Organic petrology of peak oil maturity Triassic Yanchang Formation lacustrine mudrocks, Ordos Basin, China

Paul C. Hackley¹, Lixia Zhang², and Tongwei Zhang³

Abstract

An organic petrology evaluation and a determination of solid bitumen reflectance \( \text{BR}_0 \) were completed for organic-rich Triassic Yanchang Formation mudrocks \( (n = 15) \) from the Ordos Basin, north-central China, as part of a larger investigation of “shale gas” resources. These data were integrated with information from Rock-Eval programmed pyrolysis to show that the samples are in the peak oil window of thermal maturity and that organic matter is dominated by solid bitumen with minor amounts of type III kerogen (vitrinite and inertinite) from vascular land plants. Describing a “kerogen type” for these rocks based strictly on parameters determined from programmed pyrolysis is misleading because the original organic matter has converted to hydrocarbons (present as solid bitumen), a large proportion of which may have been expelled into adjacent reservoir facies. However, based on the comparison with immature-early mature lacustrine mudrock (Garden Gulch Member of Green River Formation) and marine shale (Boquillas Formation), we suggest that the original organic matter in the organic-rich samples examined for our study may have been type I/II kerogen with hydrogen index values of >700 mg HC/g TOC.

Introduction

Unconventional gas resources in lacustrine shale and mudrock in the continental basins of northern China have received significant attention in the past few years following successful development of unconventional marine “shales” in North America (Lin et al., 2013). In China, it is estimated that more than 85% of hydrocarbon reserves are sourced from lacustrine settings, with notable differences in petroleum system characteristics compared with marine systems, e.g., thick, areally limited source rock presence with poor connectivity to higher porosity reservoir facies, and generation of highly viscous waxy hydrocarbons (Katz and Lin, 2014). Lacustrine mudrocks in China are also characterized by higher clay concentrations and lower thermal maturity than most North American shale gas systems (Tang et al., 2013a, 2013b). Despite widespread international interest and government promotion of shale petroleum systems, development has thus far been limited with only 22 wells completed in shale by 2011 (Guo and Zhao, 2012), compared with >10,000 wells spudded in 2011 in North American unconventional plays (IHS Energy Group, 2015).

The Ordos Basin in north-central China (Figure 1) is a flexural sag basin, developed on cratonic rocks when far-field compressive stresses deformed the north and south margins of the China tectonic block (Ritts et al., 2004; Zhao et al., 2006). The Upper Triassic Yanchang Formation is a lacustrine unit consisting of repetitive transgressive-regressive sequences of fluvial, shoreface, and deepwater sediments deposited in fluvial-lacustrine settings (Zhao et al., 2015). It has been divided into 10 members, called Chang 1–10, from oldest to youngest, respectively. The Chang 7 Member, comprised of interbedded dark shale, sandy shale, and mudstone, is the primary hydrocarbon source rock interval in the Yanchang Formation (Wu et al., 2015; Zhang et al., 2015a; Yang et al., 2016). Deposition of Chang 7 represents the period of greatest lake expansion (approximately 85,000 km²; Zhao et al., 2010). Previous work suggested deepwater deposition of algal-rich organic matter occurring in stratified low-salinity waters under reducing conditions (Yang and Zhang, 2005; Yuan et al., 2015). Analytical results from rock-focused studies and burial history modeling show that conditions of oil-window thermal maturity were reached in the Early
Cretaceous (Zhao et al., 1996; Ren et al., 2007) and hydrocarbon expulsion and primary migration occurred due to volume expansion associated with kerogen cracking (Zhang et al., 2006). Reservoir facies in adjacent delta-front and pro-delta Chang 6 and Chang 8 tight sandstones were charged by short-distance (hundreds of meters) hydrocarbon migration from Chang 7 mudrocks (Yao et al., 2013).

Previous studies of organic matter facies in oil-mature Yanchang Chang 7 mudrocks reported types I and II kerogen (Hanson et al., 2007; Lin et al., 2013; Tang et al., 2013a, 2013b; Wang et al., 2013; Guo et al., 2014). Kerogen typing has been primarily based on classification from programmed pyrolysis, although summarized results from organic petrography have been reported (Hanson et al., 2007; Wang et al., 2013; Guo et al., 2014). Several studies reported vitrinite reflectance ($R_o$) results (Lin et al., 2013; Tang et al., 2013a, 2013b), but they did not include descriptions of organic petrographic character. Additional studies on kerogen from Yanchang Formation strata (Lin et al., 2013; Yao et al., 2013) are written in Chinese and are largely inaccessible to western researchers. Here, we observe that kerogen typing from programmed pyrolysis reflects the present-day organic composition of the sample, which, as we will show below, is not kerogen. Instead, in the oil-window thermal maturity samples examined herein, the organic matter consists almost entirely of solid bitumen similar to descriptions of the marine shale petroleum systems developed in North America (Hackley and Cardott, 2016). However, previous workers described organic matter in a similar oil-window mature ($R_o$ 0.9%–1.1%) Yanchang Formation as “kerogen,” present in a “kerogen network” (Yao et al., 2013). The term “solid bitumen” is used by organic petrographers to describe organic matter representing secondary products of hydrocarbon generation from kerogen (Cardott et al., 2015). This term is not in exact correspondence to the geochemists definition of bitumen, which is the organic material removed from rock samples by typical organic solvents, such as dichloromethane (DCM) (Durand, 1980; Vandebroucke and Largeau, 2007). For thermally mature systems, such as the Yanchang mudrocks, the two terms describe in part the same material because what is extracted by organic solvents primarily is extracted from solid bitumen (because solid bitumen is the only labile organic matter present).

As part of a larger study of the petroleum geology of the Yanchang Formation, we present in this contribution the organic petrology and solid bitumen reflectance values ($R_o$) of peak oil mature Chang 7 and other Yanchang mudrocks and integrate these data with the results from Rock-Eval programmed pyrolysis. Furthermore, we compare our data with previous studies of organic facies and thermal maturity in the Yanchang Chang 7, discuss implications with respect to prospectivity for unconventional oil and gas resources, and make comparison with North American marine shales and other prospective lacustrine mudrocks.

Materials and methods

Samples ($n = 15$) were received at the U.S. Geological Survey (USGS) as small core chips of 3–5 g mass identified by formation/member, well name, and depth (Table 1). Samples were crushed with a mortar and pestle to approximately 1 mm top size and prepared in 2.54 mm diameter circular thermoplastic mounts via ASTM D2797 (ASTM, 2015a) for organic petrographic analysis. The mounts were imaged under oil immersion on a Zeiss AxioImager in white and blue incident light. Solid bitumen reflectance analyses ($n = 14$) were conducted according to ASTM D7708 (ASTM, 2015b). A Leica DM4000 microscope equipped with LED illumination and monochrome camera detection was used for reflectance analysis with the computer program DISKUS-FOSSIL by Hilgers Technisches Buero using a Klein and Becker YAG calibration standard ($0.908\% R_o$). Two samples (YCDT 1119 407 m and YCYV 1113 1745.32 m) were imaged via scanning electron microscopy (SEM) at USGS in a secondary and back-scattered electron mode, generally at 3–5 kV, 5–6 mm w.d., and magnifica-

Figure 1. (a) Location of the Ordos Basin within northern China. (b) Map showing the major structural elements of the Ordos Basin according to Yang et al. (2015). The black box shows study area. The blue dot is the general location of well YCYV 1112, and the red dot is the general location of well YCV1133. The other wells are distributed within the area of the rectangle shown in (b).
Table 1. Sample identification, lithology, Rock-Eval, and reflectance data for samples from members of the Yanchang Formation. Abbreviations: FM, formation; TOC, total organic carbon; HC, hydrocarbon; $R_0$ (ca), calculated vitrinite reflectance ($0.018 \times T_{\text{max}} - 7.16$; Jarvie et al., 2001); BRo (m), measured bitumen reflectance; HI, hydrogen index (mg HC/g TOC); OI, oxygen index (mg CO$_2$/g TOC); PI, production index; n.d., no data.

| Member | Sample ID | Depth (m) | TOC (wt%) | S1 (mg HC/g) | S2 (mg HC/g) | S3 (mg CO$_2$/g) | $T_{\text{max}}$ (°C) | $R_0$ (ca) (%) | BRo (m) (%) | HI | OI | S2/S3 | S1*$100$/TOC | PI $[S1/(S1+S2)]$ |
|--------|-----------|-----------|-----------|-------------|-------------|----------------|-------------------|----------------|-------------|----|----|-------|----------------|-------------------|
| **Unextracted** | | | | | | | | | | | | | | |
| Chang 7 | YCDT 1119 | 407.00 | 14.70 | 3.54 | 43.84 | 0.84 | 442 | 0.80 | 0.79 | 298 | 6 | 52.19 | 24.08 | 0.07 |
| Chang 7 | YCYV 1118 | 1141.0 | 5.19 | 7.44 | 10.47 | 0.43 | 444 | 0.83 | 0.84 | 202 | 3 | 24.35 | 143.35 | 0.2 |
| Chang 7 | YCYV 1115 | 1389.0 | 4.33 | 4.90 | 10.79 | 0.66 | 442 | 0.80 | 0.67 | 249 | 15 | 113.16 | 85.84 | 0.39 |
| Chang 7 | YCYV 1112 | 1567.0 | 4.52 | 3.88 | 6.08 | 0.66 | 457 | 1.07 | 0.95 | 135 | 15 | 92.1 | 85.84 | 0.39 |
| Chang 7 | YCYV 1123 | 1752.8 | 3.94 | 2.67 | 5.83 | 0.52 | 458 | 1.08 | n.d. | 148 | 13 | 112.1 | 67.77 | 0.31 |
| Chang 7 | YCYWV 1112 | 2297.1 | 3.71 | 1.92 | 7.60 | 0.58 | 459 | 1.10 | 0.96 | 205 | 16 | 13.10 | 51.75 | 0.2 |
| Chang 7 | YCYV 1113 | 1745.32 | 294 | 5 | 60.24 | 0.03 |
| **After Soxhlet extraction** | | | | | | | | | | | | | | |
| Chang 7 | YCDT 1119 | 407.00 | 8.62 | 0.78 | 25.30 | 0.42 | 439 | 0.74 | — | 294 | 5 | 60.24 | 0.03 |
| Chang 7 | YCYV 1118 | 1141.0 | 4.25 | 0.20 | 5.67 | 0.30 | 450 | 0.94 | — | 133 | 7 | 18.90 | 4.71 | 0.03 |
| Chang 7 | YCYV 1115 | 1389.0 | 3.81 | 0.16 | 6.50 | 0.36 | 444 | 0.83 | — | 171 | 9 | 18.06 | 4.20 | 0.02 |
| Chang 7 | YCYV 1112 | 1567.0 | 4.13 | 0.17 | 3.92 | 0.34 | 457 | 1.07 | — | 95 | 8 | 11.53 | 4.12 | 0.04 |
| Chang 9 | YCYV 1123 | 1752.80 | 3.47 | 0.18 | 4.42 | 0.21 | 458 | 1.08 | — | 127 | 6 | 21.05 | 5.19 | 0.04 |
| Chang 7 | YCYWV 1112 | 2297.05 | 2.97 | 0.15 | 4.65 | 0.27 | 458 | 1.08 | — | 157 | 9 | 17.22 | 5.06 | 0.03 |
| Chang 7 | YCYV 1113 | 1745.32 | 10.10 | 0.18 | 39.53 | 0.59 | 443 | 0.81 | — | 391 | 6 | 67.00 | 1.78 | 0.00 |
| **Unextracted** | | | | | | | | | | | | | | |
| Chang 7 | YCYV 1112 | 1070 | 5.28 | 13.14 | 0.60 | 457 | 0.96 | 0.95 | 260 | 12 | 21.90 | 120.36 | 0.32 |
| Chang 7 | YCYV 1129 | 1382.75 | 5.06 | 6.00 | 13.14 | 0.60 | 457 | 0.96 | 0.95 | 260 | 12 | 21.90 | 120.36 | 0.32 |
| Chang 7 | YCYV 1125 | 1307.75 | 3.79 | 7.56 | 8.53 | 0.60 | 434 | 0.65 | 0.93 | 225 | 16 | 14.22 | 199.47 | 0.47 |
| Chang 7 | YCYV 1125 | 1451.02 | 6.62 | 5.71 | 11.47 | 0.69 | 455 | 1.03 | 0.89 | 173 | 10 | 16.62 | 86.25 | 0.33 |
| Chang 7 | YCYV 1121 | 1504.98 | 7.08 | 4.24 | 12.77 | 0.71 | 455 | 1.03 | 0.94 | 180 | 10 | 17.99 | 59.89 | 0.25 |
| Chang 7 | YCYV 1133 | 1302.84 | 4.93 | 5.82 | 11.16 | 1.02 | 440 | 0.76 | 0.73 | 226 | 21 | 10.94 | 118.05 | 0.34 |
| Chang 7 | YCYV 1133 | 1336.03 | 8.07 | 7.59 | 21.20 | 0.91 | 451 | 0.96 | 0.81 | 263 | 11 | 23.30 | 94.05 | 0.26 |
| Chang 7 | YCYV 1133 | 1346.87 | 3.92 | 3.51 | 7.88 | 0.95 | 451 | 0.96 | 0.84 | 201 | 24 | 8.29 | 89.54 | 0.31 |
tions of 100–15,000x, to observe organic matter textures. Rock-Eval pyrolysis and total organic carbon (TOC) content were determined in a commercial laboratory (Geo-mark) by typical methods (Espitalié et al., 1977; Peters, 1986). A select group of samples (Table 1) was extracted via Soxhlet extraction with DCM according to typical procedures at the Bureau of Economic Geology (BEG) prior to Rock-Eval pyrolysis.

Results

Rock-Eval pyrolysis and TOC

The TOC concentrations are in the range of 3.7–14.7 wt% (average 6.4 wt%) for unextracted Yanchang mudrocks with the highest TOC content occurring in Chang 7 (Table 1). These results are similar to prior reports for oil-window mature Yanchang samples (Lin et al., 2013). Rock-Eval results show average S1 and S2 concentrations of 4.9 and 16.3 mg HC/g, respectively. The average hydrogen index (HI) value is 233 mg HC/g TOC, and the average S1/TOC is 89.8 mg HC/g TOC. The T_max values are in the range of 434°C–459°C and PI values average 0.28. Solvent-extracted samples show an average decrease of 21% for TOC, 93% for S1, 35% for S2, and 21% for HI. Average T_max is incrementally lower by 0.1% in extracted samples, whereas average PI is decreased by 80%.

Solid bitumen reflectance

Measured solid bitumen reflectance BRo values are in the range of 0.67%–0.95% (n = 14; Table 1), within the range of 0.52%–1.52% R_o reported by Wang et al. (2013). The BRo histograms are illustrated in Figures 2 and 3. We elected to measure and report BRo as opposed to vitrinite reflectance because vitrinite is sparse, absent, or difficult to identify with confidence in the samples examined herein. The BRo value is interpreted to be a good proxy for vitrinite reflectance in the peak oil window based on previous studies that compared the two thermal maturity parameters (Jacob, 1989; Landis and Castaño, 1994). Furthermore, we elected not to apply a conversion to BRo to obtain vitrinite reflectance equivalent values (Petersen et al., 2013) because interlaboratory studies have suggested that these empirical conversion schemes should be treated with caution (Hackley et al., 2015), and perhaps they should be used only in the strata where derived. Measured BRo values range from 0.15% less than to 0.28% greater in reflectance than R_o values calculated from T_max (using the Jarvie et al. [2001] equation: calculated R_o = 0.018 * T_max − 7.16); 11 of 14 measured BRo values are lower than the calculated R_o values, averaging 0.1% lower. The BRo values show poor correlation to present-day burial depth (r^2 = 0.19), as do the calculated R_o values (r^2 = 0.31).

Organic facies

Organic matter in the Chang 7 samples is constituted almost exclusively of solid bitumen, visually estimated as approximately 95 vol% of the total organic matter content. Solid bitumen is present in a continuum of morphologies, ranging among: (1) groundmass or “network” (Figure 4a), (2) void and pore filling (Figure 4b), (3) vein and fracture filling (Figure 4c), (4) interlayered on bedding planes (Figure 4d–4f), (5) interleaved with clays (Figure 5a and 5b), and (6) finely dispersed in mineral interstices (Figure 5c). Solid bitumen was generated and/or emplaced coevally with authigenic carbonate precipitation as is evident by frequent contact on euhedral
crystal terminations (Figure 5d) or adjacent to growth-zoned crystals (Figure 5e and 5f). Solid bitumen is present with orange-reddish fluorescence grading to nonfluorescent (Figure 6a and 6b). The BRo measurements were determined on nonfluorescent solid bitumen, which is the dominant occurrence. Solid bitumen was present in all samples; however, in the unextracted Chang 9 sample YCYV 1123 1752.8 m (TOC 3.94 wt%), the solid bitumen occurred in mineral interstices generally <5 μm in size (Figure 5c), preventing measurement of BRo.

Dominance of solid bitumen is corroborated by pyrolysis results of pre- and post-Soxhlet extracted samples, which show reductions of approximately 90% in S1 and PI. Reductions in S2 and TOC are less extreme, but they nonetheless suggest that organic carbon is dominated by an extractable material, i.e., solid bitumen. Figure 7a is a conceptual illustration of the volume percentage of solid bitumen and kerogen present in Yanchang samples at the oil-window thermal maturity, whereas Figure 7b is the geochemical corroboration, showing an average reduction in S1 due to Soxhlet extraction with DCM.

Minor type III/IV kerogen is present as small dispersed fragments of vitrinite and inertinite, visually estimated as <1 vol% of the total organic matter present. Vitrinite and inertinite fragments are lath-shaped to equant and typically 5–20 μm in diameter (Figures 5a and 6c). Rare relict cellular structure from the original plant precursor is present; char fragments also were rare (Figure 6d). Liptinite was observed as relict amorphous kerogen suggestive of “telalginite” in only one sample (YCDT 1119 407 m), in which it occurs as a rare lamellar lens up to 100 μm in length and generally <10 μm in width (Figure 6e and 6f). These telalginites have no contrast to the mineral matrix in white light (Figure 6e), but they are obvious in fluorescence illumination (Figure 6f). Some are degraded to a wispy porous groundmass evident only by its weak fluorescence. The presence of rare waxy terrestrial liptinite was suggested by one observation of leaf exine (?) cutinite, but this identification is tentative.

Discussion
Thermal maturity and hydrocarbon exploration
The measured BRo values of 0.67%–0.95% suggest conditions of early to peak oil-thermal maturity (Dembicki, 2009), if BRo is considered as a good proxy for vitrinite reflectance at this thermal maturity. Work compiled by Robert (1988) indicates that BRo is lower than Ro until approximately 1.0% Ro (see also Jacob, 1989; Mählmann and Frey, 2012), after which BRo becomes approximately Ro. Work by Landis and Castaño (1994) suggests that the value of BRo is always less than that of Ro. Considering that all prior studies have found the value of BRo to
be lower than that of \( R_0 \) at thermal maturities of \( R_0 < 1.0\% \), we observe that measured \( BR_0 \) values reported herein probably slightly underestimate thermal maturity. Corroborating this observation, calculated \( R_0 \) and measured \( BR_0 \) values indicate that Yanchang samples examined in this study are thermally mature for oil generation, with most samples showing peak oil-window thermal maturity (0.8%–1.0% \( BR_0 \)).

Hydrocarbon prospectivity from Chang 7 mudrocks is usually characterized as shale gas exploration (Tang et al., 2013b; Wang et al., 2013; Guo et al., 2014). As stated above, the thermal maturity of the Yanchang Formation samples studied herein is in the peak oil window and is appropriate for production of volatile oil to early wet gas and condensate hydrocarbon products. Exploration for shale gas from Chang 7 mudrocks at similar peak oil-window thermal maturity is perhaps more a function of governmental incentives and directives to promote shale gas (Guo and Zhao, 2012), according to the state “Twelfth five-year” plan for energy development. Furthermore, generation of long-chain waxy oils from lacustrine kerogen (Katz, 1990), and poor permeability in Chang 7 mudrocks (Liu et al., 2015; other studies in this volume) may limit oil expulsion from source beds of large thickness, although Zhang et al. (2006) predicts an average hydrocarbon expulsion efficiency of 72% from the Chang 7 Member.

**Kerogen typing**

Solid bitumen is a secondary product of hydrocarbon generation from kerogen in the peak oil mature Yanchang Formation samples examined herein. Therefore, reporting a “kerogen type” from pyrolysis is inappropriate and misleading for these samples because the organic material present is not kerogen. Type II kerogen, by definition, contains cyclic aliphatic and aromatic hydrocarbons and associated organic sulfur and yields moderate-length \( n \)-alkanes (< C\(_{25}\)) upon extraction, whereas type I kerogen is highly aliphatic, yielding long-chain \( n \)-alkanes (up to > C\(_{40}\)) in oils and rock extracts, indicating accumulation and/or selective preservation of lipid-rich material (summarized in Vandenbroucke and Largeau, 2007). The presence of a type I versus type II kerogen may imply specific depositional characteristics: i.e., for type I, photic-zone accumulation of lipid-rich bacterial biomass, such as in a microbial mat; and for type II, accumulation and preservation of planktonic algal kerogen in anoxic marine sulfate-rich waters. However, in the organic-rich Yanchang mudrock samples examined herein, the HI index from Rock-Eval pyrolysis, which is a proxy for H/C information, specifies the composition of the solid bitumen present, not the composition of the original kerogen present in the samples prior to catagenesis. Nevertheless, considering the poor permeability reported for Yanchang mudrocks (Liu et al., 2015; other studies in this volume), we presume that solid bitumen was generated in situ and has experienced little migration fractionation or oxidation via hydrothermal fluids. However, we have no means to quantify potential compositional evolution due to hydrocarbon devolatilization or other processes, e.g., gas flushing. The H/C compositions determined via pyrolysis may reflect the origi-

---

**Figure 4.** (a) Solid bitumen occurring as groundmass in sample YCYYV 1113 1745.32 m. Solid bitumen occurs as a thin (0–10 µm) discontinuous lens running diagonal from upper right to lower left and grading into the rock-mineral matrix. (b) Pore-filling solid bitumen in sample YCYYV 1113 1745.32 m. (c) Fracture-filling solid bitumen in sample YCYYV 1113 1745.32 m. Mineral matter adheres to edges of bitumen fragment. (d) Bedding-parallel solid bitumen layering in sample YCDT 1119 407 m. (e) Bedding-parallel solid bitumen layering in sample YCDT 1119 407 m. (f) Same field as (e) illuminated with blue light to illustrate fluorescence of kerogen (telalginite) and solid bitumen. Panels (a-c and e) in white light under oil immersion and (d) from SEM (conditions labeled at the base of the image, mechanically polished surface).
nal kerogen composition, in part, less the most volatile components that have been expelled.

Some workers have used pyrolysis data to back-calculate original TOC and HI values (e.g., Jarvie et al., 2007). However, this approach relies on visual kerogen data from immature samples, which were not available from the Yanchang Chang 7 Member for this study. Based on the geologic data that constrain Chang 7 deposition to deepwater facies (e.g., Zhao et al., 2015; other studies in this volume), we surmise that original sedimentary kerogen was constituted by planktonic algae and derivative products (e.g., fecal pellets) that were incorporated into sediments from the overlying water column as a “lacustrine snow,” in much the same mechanism as the well-described marine snow of Macquaker et al. (2010). Therefore, original HI values may not have been as high as a true type I lipid-rich microbial mat facies from a photic-zone system, such as the Eocene Green River Mahogany Zone oil shale (e.g., HI > 800; Hackley et al., 2015). Instead, original kerogen may have contained moderate-length n-alkanes (< C_{25}), more similar to type I/II planktonic kerogens, such as in the Upper Cretaceous Boquillas Formation (early mature Eagle Ford equivalent) of West Texas (HI > 700; Hackley et al., 2015). The present low HI values of our Yanchang Chang 7 samples in the peak oil window reflect expulsion of generated hydrocarbons, up to as high as 90% according to Zhang et al. (2006). However, oil expulsion efficiencies were found to be highly variable in the Zhang et al. (2006) study. Further, original organic matter type and abundance may have been somewhat heterogeneously distributed during Chang 7 deposition (Zhang et al., 2015b). Therefore, the large variation of residual HI values (135–486 mg HC/g TOC; Table 1) within a narrow maturity range as seen in this study may suggest either variable expulsion efficiency or variations in the original organic matter type and abundance.

**Comparison with previous petrographic studies**

Hanson et al. (2007) report geochemical analysis of a biodegraded low-maturity solid bitumen vein crosscutting Jurassic strata in the Ordos Basin, suggesting it was derived from pre-Jurassic source rocks, possibly the Yanchang, with terrestrial organic matter input. Their report includes petrographic analyses of Yanchang and other source rock strata of the Ordos Basin; however, solid bitumen was not included in the identified organic components. We note that they reported “amorphous kerogen” present in Yanchang Formation rocks at maturity of 1.15% R_o; other petrographic analyses in their report indicated “herbaceous plant” debris at lower maturity (0.60% R_o). We assume by herbaceous plant debris, the authors meant “nonwoody” material, i.e., fluorescent lipptinite macerals including sporiinite (pollen and spores), cutinit (leaf exine), and resinite (resins), all of which may persist as distinct and identifiable entities into the early- to mid-oil window (Hackley et al., 2009); however, fluorescing amorphous kerogen would have been converted to hydrocarbons at the early wet gas thermal maturity conditions indicated by 1.15% R_o (Taylor et al., 1998). Lacustrine palynofacies were not identified in any

**Figure 5.** (a) Solid bitumen interleaved with clays in sample YCYV 1133 2858 1346.9 m. The inset shows a high-magnification (1000×) view, in which solid bitumen is the whitish-gray material. Elongate inertinite lath is also present in the field. (b) Solid bitumen interleaved with clays in sample YCDT 1119 407 m (SEM image; conditions labeled at the base of the image, mechanically polished surface). (c) Finely disseminated solid bitumen in sample YCYV 1123 1752.8 m. The inset shows solid bitumen (whitish-gray) in the mineral interstices adjacent to authigenic carbonate. (d) Solid bitumen embayed against euhedral carbonate in sample YCYV 1133 2858 1346.87 m. (e) Solid bitumen embayed against zoned carbonate in sample YCYV 1133 2858 1346.87 m. The inset shows a 1000× view of solid bitumen (whitish-gray) against carbonate overgrowth. (f) Same field as (e) illuminated with blue light to show fluorescence of clay matrix. Panels (a and c-e) in white light under oil immersion.
of the Yanchang petrographic analyses reported in Hanson et al. (2007).

The study by Wang et al. (2013) on samples of oil-window thermal maturity (0.52%–1.25% $R_o$) reported “sapropelinite” (>50 vol%), vitrinite (approximately 20 vol.%), and inertinite (approximately 15 vol%), and it considered that the organic assemblage was dominated by type II kerogen with a small component of type I. We observe that sapropelinite (as defined by Mukhopadhyay et al. [1985] and used by Mukhopadhyay [1989]) refers to biodegraded algal kerogen. The term is synonymous with the amorphous kerogen identified by Hanson et al. (2007), and its identification is permitted only in rocks of low thermal maturity (<0.6% $R_o$). Therefore, identification of sapropelinite in oil-window mature Yanchang samples by Wang et al. (2013) is a mistake, unless the identification applies only to samples <0.6% $R_o$. We speculate that the sapropelinite observed by these workers may in fact be solid bitumen degraded by kerogen concentration in the laboratory. This observation particularly applies to the higher maturity samples of their study.

Guo et al. (2014) examine kerogen concentrates of Yanchang Formation samples via optical microscopy, observing the dominant presence of “amorphinite” with subordinate vitrinite and inertinite. Again, we note that amorphinite (defined by van Gijzel, 1982) is also synonymous with amorphous kerogen, and its presence cannot be reconciled with oil-window thermal maturity ($R_o$ 0.7%–1.2%) reported by Guo et al. (2014). Therefore, we speculate that the amorphinite is, rather, misidentified solid bitumen.

Xiong et al. (2016) characterize kerogen as types I–II via pyrolysis in thermally mature Chang 7 and 9 mudrocks from the Yanchang Formation. They perform solvent extractions and thereafter noted increased organic porosity in extracted mudrocks via gas-sorption experiments. The organic porosity was contained in “residual bitumen.” No organic petrography was performed in their study; we assume by residual bitumen, they meant the solid bitumens noted in this study. As noted above, a significant amount of solid bitumen is extractable by DCM, reducing the TOC by approximately 20%. Extraction of the more aliphatic and aromatic portions of solid bitumen by DCM or other solvents may result in increased organic porosity in the more polar-rich residue, as observed by other studies in this volume.

In summary, previous observations of organic petrography from the Yanchang Formation mudrocks are difficult to reconcile with reported thermal maturities. Earlier reports that described amorphous kerogen, sapropelinite, and amorphinite in peak oil-window thermal maturity samples appear to have been in error, and we speculate that these petrographic studies may have misidentified or overlooked solid bitumen.

**Comparisons with organic petrography of other lacustrine mudrocks**

Organic petrographic studies of immature to early oil-window Permian Luckagou Formation mudrocks from the lacustrine Santanghu and Junggar Basins of northwest China indicated amorphous kerogen and lamellar alginite dominate (oil-prone type I kerogen), with some planktonic Prasinophyte green algae and...
terrestrial type III kerogens present in low abundance (Tao et al., 2012; Xie et al., 2015; Hackley et al., 2016). With other influences considered equal, the presence of significant higher plant debris in Permian Lucaogou mudrocks relative to Yanchang strata may imply either more distal deposition for Yanchang mudrocks or a lower component of vascular vegetative debris in the delivered sediments. However, because the two sedimentary systems differ significantly, i.e., Yanchang mudrocks represent a balance-filled system dominated by extrabasinal detrital clays (other studies in this volume) and Lucaogou mudrocks in Santanghu Basin represent a sediment-starved under-filled to balance-filled chemical carbonate system dominated by intrabasinal sediment (Hackley et al., 2016), comparison of relative quantities of detrital terrestrial type III kerogens may be invalid.

Petrographic studies of immature (0.30% $R_o$, HI 870 mg HC/g TOC) Green River Parachute Creek Member (Mahogany zone) lacustrine oil shale (Hackley et al., 2015) showed that amorphous organic matter (oil-prone type I kerogen) dominates. This material is not present in Yanchang samples due to the oil-window thermal maturity. Similar to Yanchang, terrestrial organics including vitrinite and inertinite were sparse. However, the Mahogany zone is a chemical carbonate-dominated system. Previous studies have suggested open lacustrine, deepwater deposition of planktonic organic matter into permanently stratified strongly reducing anoxic bottom sediments (Cole, 1985). However, more recent workers have interpreted preservation of organic matter in benthic microbial mats that accumulated in the photic zone (Schieber, 2007) and overturned the notion that low-energy deepwater environments are required for mudstone deposition (Schieber et al., 2007). Based on these observations, we suggest that the Mahogany zone is not a proper analog for immature Yanchang mudrocks.

**Figure 7.** (a) Conceptual volume of total petrographically observable organic matter in Yanchang samples occupied by solid bitumen, type III/IV kerogen (vitrinite and inertinite), type II kerogen (telalginite; sample YCDT 1119 407m only), and material too fine grained to be resolved by optical microscopy. (b) The S1 values of pre and postextracted Yanchang samples. Error bars show one standard deviation. Modified from Hackley and Cardott (2016).

**Figure 8.** (a) Garden Gulch Member of Green River Formation showing rare vitrinite and structured inertinite (white incident light, oil immersion). (b) Same field as (a) illuminated with blue light showing the fluorescent lamellar algal material. Sample from J. Birdwell, USGS.

**Figure 9.** Pseudo van Krevelen diagram showing Yanchang samples, Lucaogou mudrocks (Hackley et al., 2016), and immature lacustrine and marine mudrock proxies (data from Hackley et al., 2015; unpublished data of J. Birdwell, USGS).
Another proxy for immature Yanchang mudrocks may be the illite-rich Garden Gulch Member of the Green River Formation, which was deposited in “offshore” lacustrine environments (e.g., Johnson, 2012; although, see Cole, 1985). The Garden Gulch Member contains a type I kerogen with HI values >800 mgHC/g TOC (Burnham and McConaghy, 2014; Birdwell and Washburn, 2015). Unpublished petrographic observations show that vitrinite and inertinite are rare in immature (0.28% R0) Garden Gulch samples (Figure 8a and 8b). The sample shown in Figure 8 contains an HI of 821 mgHC/g TOC, which may also be a reasonable proxy for the original HI in immature Yanchang Formation mudrocks. In Figure 9, we show the pseudo-Van Krevelen plot for Yanchang samples in comparison with the immature proxies we have suggested herein. However, until immature Yanchang mudrock samples with clay-rich mineralogy become available, it is difficult to infer an original HI or kerogen type with any degree of confidence.

Conclusion

We have evaluated herein the organic petrology and thermal maturity of organic-rich Yanchang mudrocks from the Ordos Basin, north-central China. “Kerogen typing” from Rock-Eval pyrolysis is misleading for Yanchang mudrocks due to peak oil-window thermal maturity conditions determined from solid bitumen reflectance and pyrolysis parameters. Most of the TOC present is comprised of solid bitumen, confirmed by petrography, high S1/TOC values, and comparison of pre- and postextraction S1 values. Poor permeability suggests that solid bitumen is converted from original kerogen in situ. The terrestrial kerogens vitrinite and inertinite are scarce, suggesting a distal depositional environment. Immature Yanchang mudrocks were not available for the identification of the original kerogen type. However, the immature illite-rich Garden Gulch Member of the lacustrine Green River Formation or the early mature Boquillas Formation may be potential analogs for the original kerogen type and geochemistry.

Acknowledgments

Technical reviews by S. Hawkins (USGS), B. Cardott (Oklahoma Geological Survey), C. Eble (Kentucky Geological Survey), and an anonymous journal reviewer improved this paper. B. Valentine (USGS) provided images from SEM. O. Scholl (USGS) prepared samples for petrographic examination. J. Birdwell (USGS) provided the Garden Gulch oil-shale sample and the associated data. This research was funded by the USGS Energy Resources Program, Yanchang Petroleum (Group) Co., Ltd., and the Texas BEG. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. government.

References

ASTM, 2015a, D2797 Standard practice for preparing coal samples for microscopical analysis by reflected light: Annual book of ASTM standards, petroleum products, lubricants, fossil fuels, gaseous fuels, coal, and coke: ASTM International, sec. 5, 5.06, 528–532. http://www.astm.org/Standards/D2797.htm, accessed 2 February 2017.

ASTM, 2015b, D7708 Standard test method for microscopical determination of the reflectance of vitrinite dispersed in sedimentary rocks: Annual book of ASTM standards, petroleum products, lubricants, fossil fuels, gaseous fuels, coal, and coke: ASTM International, sec. 5, 5.06, 910–919, http://www.astm.org/Standards/D7708.htm, accessed 2 February 2017.

Birdwell, J. E., and K. E. Washburn, 2015, Rapid analysis of kerogen hydrogen-to-carbon ratios in shale and mudrocks by laser-induced breakdown spectroscopy: Energy & Fuels, 29, 6999–7004, doi: 10.1021/acs.energyfuels.5b01566.

Burnham, A. K., and J. R. McConaghy, 2014, Semi-open pyrolysis of oil shale from the Garden Gulch Member of the Green River Formation: Energy & Fuels, 28, 7426–7439.

Cardott, B. J., C. R. Landis, and M. E. Curtis, 2015, Post-oil solid bitumen network in the Woodford Shale, USA: A potential primary migration pathway: International Journal of Coal Geology, 139, 106–113, doi: 10.1016/j.coal.2014.08.012.

Cole, R. D., 1985, Depositional environments of oil shale in the Green River Formation, Douglas Creek arch, Colorado and Utah, in M. D. Picard, ed., Geology and energy resources, Uinta Basin of Utah: Utah Geological Association Publication, 211–224.

Dembicki, H., Jr., 2009, Three common source rock evaluation errors made by geologists during prospect or play appraisals: AAPG Bulletin, 93, 341–356, doi: 10.1306/10230808076.

Durand, B., 1980, Sedimentary organic matter and kerogen: Definition and quantitative importance of kerogen, in B. Durand, ed., Kerogen: Insoluble organic matter from sedimentary rocks: Editions Technip, 13–34.

Espitalié, J., J. L. Laporte, M. Madec, F. Marquis, P. Leplat, and J. Paulet, 1977, Méthode rapide de caractérisation des rochès, de leur potential pétrolier et de leur degree d’évolution: Revue de L’Institut Français du Pétrole, 32, 23–43.

Guo, H., W. Jia, P. Peng, Y. Lei, X. Luo, M. Cheng, X. Wang, L. Zhang, and C. Jiang, 2014, The composition and its impact on the methane sorption of lacustrine shales from the Upper Triassic Yanchang Formation, Ordos Basin, China: Marine and Petroleum Geology, 57, 509–520, doi: 10.1016/j.marpetgeo.2014.05.010.

Guo, J., and Z. Zhao, 2012, China vigorously promoting shale gas exploration, development: Oil & Gas Journal, 110, 60–65.

Hackley, P. C., C. V. Araujo, A. G. Borrego, A. Bouzinos, B. J. Cardott, A. C. Cook, C. Eble, D. Flores, T. Gentzis, P. A. Gonçalves, J. G. Mendonça Filho, M. Hámor-Vidó, I. Je- lonek, K. Kommeren, W. Knowles, J. Kus, M. Mastalerz, D. Marrs, D. Miroiu, D. J. Munro, M. E. N. Nogueira, P. C. O. Gonçalves, M. Picard, M. R. Picard, X. Sánchez-Carretero, G. Sanz, and J. Paulet, 1987, A petrographic examination of the Painted Desert Formation, Arizona: Marine and Petroleum Geology, 4, 527–532.
Hackley, P. C., N. Fishman, T. Wu, and G. Baugher, 2016, Organic petrology of North American shale petroleum systems: A review: International Journal of Coal Geology, 163, 8–51, doi: 10.1016/j.coal.2016.06.010.

Hackley, P. C., N. Fishman, T. Wu, and G. Baugher, 2016, Organic petrology of the lacustrine Lucaogou Formation, Santanghu Basin, northwest China: Application to lake basin evolution: International Journal of Coal Geology, 168, 20–34, doi: 10.1016/j.coal.2016.05.011.

Hackley, P. C., E. H. Guevara, T. F. Hentz, and R. W. Hook, 2009, Thermal maturity and organic composition of Pennsylvanian coals and carbonaceous shales, north-central Texas: Implications for coalbed gas potential: International Journal of Coal Geology, 77, 294–309, doi: 10.1016/j.coal.2008.05.006.

Hanson, A. D., B. D. Ritts, and J. M. Moldowan, 2007, Organic geochemistry of oil and source rock strata of the Ordos Basin, north-central China: AAPG Bulletin, 91, 1273–1293, doi: 10.1306/05040704151.

IHS Energy Group, 2015, U.S. well and production data, https://my.ihs.com/energy, accessed December 2015.

Jacob, H., 1989, Classification, structure, genesis and practical importance of natural solid oil bitumen (“migrabitumen”): International Journal of Coal Geology, 11, 65–79, doi: 10.1016/0166-5162(89)90113-4.

Jarvie, D. M., B. L. Claxton, F. Henk, and J. T. Breyer, 2001, Oil and shale gas from the Barnett Shale, Fort Worth basin, Texas: Presented at the AAPG Annual Meeting.

Jarvie, D. M., R. J. Hill, T. E. Ruble, and R. M. Pollastro, 2007, Unconventional shale-gas systems: The Mississippian Barnett Shale of north-central Texas as one model for thermogenic shale gas assessment: AAPG Bulletin, 91, 475–499, doi: 10.1306/121906060608.

Johnson, R. C., 2012, The systematic geologic mapping program and a quadrangle-by-quadrangle analysis of time-stratigraphic relations within oil shale-bearing rocks of the Piceance Basin, western Colorado: U.S. Geological Survey Scientific Investigations Report 2012-5041, 28, http://pubs.usgs.gov/sir/2012/5041/report/SIR12-5041.pdf, accessed January 2016.

Katz, B. J., 1990, Controls on distribution of lacustrine source rocks through space and time, in B. J. Katz, ed., Lacustrine basin exploration: Case studies and modern analogs: AAPG Memoir 50, 61–76.

Katz, B. J., and F. Lin, 2014, Lacustrine basin unconventional resource plays: Key differences: Marine and Petroleum Geology, 56, 255–265, doi: 10.1016/j.marpetgeo.2014.02.013.

Landis, C. R., and J. R. Castaño, 1994, Maturation and bulk chemical properties of a suite of solid hydrocarbons: Organic Geochemistry, 22, 137–149, doi: 10.1016/0146-6380(94)90013-6.

Lin, S., X. Yuan, S. Tao, Z. Yang, and S. Wu, 2013, Geochemical characteristics of the source rocks in Mesozoic Yanchang Formation, central Ordos Basin: Journal of Earth Science, 24, 804–814, doi: 10.1007/s12583-013-0379-1.

Liu, Z., F. Shen, X. Zhu, F. Li, and M. Tan, 2015, Formation conditions and sedimentary characteristics of a Triassic shallow water braided delta in the Yanchang Formation, southwest Ordos Basin, China: PLoS ONE, 10, e0119704, doi: 10.1371/journal.pone.0119704.

Macquaker, H. S., M. A. Keller, and S. J. Davies, 2010, Algal blooms and “marine snow”: Mechanisms that enhance preservation of organic carbon in ancient fine-grained sediments: Journal of Sedimentary Research, 80, 934–942, doi: 10.2110/jsr.2010.085.

Mählmann, R. F., and M. Frey, 2012, Standardization, calibration, and correlation of the Kübler-index and the vitrinite/bituminite reflectance: An interlaboratory and field related study: Swiss Journal of Geosciences, 105, 153–170, doi: 10.1007/s00015-012-0110-8.

Mukhopadhyay, P. K., 1989, Characterization of amorphous and other organic matter types by microscopy and pyrolysis-gas chromatography: Organic Geochemistry, 14, 269–284, doi: 10.1016/0146-6380(89)90055-7.

Mukhopadhyay, P. K., H. W. Hagemann, and J. R. Gormly, 1985, Characterization of kerogens as seen under the aspect of maturation and hydrocarbon generation: Erdöl Kohle, 38, 7–18.

Peters, K., 1986, Guidelines for evaluating petroleum source rock using programmed pyrolysis: AAPG Bulletin, 70, 318–329.

Petersen, H. I., N. H. Schovsbo, and A. T. Nielsen, 2013, Reflectance measurements of zooclasts and solid bitumen in Lower Paleozoic shales, southern Scandinavia: Correlation to vitrinite reflectance: International Journal of Coal Geology, 114, 1–18, doi: 10.1016/j.coal.2013.03.013.

Ren, Z., S. Zhang, S. Gao, J. Cui, Y. Xiao, and H. Xiao, 2007, Tectonic thermal history and its significance on the formation of oil and gas accumulation and mineral deposit in Ordos Basin: Science in China Series D: Earth Sciences, 50, 27–38.

Ritts, B. D., A. D. Hanson, B. J. Darby, L. Nanson, and A. Berry, 2004, Sedimentary record of Triassic intraplate extension in north China: Evidence from the nonmarine NW Ordos Basin, Helan Shan and Zhuozi Shan: Tecto-
nophysics, 386, 177–202, doi: 10.1016/j.tecto.2004.06.003.

Robert, P., 1988, Organic metamorphism and geothermal history: Microscopic study of organic matter and thermal evolution of sedimentary basins: Elf Aquitaine, 311.

Schieber, J., 2007, Benthic microbial mats as an oil shale component: Green River formation (Eocene) of Wyoming and Utah, in J. Schieber, P. K. Bose, P. G. Eriksson, S. Banerjee, S. Sarkar, W. Altermann, and O. Catuneau, eds., Atlas of microbial mat features preserved within the clastic rock record: Elsevier Atlases in Geosciences, 225–232.

Schieber, J., J. Southard, and K. Thaisen, 2007, Accretion of mudstone beds from migrating floccule ripples: Science, 318, 1760–1763, doi: 10.1126/science.1147001.

Tang, X., J. Zhang, X. Wang, B. Yu, W. Ding, and L. Zhang, 2013a, Geochemical characteristics and estimation of gas content of the low-middle mature continental shales: A case study from the Ordos Basin: AAPG Search and Discovery Article 10517, http://www.searchanddiscovery.com/documents/2013/10517/tangndx_tang.pdf, accessed December 2015.

Tang, X., J. Zhang, B. Yu, and W. Ding, 2013b, Shale gas characteristics in the southeastern part of the Ordos Basin, China: Implications for the accumulation condition and potential of continental shale gas, AAPG Search and Discovery Article 10481, http://www.searchanddiscovery.com/documents/2013/10481/tangndx_tang.pdf, accessed December 2015.

Tao, S., Y. Wang, D. Tang, D. Wu, H. Xu, and W. He, 2012, Organic petrology of the Fukang Permian Lucaogou Formation oil shales at the northern foot of Bogda Mountain, Junggar Basin, China: International Journal of Coal Geology, 99, 27–34, doi: 10.1016/j.coal.2012.05.001.

Taylor, G. H., M. Teichmüller, A. Davis, C. F. K. Diessel, R. Littke, and P. Robert, 1998, Organic Petrology: German edition (English abstract): Journal of Lanzhou University (Natural Sciences), 34, 177–202, doi: 10.1016/S1876-3804(15)30005-7.

Xie, X., T. Borjigin, Q. Zhang, Z. Zhang, J. Qin, L. Bian, and J. K. Volkman, 2015, Intact microbial fossils in the Permian Lucaogou Formation oil shale, Junggar basin, NW China: International Journal of Coal Geology, 146, 166–178, doi: 10.1016/j.coal.2015.05.011.

Xiong, F., Z. Jian, J. Chen, X. Wang, Z. Huang, G. Liu, F. Chen, Y. Li, L. Chen, and L. Zhang, 2016, The role of the residual bitumen in the gas storage capacity of mature lacustrine shale: A case study of the Triassic Yanchang shale, Ordos Basin, China: Marine and Petroleum Geology, 69, 205–215, doi: 10.1016/j.marpetgeo.2015.10.022.

Yang, H., and W. Zhang, 2005, Leading effect of the seventh member high-quality source rock of Yanchang Formation in Ordos Basin during the enrichment of low-penetrating oil-gas accumulation: Geology and geochemistry (in Chinese with English abstract): Geochnica, 34, 147–154.

Yang, M., L. Li, J. Zhou, H. Jia, X. Sun, X. Qu, D. Zhou, T. Gong, and C. Ding, 2015, Mesozoic structural evolution of the Hangjinqi area in the northern Ordos Basin, North China: Marine and Petroleum Geology, 66, 695–710, doi: 10.1016/j.marpetgeo.2015.07.014.

Yang, W., G. Liu, and Y. Feng, 2016, Geochemical significance of 17α(H)-diahopane and its application in oil-source correlation of Yanchang formation in Longdong area, Ordos basin, China: Marine and Petroleum Geology, 71, 238–249, doi: 10.1016/j.marpetgeo.2015.10.016.

Yao, J., X. Deng, Y. Zhao, T. Han, M. Chu, and J. Pang, 2013, Characteristics of tight oil in Triassic Yanchang Formation, Ordos Basin: Petroleum Exploration and Development, 40, 161–169, doi: 10.1016/S1876-3804(13)60019-1.

Yuan, X., S. Lin, Q. Liu, J. Yao, L. Wang, H. Guo, X. Deng, and D. Cheng, 2015, Lacustrine fine-grained sedimentary features and organic-rich shale distribution pattern: A case study of Chang 7 Member of Triassic Yanchang Formation in Ordos Basin, northwest China: Petroleum Exploration and Development, 42, 37–47, doi: 10.1016/S1876-3804(15)60004-0.

Zhang, H., N. Deng, Q. Li, Z. Zhang, Y. Liu, S. Zhao, and W. Liang, 2015b, Distribution and geochemistry characteristic of the source rocks from Yanchang Formation in the southern part of Ordos Basin (in Chinese with English abstract): Journal of Lanzhou University (Natural Sciences), 51, 31–36.

Zhang, M., L. Ji, Y. Wu, and C. He, 2015a, Palynofacies and geochemical analysis of the Triassic Yanchang Formation, Ordos Basin: Implications for hydrocarbon generation potential and the paleoenvironment of continental
source rocks: International Journal of Coal Geology, 152, 159–176, doi: 10.1016/j.coal.2015.11.005.
Zhang, W., H. Yang, J. F. Li, and J. Ma, 2006, Leading effect of high class source rock of Chang 7 in Ordos Basin on enrichment of low permeability oil gas accumulation (in Chinese with English abstract): Petroleum Exploration and Development, 33, 289–293.
Zhao, J., N. P. Mountney, C. Liu, H. Qu, and J. Lin, 2015, Outcrop architecture of a fluvo-lacustrine succession: Upper Triassic Yanchang Formation, Ordos Basin, China: Marine and Petroleum Geology, 68, 394–413, doi: 10.1016/j.marpetgeo.2015.09.001.
Zhao, M., H. Behr, H. Ahrendt, K. Wenmer, Z. Ren, and Z. Zhao, 1996, Thermal and tectonic history of the Ordos basin, China: Evidence from apatite fission track analysis, vitrinite reflectance, and K-Ar dating: AAPG Bulletin, 80, 1110–1134.
Zhao, W., H. Wang, X. Yuan, Z. Wang, and G. Zhu, 2010, Petroleum systems of Chinese nonmarine basins: Basin Research, 22, 4–16, doi: 10.1111/j.1365-2117.2009.00451.x.
Zhao, W. Z., X. M. Wang, and Y. R. Guo, 2006, Restoration and tectonic reworking of the Late Triassic basin in western Ordos Basin: Petroleum Exploration and Development, 33, 6–13.

Paul Hackley received an undergraduate degree from Shippensburg University, Pennsylvania, and an M.S. in geology from George Washington University, District of Columbia. He is a research geologist at the U.S. Geological Survey in Reston, Virginia, and manages the USGS Organic Petrology Laboratory. His experience includes international work on coal deposits and source rocks, and Gulf Coast basin energy resource studies including coalbed methane, coal resources, conventional oil and gas, and shale petroleum systems. His research interests include organic petrology and its application to fossil fuel assessment.

Lixia Zhang received an undergraduate degree (1987) in petroleum geology from Northwest University of China. She is a professor and vice-president of the Research Institute of Shaanxi Yanchang Petroleum (Group) Corp. Ltd. Her research interests include unconventional oil and gas exploration and development.

Tongwei Zhang received a B.S. (1986) in geology from Northwest University, China, and a Ph.D. (2000) in isotope geochemistry from Chinese Academy of Sciences. He is a research scientist and organic geochemist with the Bureau of Economic Geology, The University of Texas at Austin. He was a postdoctoral scholar in chemistry at the California Institute of Technology (Caltech) (2001–2007). His research interests include gas and organic geochemistry, isotope geochemistry, gas generation kinetics and basin modeling, and fluid transport processes in basins and reservoirs. His recent research interests include shale gas geochemistry, gas adsorption, and pore-size distribution with N2 adsorption.