eaton's method and acoustic interval transit time data, the formation

pressure of Chang 7 shales and mudstones can be predicted in the study area based on Formula 3.1.

$$P_Z = \rho_r g Z + \frac{(\rho_r - \rho_w)g}{C} \ln \frac{\Delta t}{\Delta t_0} \quad (3.1)$$

Here, P_Z is the formation pressure of shales and mudstones (MPa), ρ_r is the average density of overlying rocks (kg/m^3), g is the gravity acceleration (m/s^2), Z is the burial depth of disequilibrium compaction shales and mudstones (m), ρ_w is the density of formation water (kg/m^3), Δt is the value of acoustic interval transit time of shales and mudstones ($\mu\text{s/m}$), Δt_0 is the value of acoustic interval transit time of earth surface ($\mu\text{s/m}$), and C is the compacting coefficient of normally compacted shales and mudstones (m^{-1}).

Comparing the calculated pressures with the measured values revealed a good relationships (Fig. 5), and utilizing this method to calculate the formation pressure of the Chang 7 shales and mudstones is considerable acceptable.

Results

Fluid Inclusion Petrography

The fluid inclusions in the tight sandstones of the Chang 6 can be divided into three types: aqueous inclusions, oil inclusions, and gas inclusions. The petrographic characterization indicates that the burial fluids trapped inclusions display a variety of shapes, but mainly in circle and ellipse. The size of fluid inclusions ranges from 3 μm to 15 μm , and generally less than 10 μm in longest dimension. Analyses of petrographic and diagenetic sequence of the host minerals have enabled the identification of six distinct types of FIA (Table 2). The six types of FIA are: 1) oil

inclusions and aqueous inclusions, trapped along healed fractures that occur within the quartz grains (Type I) (Fig. 6a, b, c); 2) oil inclusions and aqueous inclusions, trapped along healed fractures that cut across the quartz grains (Type II) (Fig. 6d, e); 3) oil inclusions and aqueous inclusions, trapped in the quartz overgrowth (Type III) (Fig. 6f); 4) oil inclusions and aqueous inclusions, trapped in the calcite cements (Type IV) (Fig. 6g); 5) oil inclusions and aqueous inclusions, trapped along healed fractures that occur within the feldspar grains (Type V) (Fig. 6h); 6) gas inclusions and aqueous inclusions, trapped along healed fractures that cut across the quartz grains (Type VI) (Fig. 6i).

Characteristics of Fluorescence Micro-spectrometry

The peak wavelength of the fluorescence micro-spectrometry of the oil inclusions in the Chang 6 reservoir beds mainly ranges from 495 nm to 541 nm (Table 3). $Q_{650/500}$ is mainly 0.22–0.52, with a mean of 0.32 and a standard deviation of 0.06 (Table 3). Q_{F535} is mainly 0.73–1.39, with a mean of 1.05 and a standard deviation of 0.14 (Table 3).

Fluid Inclusion Micro-thermometry Results

Homogenization temperatures of the aqueous inclusions have five peaks, while those of the oil inclusions have three peaks (Fig. 7, Table 4).

The homogenization temperature of the 1st peak of the aqueous inclusions is 31.5 °C. The homogenization temperature of the 2nd peak of the aqueous inclusions is 75.0 °C. The homogenization temperatures of the 3rd peak of the aqueous inclusions range from 81.6 °C to 95.4 °C, with a mean of 86.8 °C. The homogenization temperatures

of the 4th peak of the aqueous inclusions range from 102.0 °C to 117.1 °C, with a mean of 111.1 °C. The homogenization temperatures of the 5th peak of the aqueous inclusions range from 120.5 °C to 137.1 °C, with a mean of 132 °C.

The homogenization temperatures of the 1st peak of the oil inclusions range from 77.1 °C to 93.1 °C, with a mean of 86.1 °C. The homogenization temperatures of the 2nd peak of the oil inclusions range from 101.7 °C to 119.4 °C, with a mean of 109.0 °C. The homogenization temperatures of the 3rd peak of the oil inclusions range from 120.7 °C to 134.9 °C, with a mean of 130.7 °C.

Trapping Pressure Simulations

Based on simulations and calculations (Fig. 8), eight trapping pressure values of oil inclusions from different charging episodes in the Chang 6 tight sandstones from different wells are obtained (Table 5). The trapping pressures of the oil inclusions with the 1st peak homogenization temperatures were relatively low, approximately 20.0 MPa. However, the trapping pressures of the oil inclusions with the 2nd and 3rd peaks homogenization temperatures were relatively high, greater than 25.0 MPa.

Discussion

Crude Oil Charging Episodes

Three peak wavelength values, namely, 539 nm (Fig. 9a), 519 nm (Fig. 9b), and 498 nm (Fig. 9c), can be recognized on the overlapping diagrams of fluorescence micro-spectrometry curves. These peaks indicate that three episodes of oil charging with different maturities occurred in the Chang 6 tight sandstones. According to the scatterplots of $Q_{650/500}-\lambda_{\max}$ (Fig. 10) and $Q_{F535}-\lambda_{\max}$ (Fig. 11), $Q_{650/500}$ values exhibit

three intervals (0.22–0.36, 0.28–0.37, and 0.40–0.45), and Q_{F535} values also exhibit three intervals (0.73–1.14, 1.01–1.20, and 1.27–1.40), which correspond to three peak wavelength values (498 nm, 519 nm, and 539 nm), respectively.

Theoretically, oil thermal-maturity increases gradually over time if the subsidence continues. Oil inclusions, characterized by the yellow-green fluorescence color (Fig. 6), are mainly distributed in fractures that cut across and occur within quartz grains and partly located in the quartz overgrowth, and predominantly consist of liquid-only phase inclusions. The peak wavelength values of these inclusions are predominantly 539 nm (Fig. 9a), corresponding to the $Q_{650/500}$ value interval being 0.40–0.45 (Fig. 10) and Q_{F535} value interval being 1.27–1.40 (Fig. 11). These inclusions indicate the oil charging with relatively low oil thermal-maturity, which represent the 1st episode of oil charging in the Chang 6 tight sandstones.

Oil inclusions, characterized by the green fluorescence color (Fig. 6), are mostly distributed in the fractures that cut across quartz grains and partly located in fractures that occur within the feldspar grains, and mostly include liquid-only phase inclusions. The peak wavelength values of these inclusions are predominantly 519 nm (Fig. 9b), corresponding to the $Q_{650/500}$ value interval being 0.28–0.37 (Fig. 10) and Q_{F535} value interval being 1.01–1.20 (Fig. 11). These inclusions indicate the oil charging with intermediate oil thermal-maturity, which represent the 2nd episode of oil charging in the Chang 6 tight sandstones.

Oil inclusions, characterized by the blue-green fluorescence color (Fig. 6), are

mostly distributed in fractures that cut across quartz grains and partly located in the quartz overgrowth, the calcite cements, and in fractures that occur within the feldspar grains. These inclusions are mostly liquid-only phase inclusions and some gas-liquid inclusions. The peak wavelength values of these inclusions are predominantly 498 nm (Fig. 9c), corresponding to the $Q_{650/500}$ value interval being 0.22–0.36 (Fig. 10) and Q_{F535} value interval being 0.73–1.14 (Fig. 11). These inclusions indicate the oil charging with relatively high oil thermal-maturity, which represent the 3rd episode of oil charging in the Chang 6 tight sandstones. To summarize, three episodes of oil charging with different maturities can be recognized through oil inclusion petrographic characters, fluorescence micro-spectrometry, $Q_{650/500}$, and Q_{F535} .

Gas inclusions with no fluorescence can be observed locally in fractures that cut across quartz grains (Fig. 6i), which might have been trapped during the upward diffusion of natural gas from the generation of underlying Paleozoic source rocks during the highly mature to overly mature stages. Intergranular pores were filled with bitumen, which has no fluorescence and may have formed from secondary changes in crude oils during early charging.

Crude Oil Charging Timing

Based on the previous studies in the Section 4.c and 5.a, aqueous inclusions with five peaks of homogenization temperatures and oil inclusions with three peaks of homogenization temperatures have been identified in the Chang 6 tight reservoir beds (Figs. 6, 7, 9–11, Table 3, 4). The variation in the homogenization temperatures of the oil inclusions was more than those of the aqueous inclusions (Goldstein 2001; Liu et

al. 2003). It is more accurate to use the homogenization temperatures of the aqueous inclusions to determine the trapping temperatures of the oil inclusions and coeval aqueous inclusions.

The homogenization temperatures of the aqueous inclusions with the 1st and 2nd peaks were relatively low, which might be attributed to early diagenetic fluid activities. The temperatures at which the aqueous inclusions with the 1st and 2nd peaks of homogenization temperatures formed did not reach the temperature of ‘oil window’, leading to no hydrocarbons formed or migrated. As a result, no oil inclusions is coeval with the aqueous inclusions with the 1st and 2nd peaks of homogenization temperatures. However, the temperatures at which the aqueous inclusions with the 3rd, 4th, and 5th peaks of homogenization temperatures indicate that the source rocks had reached the oil window, and large amounts of hydrocarbons are likely to have been generated. Meanwhile, the aqueous inclusions with the 3rd, 4th, and 5th peaks of homogenization temperatures have similar characters of petrography and micro-thermometry with the oil inclusions with the 1st, 2nd, and 3rd peaks of homogenization temperatures, respectively. It suggests that the aqueous inclusions with the 3rd, 4th, and 5th peaks of homogenization temperatures are coeval with the oil inclusions with the 1st, 2nd, and 3rd peaks of homogenization temperatures, respectively. The fluorescence colors of the oil inclusions with the 1st, 2nd, and 3rd peaks of homogenization temperatures are yellow-green, green, and blue-green, respectively.

According to the characters of micro-thermometry of the aqueous inclusions in

the Chang 6 tight reservoir beds, the homogenization temperatures of the aqueous inclusions can be recognized three peak intervals, namely, 80–90 °C, 110–120 °C, and 130–140 °C (Fig. 12), which represent the temperatures at which three episodes of tight oil charge occurred. The oil inclusions formed in the 1st peak interval of 80–90 °C represent the 1st episode of oil charging with relatively low oil thermal-maturity in the Chang 6 tight sandstones, corresponding to the fluorescence color being yellow-green. The oil inclusions formed in the 2nd peak interval of 110–120 °C represent the 2nd episode of oil charging with intermediate oil thermal-maturity, corresponding to the fluorescence color being green. The oil inclusions formed in the 3rd peak interval of 130–140 °C represent the 3rd episode of oil charging with relatively high oil thermal-maturity, corresponding to the fluorescence color being blue-green.

Influenced by the tectonic thermal events that were caused by the enhancement of tectonic compression and magmatic activity in the deep lithosphere (geothermal gradient up to 3.5–4.5 °C/100m) in the Early Cretaceous (140–100 Ma) (Ren and Zhao 2001), lacustrine oil shales of Chang 7 matured rapidly and fluid activities were enhanced effectively. The main generation (expulsion) timing of the Chang 7 source rocks was the Early Cretaceous (140–110 Ma) (Zhang et al. 2006). According to the stratigraphic burial and geothermal evolution histories of typical well established by Xu et al. (2017a) in the study area, three charging episodes, namely, 141–136 Ma, 126–118 Ma, and 112–103 Ma (Fig. 13), were identified by projecting the

homogenization temperatures of aqueous inclusions onto the geological time axis. The charging timing slightly lagged behind the main generation timing of Chang 7 oil shales, due to the primary migration and secondary migration over a short distance of tight oil reservoirs (Zou et al. 2013, 2015).

Crude Oil Charging Drive

Buoyancy forces in unconventional continuous reservoirs are weak due to the tight reservoir beds, the flat slope (the dip of the study area being to the east with a dip angle of 1°–2°), and the limited free water (Bai et al. 2013; Yao et al. 2014; Xu et al. 2017a). In this case, non-buoyancy migration, primary migration and secondary migration over a short distance are the basic migration characteristics of tight oil reservoirs (Zou et al. 2013, 2015). The migration processes are complex, and the factors that affect the migration are various. Generally, the geological fluids flow from areas of high excess pressure to those of low excess pressure in source rocks, in reservoir beds, and between them (Hunt 1990).

Numerous research has suggested that normal compaction and overpressure caused by the disequilibrium compaction, hydrocarbon generation, tectonic stress, and clay minerals dehydration should be the main hydrocarbon charging drive for primary migration (Hunt 1990; Osborne and Swarbrick 1997; Gudmundsson 2001; Tingay et al. 2009). In the study area, overpressure formed in the oil shales of Chang 7 in the early stage was mainly controlled by the disequilibrium compaction of shales and mudstones, and in the later stage it was predominantly influenced by the hydrocarbon generation. The pressurization of disequilibrium compaction and hydrocarbon

generation continuously created overpressure with high pressure coefficients in time and space.

For the elasticity and plasticity differences between the sandstone and shale-mudstone, the overpressure developed in the shale-mudstone will be retained while the strata are uplifting. Conversely, the overpressure developed in the sandstone will be released (Bowers 2002; He et al. 2010; Wang 2014). According to the tectonic evolution history of the Ordos Basin, the shales and mudstones in Chang 7 reached their maximum burial depth during the Early Cretaceous and then were continuously uplifted afterwards (Yang et al. 2005b). The source rocks will retain a significant volume of oil, either within its pore system or adsorbed in or onto the kerogen (Pepper 1991; Sandvik et al. 1992; Jarvie 2012), which causes the fluid pressure retained in shales and mudstones due to their plasticity. Therefore, the present overpressures in shales and mudstones can approximately represent the overpressures at the maximum burial depth of the Chang 7 shales and mudstones (Early Cretaceous), namely, the formation pressures of the shales and mudstones during the main charging stage. The excess pressure differences between the Chang 7 source rocks and the Chang 6 sandstones are the main charging drive for crude oil to charge from the Chang 7 source rocks into the Chang 6 reservoir beds, which are quantitative parameters to ascertain the charging drive in the charging process.

Trapping pressures of the Chang 6 oil inclusions represent the formation pressure of the Chang 6 reservoir beds while the crude oil was charging. At the same time, we

551 can calculate the hydrostatic pressure of the Chang 6 reservoir beds while the crude
552 oil was charging. The paleo burial depth could be ascertained by the homogenization
553 temperature of the coeval aqueous inclusions. Based on the paleo burial depth, the
554 paleo-geothermal gradient (4.06 °C/100m) (Ren et al. 2001), and the density of
555 formation water (1.04 g/cm³), the hydrostatic pressures could be calculated (Table 5).
556 According to the formation pressures and hydrostatic pressures, the excess pressure
557 (the differences between formation pressure and hydrostatic pressure at the same
558 depth) of the Chang 6 reservoir beds during the crude oil charge can be ascertained
559 (Table 5).

560 Based on Formula 3.1, we statistically analyzed well-logging data from 10 wells
561 and calculated the single well formation pressures. Combined with the previous
562 research (Deng 2011), the spatial distribution of excess pressure of Chang 7 source
563 rocks at their maximum burial depth in the late period of the Early Cretaceous was
564 drawn (Fig. 14). Making these distributions of the excess pressures as a constraint
565 condition, Guo (2013) and Yao et al. (2014) have made the evolution histories of the
566 formation pressures and hydrostatic pressures of the Chang 7 source rocks during the
567 Early Cretaceous (Table 6). Based on these pressures, the excess pressures of the
568 Chang 7 source rocks have been calculated (Table 6).

569 As shown in Table 6, the excess pressure differences between the Chang 7 source
570 rocks and the Chang 6 reservoir beds range from 0.4 MPa to 10.8 MPa during the
571 main charging period. The QGF and QGF-E values show that the samples we

analyzed are located in the ancient oil reservoirs and residual current oil reservoirs. The excess pressure differences were 0.6-6.8 MPa, with a mean of 3.7 MPa, during the 1st episode of tight oil charging. The excess pressure differences ranged from 0.4 MPa to 4.2 MPa, with a mean of 2.3 MPa, during the 2nd episode of tight oil charging. The excess pressure differences were 10.7–10.8 MPa, with a mean of 10.7 MPa, during the 3rd episode of tight oil charging. The excess pressure differences were relatively high during the 1st and 3rd episodes of tight oil charging, which may be explained as follows. First, the tight reservoir beds were filled with water before oil charging. Based on the principle of ‘like dissolves like’, higher pressure is required for oils to displace water and charge into reservoir beds for the first time. Second, the source rocks rapidly created overpressure with high pressure coefficients during the 3rd episode of tight oil charging because of the pressurizations from disequilibrium compaction and hydrocarbon generation in time and space, so the source rocks could not transfer the high pressure into the reservoir beds timely and effectively. The lower limit of the excess pressure differences was 2.3 MPa in the main oil charging period. When excess pressure differences are greater than 2.3 MPa, tight oil reservoirs could form; when they are greater than 10.8 MPa, tight oil reservoirs with large scale charging could form.

Conclusions

Based on the systematic analyses of the episodes, timing, and intensities of the hydrocarbon charging of the Chang 6 lacustrine tight oil, the following conclusions

593 can be drawn:

594 1) Aqueous inclusions with five peaks of homogenization temperatures and oil
595 inclusions with three peaks of homogenization temperatures were found in the study
596 area based on the micro-thermometry of fluid inclusions from the Chang 6 tight
597 reservoir beds. The aqueous inclusions with the 3rd, 4th, and 5th peaks of
598 homogenization temperatures are coeval with the oil inclusions with the 1st, 2nd, and
599 3rd peaks of homogenization temperatures, respectively.

600 2) Three oil charging episodes with different maturities were recognized in the
601 southwest Ordos Basin, according to the petrography, fluorescence
602 micro-spectrometry, and micro-thermometry of oil inclusions in the Chang 6 tight
603 reservoir beds.

604 3) The timing of the three charging episodes were 141–136 Ma, 126–118 Ma,
605 and 112–103 Ma, according to the stratigraphic burial history, geothermal evolution
606 history, and micro-thermometry of aqueous inclusions from the Chang 6 tight
607 reservoir beds in the study area. The main generation (expulsion) timing of the Chang
608 7 oil shales was the Early Cretaceous (140–110 Ma). Although the main generation
609 timing approximately covered the time span of the three charging episodes, the main
610 charging timing of the Chang 6 tight oil slightly lagged behind the main generation
611 timing of Chang 7 oil shales.

612 4) The excess pressure differences between the Chang 7 source rocks and the
613 Chang 6 reservoir beds, ranging from 0.4 MPa to 10.8 MPa, are the main charging

drive for crude oil during the main charging period. The excess pressure differences were relatively high during the 1st and 3rd episodes of tight oil charging.

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821

822 **Table**

823

Table 1. Geological setting of the study samples

Well	Location	Depth (m)	Age	Sample description
C120	Huachi	1927.42	Chang 6	Grey lithic arkose
C120	Huachi	1928.20	Chang 6	Grey lithic arkose
L89	Huanxian	2237.90	Chang 6	Grey-green feldspathic litharenite
L89	Huanxian	2262.20	Chang 6	Grey feldspathic litharenite
L89	Huanxian	2262.50	Chang 6	Grey feldspathic litharenite
N33	Zhengning	1621.24	Chang 6	Grey-green feldspathic litharenite
N33	Zhengning	1621.55	Chang 6	Grey-green feldspathic litharenite
T1	Huachi	1686.95	Chang 6	Grey-green lithic arkose
T1	Huachi	1687.10	Chang 6	Grey-green lithic arkose
X79	Qingcheng	1927.15	Chang 6	Grey feldspathic litharenite
X79	Qingcheng	1927.30	Chang 6	Grey feldspathic litharenite
Z76	Huachi	2000.10	Chang 6	Grey lithic arkose
Z76	Huachi	2000.35	Chang 6	Grey lithic arkose

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Table 2 Petrographic characters of six FIA in the Chang 6 Member in the southwest Ordos Basin

Type and Parameters	Type I and Type II	Type III	Type IV	Type V	Type VI
Occurrence	Trapped along healed fractures that cut across and occur within the quartz grains	Trapped in the quartz overgrowth	Trapped in the calcite cements	Trapped along healed fractures that occur within the feldspar grains	Trapped along healed fractures that cut across the quartz grains
Quantity proportion (%) of the total FIAs	75%	10%	5%	5%	5%
Quantity proportion (%) of the fluid inclusions in the same FIA	75%–85%	80%	80%	85%	90%
Phase	Gas-liquid phases	Gas-liquid phases	Gas-liquid phases	Gas-liquid phases	Gas-liquid phases
Color under polarized light	Colorless and transparent	Colorless and transparent	Colorless and transparent	Colorless and transparent	Colorless and transparent
Distribution	Trails along healed fractures or bead clusters	Bead clusters	Bead clusters	Trails along healed fractures	Trails along healed fractures
Diameter (μm) of individual inclusion	3–10 μm	3–7 μm	3–8 μm	3–8 μm	3–10 μm
Shape of individual inclusion	Elliptical, near circular	Elliptical, near circular	Elliptical	Elliptical	Elliptical
G/L ratio (Vol. %)	4%–10%	4%–9%	4%–10%	4%–8%	4%–9%
Oil inclusion	Quantity proportion (%) of the fluid	15%–25%	20%	15%	—

inclusions in the same FIA					
	Phase	Liquid-only phase and gas-liquid phases	Liquid-only phase	Liquid-only phase	Liquid-only phase and gas-liquid phases
	Fluorescence color	Blue-green, green, and yellow-green	Blue-green and yellow-green	Blue-green	Blue-green and green
	Distribution	Trails along healed fractures or bead clusters	Bead clusters	Bead clusters	Trails along healed fractures
	Diameter (μm) of individual inclusion	3–15 μm	3–10 μm	3–11 μm	3–12 μm
	Shape of individual inclusion	Elliptical or irregular	Elliptical or irregular	Elliptical	Elliptical
	G/L ratio (%)	2%–8%	—	—	2%–10%
Quantity t proportion (%) of the fluid inclusions in the same FIA		—	—	—	10%
Gas inclusion	Phase	—	—	—	Gas-only phase
	Fluorescence color	—	—	—	Colorless
	Distribution	—	—	—	Trails along healed fractures
	Diameter (μm) of individual inclusion	—	—	—	3–7 μm

Shape of individual inclusion	—	—	—	—	Elliptical
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Note: “—” = no data

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826 **Table 3. Peak wavelength, Q_{F535} and $Q_{650/500}$ values of the fluorescence**
 827 **micro-spectrometry of the oil inclusions in the Chang 6 reservoir beds in the**
 828 **Ordos Basin**

Well	Depth (m)	Peak wave-length (nm)	$Q_{650/500}$	Q_{F535}	Well	Depth (m)	Peak wave-length (nm)	$Q_{650/500}$	Q_{F535}
C120	1927.42	497	0.36	1.05	N33	1621.55	498	0.32	1.05
C120	1927.42	497	0.52	1.39	N33	1621.55	494	0.29	0.95
C120	1928.20	508	0.25	0.95	T1	1686.95	496	0.22	0.80
C120	1928.20	502	0.32	1.08	T1	1686.95	496	0.34	1.00
C120	1928.20	504	0.25	0.92	T1	1686.95	496	0.35	1.04
L89	2237.90	497	0.28	0.92	T1	1687.10	497	0.26	0.88
L89	2237.90	497	0.29	0.96	T1	1687.10	540	0.43	1.35
L89	2237.90	539	0.42	1.37	T1	1687.10	497	0.31	0.99
L89	2262.52	499	0.32	1.00	T1	1687.10	497	0.34	1.01
L89	2262.52	499	0.31	0.99	X79	1927.15	521	0.31	1.09
L89	2262.20	497	0.31	1.03	X79	1927.15	517	0.28	1.01
L89	2262.20	523	0.37	1.20	X79	1927.30	509	0.30	1.01
L89	2262.20	541	0.45	1.40	X79	1927.30	518	0.31	1.08
L89	2262.20	499	0.34	1.14	X79	1927.30	537	0.44	1.28
L89	2262.20	522	0.30	1.12	X79	1927.30	502	0.24	0.92
L89	2262.20	540	0.40	1.29	X79	1927.30	501	0.33	1.03
N33	1621.24	501	0.26	1.02	X79	1927.30	497	0.28	0.94
N33	1621.24	496	0.36	1.10	Z76	2000.10	498	0.34	1.07
N33	1621.24	518	0.37	1.20	Z76	2000.10	495	0.22	0.73
N33	1621.55	497	0.33	1.06	Z76	2000.35	541	0.42	1.27
N33	1621.55	515	0.31	1.11	Z76	2000.35	526	0.41	1.36

829 **Table 4. Homogenization temperatures of the fluid inclusions in the Chang 6**
830 **reservoir beds in the southwest Ordos Basin**

Well	Depth (m)	Occurrence along healed fractures	Th _{aq} (°C)					Th _{oil} (°C)		
			Th ₁	Th ₂	Th ₃	Th ₄	Th ₅	Th ₁	Th ₂	Th ₃
Z76	2000.10	Cross quartz grain	—	—	95.4	—	132.8	—	—	134.7
L89	2237.90	Cross quartz grain	—	—	—	113.8	—	—	101.7	—
T1	1686.95	Cross quartz grain	—	—	—	113.4	134.2	—	—	132.3
X79	1927.30	Cross quartz grain	—	—	—	—	120.5	91.7	109.9	130.9
C120	1927.42	Cross quartz grain	—	—	86.1	—	132.3	—	—	120.7
N33	1621.24	Cross quartz grain	—	—	81.6	102.0	—	93.1	—	132.9
L89	2262.20	Cross quartz grain	—	—	85.1	—	124.6	78.3	116.4	134.9
X79	1927.15	Cross quartz grain	—	—	—	—	137.1	—	119.4	—
		Within quartz grain	31.5	—	—	—	136.6	—	—	134.9
L89	2262.52	Cross quartz grain	—	75.0	—	113.8	—	88.1	—	—
C120	1928.20	Cross quartz grain	—	—	87.3	—	130.4	88.5	103.5	—
Z76	2000.35	Cross quartz grain	—	—	85.3	—	133.7	—	107.6	—
N33	1621.55	Cross quartz grain	—	—	—	106.5	132.7	—	—	127.6
		Cross feldspar grain	—	—	—	—	—	—	—	127.0
T1	1687.10	Cross quartz grain	—	—	—	117.1	137.0	77.1	104.8	—

Note: Th_{oil} represents the homogenization temperatures of the oil inclusions. Th_{aq} represents the homogenization temperatures of the aqueous inclusions. Th₁ represents the 1st peaks of homogenization temperatures. Th₂ represents the 2nd peaks of homogenization temperatures. Th₃ represents the 3rd peaks of homogenization temperatures. Th₄ represents the 4th peaks of homogenization temperatures. Th₅ represents the 5th peaks of homogenization temperatures. The symbol ‘—’ represents no data.

Table 5. Trapping pressures of the fluid inclusions in the Chang 6 reservoir beds
in the southwest Ordos Basin

Well	Depth (m)	Episode	Th _{aq} (°C)	Th _{oil} (°C)	G/L (%)	P _{H-Charge} (MPa)	P _{trap} (MPa)	P _{E-Charge} (MPa)
L89	2262.20	1 st	86.2	77.4	6.5	18.7	22.7	4.0
X79	1927.15	1 st	95.4	74.7	4.0	21.3	18.4	-2.9
L89	2237.90	2 nd	117.3	98.1	9.4	24.1	30.1	6.0
L89	2262.20	2 nd	123.5	115.6	12.0	25.6	28.7	3.1
N33	1621.24	2 nd	101.0	92.3	10.2	20.0	27.3	7.3
X79	1927.30	2 nd	117.2	93.6	7.5	24.1	28.4	4.3
L89	2262.50	3 rd	137.4	126.5	11.0	28.6	28.2	-0.4
X79	1927.30	3 rd	135.7	119.5	9.0	28.2	26.3	-1.9

Note: Th_{oil} represents the homogenization temperatures of the oil inclusions. Th_{aq} represents the homogenization temperatures of the aqueous inclusions. G/L represents the gas-liquid ratio. P_{trap} represents the trapping pressure of the oil inclusions. P_{H-Charge} represents the hydrostatic pressure during the crude oil charge. P_{E-Charge} represents the excess pressure between the hydrostatic pressure and formation pressure during the crude oil charge.

833 **Table 6. Excess pressure differences between the Chang 7 source rocks and the Chang 6 reservoir beds during the crude oil charge in the**
834 **southwest Ordos Basin**

Well	Depth (m)	Episode	P _{H-charge-Ch7} (MPa)	P _{F-charge-Ch7} (MPa)	P _{E-Charge-Ch7} (MPa)	P _{E-Max-Ch7} (MPa)	P _{E-Charge-Ch6} (MPa)	P _{E-Charge} differences (MPa)	QGF	QGF-E
L89	2262.20	1 st	17.5	22.1	4.6	10.5	4.0	0.6	9.7	368.04
X79	1927.15	1 st	14.1	18.0	3.9	9.0	-2.9	6.8	10.36	520.74
L89	2237.90	2 nd	21.0	27.6	6.6	10.5	6.0	0.6	11.3	265.12
L89	2262.20	2 nd	22.7	30.0	7.3	10.5	3.1	4.2	9.7	368.04
N33	1621.24	2 nd	15.2	22.9	7.7	8.5	7.3	0.4	10.0	345.46
X79	1927.30	2 nd	18.7	27.1	8.4	9.0	4.3	4.1	19.1	621.15
L89	2262.50	3 rd	24.9	35.2	10.3	10.5	-0.4	10.7	9.1	304.79
X79	1927.30	3 rd	21.8	30.7	8.9	28.2	-1.9	10.8	19.1	621.15

Note: P_{H-Charge-Ch7} represents the hydrostatic pressure of the Chang 7 source rocks during the crude oil charge. P_{F-Charge-Ch7} represents the formation pressure of the Chang 7 source rocks during the crude oil charge. P_{E-Charge-Ch7} represents the excess pressure of the Chang 7 source rocks between the hydrostatic pressure and formation pressure during the crude oil charge. P_{E-Max-Ch7} represents the excess pressure of the Chang 7 source rocks between the hydrostatic pressure and formation pressure at the maximum burial depth. P_{E-Charge-Ch6} represents the excess pressure of the Chang 6 reservoir beds between the hydrostatic pressure and formation pressure during the crude oil charge. P_{E-Charge} differences represent the pressure differences between P_{E-Charge-Ch7} and P_{E-Charge-Ch6} during the crude oil charge.

Figure captions

Fig. 1 Location of the Ordos Basin in China (a). Tectonic units and tight oil reservoirs in the Ordos Basin (b) (Modified after **Xu et al. 2017a**). Geographic and geological information of the study area (c).

Fig. 2 Comprehensive stratigraphic column of the Triassic Chang 7-Chang 4+5 in the Ordos Basin (Modified after **Xu et al. 2017a**).

Fig. 3 Paragenetic sequence of the primary diagenetic features observed in the Chang 6 tight sandstones in the Ordos Basin (modified after Zheng et al. 2007; Dou et al. 2009; Zhao et al. 2009).

Fig. 4 P-T plot showing the determination of trapped temperature and pressure of an oil inclusion using isochore equations for coeval oil and aqueous inclusions (Modified after **Aplin et al. 2000**).

Fig. 5 Comparison charts of single well measured pressure and calculated pressure by the interval transit time and distribution characteristics of the fluid pressure (Well X71).

Fig. 6 Microscopic characters of the fluid inclusions that are trapped in the minerals of the Chang 6 reservoir beds in the southwest Ordos Basin. (a1) Aqueous inclusions and oil inclusions distributed in fractures that cut across the quartz grain, trails along the fractures, Well L89, 2237.90 m, polarized light. (a2) Oil inclusions distributed in fractures that cut across the quartz grain with blue-green fluorescence, trails along the fractures, Well L89, 2237.90 m,

856 **fluorescent light. (b1) Aqueous inclusions and oil inclusions distributed in**
857 **fractures that cut across the quartz grain, trails along the fractures, Well Z76,**
858 **2000.35 m, polarized light. (b2) Oil inclusions distributed in fractures that cut**
859 **across the quartz grain with green fluorescence, trails along the fractures, Well**
860 **Z76, 2000.35 m, fluorescent light. (c1) Aqueous inclusions and oil inclusions**
861 **distributed in fractures that cut across the quartz grain, trails along the fractures,**
862 **Well L89, 2262.20 m, polarized light. (c2) Oil inclusions distributed in fractures**
863 **that cut across the quartz grain with yellow-green fluorescence, trails along the**
864 **fractures, Well L89, 2262.20 m, fluorescent light. (d1) Aqueous inclusions and oil**
865 **inclusions distributed in fractures that occur within the quartz grain, trails along**
866 **the fractures, Well L89, 2262.20 m, polarized light. (d2) Oil inclusions distributed**
867 **in fractures that occur within the quartz grain with blue-green fluorescence,**
868 **trails along the fractures, Well L89, 2262.20 m, fluorescent light. (e1) Aqueous**
869 **inclusions and oil inclusions distributed in fractures that occur within the quartz**
870 **grain, bead clusters, Well C120, 1928.20 m, polarized light. (e2) Oil inclusions**
871 **distributed in fractures that occur within the quartz grain with blue-green**
872 **fluorescence, bead clusters, Well C120, 1928.20 m, fluorescent light. (f1) Aqueous**
873 **inclusions and gas inclusions distributed in fractures that cut across the quartz**
874 **grain, bead clusters, Well C120, 1927.42 m, polarized light. (f2) Gas inclusions**
875 **distributed in fractures that cut across the quartz grain with no fluorescence,**
876 **bead clusters, Well C120, 1927.42 m, fluorescent light. (g1) Aqueous inclusions**

877 and oil inclusions distributed in the quartz overgrowth, bead clusters, Well N33,
878 1621.24 m, polarized light. (g2) Oil inclusions distributed in the quartz
879 overgrowth with yellow-green fluorescence, bead clusters, Well N33, 1621.24 m,
880 fluorescent light. (h1) Aqueous inclusions and oil inclusions distributed in the
881 calcite cements, bead clusters, Well Z76, 2000.35 m, polarized light. (h2) Oil
882 inclusions distributed in the calcite cements with blue-green fluorescence, bead
883 clusters, Well Z76, 2000.35 m, fluorescent light. (i1) Aqueous inclusions and oil
884 inclusions distributed in fractures that occur within the feldspar grain, trails
885 along the fractures, Well Z76, 2000.10 m, polarized light. (i2) Oil inclusions
886 distributed in fractures that occur within the feldspar grain with blue-green
887 fluorescence, trails along the fractures, Well Z76, 2000.10 m, fluorescent light.

888 **Fig. 7 Micro-thermometry of the aqueous inclusions and oil inclusions in the**
889 **Chang 6 reservoir beds in the southwest Ordos Basin (°C). (a) Aqueous**
890 **inclusions distributed in fractures that cut across the quartz grain, Well X79,**
891 **1927.30 m. (b) Oil inclusions distributed in fractures that cut across the quartz**
892 **grain, Well L89, 2237.90 m. (c) Aqueous inclusions and oil inclusions distributed**
893 **in fractures that cut across the quartz grain, Well C120, 1928.20 m. (d) Oil**
894 **inclusions distributed in fractures that occur within the quartz grain, Well N33,**
895 **1621.55 m. (e) Aqueous inclusions distributed in fractures that occur within the**
896 **quartz grain, Well Z76, 2000.10 m. (f) Aqueous inclusions and oil inclusions**
897 **distributed in fractures that occur within the quartz grain, Well C120, 1927.42 m.**

898 (g) Oil inclusions distributed in the calcite cements, Well Z76, 2000.35 m. (h) Oil
899 inclusions distributed in fractures that occur within the feldspar grain, Well L89,
900 2262.50 m. (i) Oil inclusions distributed in the quartz overgrowth, Well C120,
901 1928.24 m. The red arrows represent the oil inclusions and the blue arrows
902 represent the aqueous inclusions.

903 Fig. 8 Phase diagrams of the trapping pressure of the fluid inclusions in the
904 Chang 6 reservoir beds in the southwest Ordos Basin. 'Aqueous homogenization
905 temperature' represents 'Trapping temperature of oil inclusion'. (a)–(b) represent
906 the trapping pressure of the oil inclusion with the 1st peak of homogenization
907 temperatures. (c)–(f) represent the trapping pressure of the oil inclusion with the
908 2nd peak of homogenization temperatures. (g)–(h) represent the trapping
909 pressure of the oil inclusion with the 3rd peak of homogenization temperatures.

910 Fig. 9 Peak wavelength distributions of the fluorescence micro-spectrometry of
911 the oil inclusions in the Chang 6 reservoir beds in the southwest Ordos Basin.

912 Fig. 10 Correlogram between the $Q_{650/500}$ and $\lambda_{\max}$ of the oil inclusions in the
913 Chang 6 reservoir beds in the south west Ordos Basin.

914 Fig. 11 Correlogram between the Q_{F535} and $\lambda_{\max}$ of the oil inclusions in the Chang
915 6 reservoir beds in the southwest Ordos Basin.

916 Fig. 12 Histogram of the homogenization temperatures of the aqueous inclusions
917 in the Chang 6 reservoir beds in the southwest Ordos Basin.

918 Fig. 13 Hydrocarbon charging timing of the tight oil reservoirs in the Chang 6

919 **reservoir beds in the southwest Ordos Basin (Modified after [Xu et al. 2017a](#)).**

920 **Fig. 14 Planar distribution map of the oil shale excess pressure in Chang 7**

921 **during the Early Cretaceous in the southwest Ordos Basin.**

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Fig. 1 Location of the Ordos Basin in China (a). Tectonic units and tight oil reservoirs in the Ordos Basin (b) (Modified after Xu et al. (2017a)). Geographic and geological information of the study area (c).

224x211mm (300 x 300 DPI)

Fig. 2 Comprehensive stratigraphic column of the Triassic Chang 7-Chang 4+5 in the Ordos Basin (Modified after Xu et al. (2017a))

60x42mm (300 x 300 DPI)

Fig. 3 Paragenetic sequence of the primary diagenetic features observed in the Chang 6 tight sandstones in the Ordos Basin (modified after Zheng et al., 2007; Dou et al., 2009; Zhao et al., 2009)

69x55mm (300 x 300 DPI)

Fig. 4 P-T plot showing the determination of trapped temperature and pressure of an oil inclusion using isochore equations for coeval oil and aqueous inclusions (Modified after Aplin et al. (2000))

59x40mm (300 x 300 DPI)

Fig. 5 Comparison charts of single well measured pressure and calculated pressure by the interval transit time and distribution characteristics of the fluid pressure (Well X71)

80x75mm (300 x 300 DPI)

Fig. 6 Microscopic characters of the fluid inclusions that are trapped in the minerals of the Chang 6 reservoir beds in the southwest Ordos Basin

237x308mm (300 x 300 DPI)

Fig. 7 Micro-thermometry of the aqueous inclusions and oil inclusions in the Chang 6 reservoir beds in the southwest Ordos Basin (°C)

236x308mm (300 x 300 DPI)

Fig. 8 Phase diagrams of the trapping pressure of the fluid inclusions in the Chang 6 reservoir beds in the southwest Ordos Basin

181x138mm (300 x 300 DPI)

Fig. 9 Peak wavelength distributions of the fluorescence micro-spectrometry of the oil inclusions in the Chang 6 reservoir beds in the southwest Ordos Basin

59x14mm (300 x 300 DPI)

Fig. 10 Correlogram between the $Q_{650/500}$ and λ_{max} of the oil inclusions in the Chang 6 reservoir beds in the south west Ordos Basin

220x80mm (150 x 150 DPI)

218x76mm (150 x 150 DPI)

Fig. 12 Histogram of the homogenization temperatures of the aqueous inclusions in the Chang 6 reservoir beds in the southwest Ordos Basin

184x85mm (150 x 150 DPI)

Fig. 13 Hydrocarbon charging timing of the tight oil reservoirs in the Chang 6 reservoir beds in the southwest Ordos Basin (Modified after Xu et al. (2017a))

88x91mm (300 x 300 DPI)

Fig. 14 Planar distribution map of the oil shale excess pressure in Chang 7 during the Early Cretaceous in the southwest Ordos Basin

86x87mm (300 x 300 DPI)