Source rock types, distribution and their hydrocarbon generative potential within the Paleogene Sokor-1 and LV formations in Termit Basin, Niger

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Abstract
The Paleogene lacustrine mudstone is one of the most important sets of source rocks in Termit Basin, Niger. However, studies on the Paleogene source kitchen are scarce. In this study, the source rock types, spatial distribution and their hydrocarbon generative potential within the Paleogene Sokor-1 and LV formations are systematically evaluated. A total of two third-order sequences (SSQ1 and SSQ2, from the bottom to top) and six systems tracts were identified in the Sokor-1 Formation, while the LV Formation mainly comprises pure shale and is regarded as a compositive stratigraphic sequence with no need of subdivision. Six types of source rocks could be distinguished within the three depositional environments of the sequence stratigraphic framework: (1) deep lake mudstones and shale deposited in the lacustrine deep-water facies, (2) shallow lake mudstones and carbonaceous mudstones occurring in the shallow lake environment, and (3) deltaic-front mudstones and prodeltaic mudstones developed in the deltaic facies.

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Deep lake mudstones/shale, which mainly occurred in the SSQ1-TST (transgressive systems tract), SSQ2-TST and LV Formation, are considered organic-rich source rocks with oil-prone generative potential. The shallow lake mudstones and deltaic mudstones were predominantly distributed in the tectonic slope and marginal areas of the Agadem Block within the lowstand systems tract and high stand systems tract of the SSQ1 and SSQ2. Nevertheless, geochemical results indicated that the deltaic mudstones are good gas-prone source rocks but the shallow lake mudstones were classified as poor potential source rocks. The variance in organic matter accumulation and preservation conditions within different depositional facies and the fluctuation of relative lake level are the controlling factors for the occurrence and distribution of high-quality source rocks. The effective Paleogene source kitchen is limitedly distributed around the depocenter of the Dinga Depression within a small scale, and therefore exploration for oil and gas resources from the Paleogene source kitchen should focus on the eastern Dinga fault-step zone adjacent to the depocenter of the Dinga Depression.

**Keywords**
Source rock types, geochemical characteristics, hydrocarbon generative potential, lacustrine mudstone, source kitchen

**Introduction**
Termit Basin is a typical Mesozoic-Cenozoic extensional rift basin located in the southeast of Niger (Figure 1(a)) (Fairhead, 1986; Genik, 1992, 1993; Liu et al., 2012a, 2012b). It is the second largest hydrocarbon prolific basin following the Muglad Basin in the West and Central African Rift System (WCARS) (Genik, 1992, 1993; Liu et al., 2012a, 2017; Wan et al., 2014; Xiao et al., 2019; Xue et al., 2014; Zanguina et al., 1996, 1998; Zhao and Li, 2016; Zhou et al., 2017). Two oil families, i.e. oil family I mainly sourced from marine organic matter and oil family II from lacustrine organic matter, have been verified in Termit Basin on the basis of a comprehensive oil-to-oil correlation (Dong et al., 2016; Liu et al., 2017, 2019; Mao et al., 2016a; Wan et al., 2014; Xiao et al., 2019). In addition, two petroleum systems have been distinguished, namely, Sokor-Yogou (!) and Sokor–Sokor (!) (Zhao and Li., 2016). The geological and geochemical characteristics of the source kitchen of the Sokor-Yogou (!) petroleum system have been reported in detail in recent years (Harouna and Philp, 2012; Harouna et al., 2017; Lai et al., 2018, 2019; Liu et al., 2015; Tang et al., 2017; Xiao et al., 2019). However, the spatial distribution and hydrocarbon generative potential of probable source rocks of the Sokor–Sokor (!) petroleum system are still poorly known, allowing for a very vague estimation of resources (oil family II) in this petroleum system.

In this study, the source rock types, spatial distribution, and their hydrocarbon generative potential within the Paleogene Sokor-1 and LV formations are systematically discussed on the basis of an integrated geological–geochemical investigation with a series of well logs, seismic sections, and organic geochemical data. Our data provide a basis for estimates of source rock quality and hydrocarbon generative potential of the Sokor–Sokor (!) petroleum system, which can be highly significant for further petroleum exploration in Termit Basin. Furthermore, this study expands a practical approach for source rock assessment with an
integrated investigation of sequence stratigraphic framework, depositional facies, and organic geochemical results, which may particularly benefit those hydrocarbon-bearing basins with a limited number of wells and geological samples.

**Geological setting**

Termit Basin comprises the northwestern part of the WCARS and is divided into 10 secondary tectonic units (Figure 1(a)) (Lai et al., 2018, 2019; Liu et al., 2012a, 2012b). The central part of Termit Basin (known as Agadem Block, Figure 1(a)), with a length of approximately 300 km and a width of ∼60–110 km (Lai et al., 2018, 2019; Liu et al., 2012a, 2012b), includes two negative tectonic units (i.e. Dinga and Moul depressions) and four positive tectonic units (i.e. Dinga step-fault zone, Araga Graben, Fana Uplift, and Yogou Slope) (Figure 1(a)) (Genik, 1992, 1993; Lai et al., 2018, 2019; Liu et al., 2012a, 2012b). Termit Basin is filled with Mesozoic-Cenozoic strata from the Lower Cretaceous to Quaternary, with a maximum thickness of approximately 12,000 m in the depocenter of the Dinga Depression (Figure 1(b)) (Lai et al., 2018, 2019; Liu et al., 2012a, 2012b).

During the first rifting phase caused by the breakup of Gondwana (∼150–98.9 Ma), a set of stratigraphic successions (K₁ Formation), consisting of terrigenous sediments with several

![Figure 1. Geographic location and schematic structure of the Agadem Block in the Termit Basin (a), the representative geological profile (section A-A′) showing the stratum and faults (b) and the generalized stratigraphic column of the Termit Basin (c). (Modified after Genik, 1993; Lai et al., 2018, 2019; Wan et al., 2014). Quat.: Quaternary; Fm.: Formation. Section B-B′ is the location of seismic profile in Figure 3(a), while the section C-C′ and D-D′ are the location of seismic profiles in Figure 12(b) and 12(c), respectively.](image)
kilometers in thickness, were deposited on the Precambrian-Jurassic metamorphic basement (Figure 1(c)) (Fairhead and Binks, 1991; Genik, 1992, 1993; Liu et al., 2012b; Mao et al., 2016b). Large-scale marine transgression from the Tethys in the north and the Atlantic in the south prevailed in the Termit region in the backdrop of the regional thermal subsidence during the Late Cretaceous (∼98.9–65.6 Ma) (Genik, 1992, 1993; Guiraud et al., 2005). As a result, thick Upper Cretaceous marine mudstones of the Donga and Yogou formations occur throughout the Agadem Block area (Figure 1(c)), which are regarded as the main effective source kitchen of the Sokor-Yogou (!) petroleum system (Harouna and Philp, 2012; Harouna et al., 2017; Lai et al., 2018, 2019; Liu et al., 2015, 2017; Wan et al., 2014; Xiao et al., 2019; Zhao and Li, 2016). A new rift cycle developed in the Termit Basin area during the Paleogene to Eocene and then transformed into thermo-tectonic sinking in the Oligocene (Genik, 1992, 1993), resulting in a new terrigenous stratigraphic sequence (Sokor-1, LV, and Sokor-2 formations) deposited over the Upper Cretaceous Madama Formation (Figure 1(c)). A fluvial-deltaic-lacustrine depositional system widely developed in the Sokor-1 Formation, and the deltaic sand bodies therein have been identified as the main reservoirs of Termit Basin (Genik, 1993; Liu, 2012b; Zhou et al., 2017). In addition, the deltaic and lacustrine mudstones in the Sokor-1 Formation are generally accepted as the main source rocks of the Sokor–Sokor (!) petroleum system (Wan et al., 2014; Zhao and Li, 2016). The lithology of the LV and Sokor-2 formations is dominated by thick lacustrine shale or mudstones, which serve as excellent regional cap rocks for the two petroleum systems. A minor part of LV shale occurred in the depocenter of Dinga Depression may have entered the oil generation window ($R_o = 0.5\%$) that can be also considered as a part of source rocks of the Sokor–Sokor (!) petroleum system. During the Neogene to Quaternary (∼23.8–0 Ma), Termit Basin was significantly faulted and uplifted (Fitton, 1980; Genik, 1992, 1993), promoting the formation of favorable hydrocarbon traps and migration conduits. The Neogene to Quaternary stratigraphic sequence is composed of thick continental sediments, such as alluvial, fluvial, deltaic, and lacustrine sediments (Fitton, 1980; Genik, 1992, 1993).

Materials and methods

Sample selection and geological dataset

A total of 13 drill cores from wells DB-3, DD-2, AG-2, and GLW-2 and 44 cutting samples from wells TH-1, OU-1, DD-3, and DB-1 were collected in this study (well locations are shown in Figure 1). The samples were obtained from the mudstone layers within the Paleogene Sokor-1 and LV formations. All of the samples were selected for total organic carbon (TOC) content analysis and Rock-Eval pyrolysis. In addition, 15 samples were selected for the determination of organic elements, stable carbon isotope compositions, and vitrinite reflectance ($R_o$) measurements. Finally, well-logging curves from 40 wells, together with two-dimensional (2D) seismic data from 23 seismic sections, were collected for this study.

Organic geochemical experiments

All samples were sieve-washed using distilled water to remove possible contaminants from water-based drilling mud filtrate, then crushed and ground to <80 mesh (Lai et al., 2018).
Samples were treated with diluted hydrochloric acid (1.5 mol/L) to remove carbonates prior to measuring their TOC content with a LECO CS-230 carbon/sulfur determinator. The Rock-Eval pyrolysis parameters of selected samples, i.e. volatile hydrocarbon content \( (S_1) \), remaining hydrocarbon generative potential \( (S_2) \), and temperature at maximum pyrolysis yield \( (T_{\text{max}}) \), were determined using an OGE-VI Rock Pyrolysis Instrument following the procedures described by Espitalié et al. (1986). Kerogen was isolated from whole-rock samples following the method proposed by Saxby (1976) and then analyzed for organic elements, stable carbon isotope compositions, and vitrinite reflectance \( (R_o) \). To prepare samples for \( R_o \) measurement, the isolated kerogen powder was evenly scattered on a small container, then fixed with epoxy resin and polished at least one side. \( R_o \) was measured under reflected white light using a Leica CTR 6000-M microscope equipped with DISKUS fossil software and a 50× oil-immersion objective (Luo et al., 2016). The organic element content \( (C, H, \text{and} O) \) of kerogen was determined on the Elementar analyzer (Vario EL cube), while the stable carbon isotope compositions were measured with a Flash HT EA-MAT 253 IRMS instrument. All of the geochemical experiments were conducted at the State Key Laboratory of Petroleum Resources and Prospecting, China University of Petroleum (Beijing), Beijing, China.

In addition, the burial and thermal histories of representative wells were evaluated using the petroleum system modeling software (BasinMod 1-D) of Platte River Associates, Inc. The input data used for numerical modelling of the representative wells are shown in Table 1. The top depth and thickness of each formations or sequences of the three representative wells are from the well logs in combination with the sequence stratigraphic scheme. The lithological data of the three wells are from the cutting samples and lithological logging interpretation. The measured \( R_o \) data of well DD-3, YgN-1, and ML-1 are cited from Lai et al. (2019). The values of heat flow and surface temperature histories are selected on the basis of the tectonic activities and geological background of Termit Basin introduced by Genik (1992, 1993) and Liu et al. (2012a, 2012b).

**Evaluation of the areal distribution of mudstones**

In this study, we firstly identified and calculated the thickness of mudstone intervals, the stratum thickness, and the mudstone to stratum thickness ratios \( (\text{MS ratios}) \) of different sequence units in individual wells based on the observation of cutting samples, continuous well logging curves, and lithological logging interpretation data. Then we analyzed the depositional facies of different sequence units in individual wells without samples based on MS ratios. After the corresponding relationship between seismic and geological data from well logs was established by means of accurate well-seismic calibration, we can estimate the areal distribution of stratum thickness of different sequence units. We obtained the areal distribution of mudstones by integrated application the MS ratio, the stratum thickness, and the depositional facies of different sequence units, calibrated by the measured thickness data from the drilled wells (Lai et al., 2019).

**Workflow of the integrated geological–geochemical investigation**

The integrated geological–geochemical investigation on source rock is a multi-disciplinary approach that aims to evaluate and predict the probable source kitchen of a particular petroliferous basin with low exploration degree. First, the areal distribution and evolution
of depositional facies within an isochronous sequence unit should be studied once the isochronous sequence stratigraphic framework of the study area has been established. Then, source rock types and their areal distributions can be readily identified and predicted on the basis of the depositional facies within the sequence stratigraphic framework. Subsequently, representative samples of different types of source rocks within each isochronous sequence unit need to be collected and systematically analyzed to assess their hydrocarbon generative potential.

Finally, the effective source kitchen within the sequence stratigraphic framework can be reasonably predicted based on collective results from the abovementioned steps. The workflow of this approach is shown in Figure 2.
Results and discussions

Sequence stratigraphic and depositional characteristics

Sequence stratigraphic framework. The sequence stratigraphic framework of Termit Basin has been discussed in previous studies (Fu et al., 2012; Lai et al., 2018, 2019; Tang et al., 2015; Wang et al., 2016). Two first-order sequences (FS1 and FS2) and four second-order sequences (TS1, TS2, TS3, and TS4) have been identified on the basis of four sets of regional unconformities in Termit Basin (Lai et al., 2019). The top and bottom boundaries of the Paleogene are consistent with those of the TS3 second-order sequence (Lai et al., 2019). In this study, the Paleogene Sokor-1 Formation was further divided into two third-order sequences (SSQ1 and SSQ2) in the representative well DB-1 (Figure 3(b)) and the corresponding seismic section (Figure 3(a)), following the approach of sequence stratigraphy proposed by van Wagoner et al. (1990). The LV Formation was mainly composed with
pure lacustrine shale (Fu et al., 2012; Lü et al., 2015); therefore, in this study, it was regarded as an integrate stratigraphic sequence that does not need subdivision.

The bottom boundary of the Sokor-1 Formation, i.e. the regional Paleogene/Upper Cretaceous unconformity, was readily identified in the well profiles and seismic sections (Figure 3(a) and (b)). The LV Formation consisting mainly of lacustrine deep-water shale/mudstones ranging in the thickness from 50 to 150 m is generally accepted as the regional marker for identifying the top surface of the Sokor-1 Formation (Fu et al., 2012; Lü et al., 2015) (Figure 3(a) and (b)). In addition, a third-order sequence interface within the
Sokor-1 Formation was easily identified and tracked in well or seismic profiles, which is regarded as the boundary of the third-order SSQ1 and SSQ2 sequences (Figure 3). In this study, a well log correlation within a geological section is completed to further describe the systems tracts within the SSQ1 and SSQ2 sequences (Figure 3(c)), in which the first flooding surface (FFS) and maximum flooding surface (MFS) of these two third-order sequences were identified laterally and tracked. Lowstand systems tract (LST), transgressive systems tract (TST), and highstand systems tract (HST) were systematically identified within the SSQ1 and SSQ2 sequences based on the FFS and MFS (Figure 3(c)).

**Depositional characteristics within the sequence framework.** A deltaic-lacustrine depositional system prevailed in Termit Basin during the Paleogene (Fu et al., 2012; Genik, 1992, 1993; Liu et al., 2012b). In this study, a well log correlation within a geological section (Figure 3(c)) was used to reveal the depositional characteristics and evolution within the sequence stratigraphic framework of the Paleogene Sokor-1 Formation.

The lithology of the LST of SSQ1 around the southern Dinga fault-step zone was characterized by dominant deltaic-front sandstones interceded with minor thin mudstone interlayers, which is in good response to the relatively low lake level during that period. With the lake level rising during the period of TST of SSQ1, the lacustrine deep-water facies (or the semi-deep to deep lake depositional environment) gradually moved toward the marginal area of Termit Basin. As a result, thick lacustrine mudstones were distributed throughout Agadem Block, as well as some turbidite sandbodies around the depression area. The lake level dropped rapidly during the HST period of SSQ1, leading to delta progradation into the western and eastern positive tectonic units again. The depositional characteristics within different systems tracts of the SSQ2 were similar to those of SSQ1, characterized by sand-rich deltaic-front facies in the LST and mud-rich lacustrine deep-water facies in the TST, as well as delta progradation during the early stage of the HST. However, the sand-rich deltaic-front environment in the Dinga fault-step zone transformed into a mud-rich shallow lake environment during the late HST stage.

The LV Formation is generally known as the LV shale marker layer, which unconformably overlies the HST of SSQ2 and can be tracked regionally. It is characterized by a series of lacustrine deep-water shale/mudstones that developed in the semi-deep to deep lake environment. These lines of evidence indicate that a gradual lake expansion occurred in Termit Basin during the period from the Sokor-1 Formation to the LV Formation, although the deposition process of sediments within a third-order sequence period was still controlled by the lake level change cycle.

**Source rocks within stratigraphic sequence units**

**Source rock types and their logging characteristics.** The depositional evolution within the third-order sequences of the Sokor-1 Formation is characterized by the lake transgression (i.e. LST and TST) and regression (i.e. HST) depositional cycles. The relatively shallow-water depositional facies, such as lakeshore, shallow lake and deltaic facies, were prevailing during the lake contraction period with lower relative lake level (e.g. LST and HST of the SSQ1), while relatively deep-water depositional facies, e.g., semi-deep to deep lake facies, were widely distributed in Termit Basin during the higher relative lake level period (e.g. TST of the SSQ1) (Figure 4(a)).
A total of six types of probable source rocks could be distinguished in the three different deltaic-lacustrine depositional environments within the sequence stratigraphic framework of the Sokor-1 and LV formations: (1) deep lake mudstones and shale (especially the LV shale) deposited in the lacustrine deep-water facies (Figure 4(b) and (e)), (2) shallow lake mudstones and carbonaceous mudstones occurring in the shallow lake environment (Figure 4(b) and (d)), and (3) deltaic-front mudstones and prodeltaic mudstones developed in the deltaic facies (Figure 4(c)). The depositional and logging characteristics of these six types of source rocks are described in detail below.

1. Deep lake mudstones and shale. These two types of source rocks mainly occurred in the lacustrine deep-water environments with quiet hydrodynamic conditions, such as the depocenter of the Dinga and Moul depressions. They are always characterized by relatively high values of gamma-ray logging (GR) and lower values of deep lateral resistivity logging (LLD) (Figure 4(b) and (e)). Moreover, shale (e.g. LV shale) is further distinguished from deep lake mudstones by the relatively higher GR logging values and lower values of acoustic logging (DT) (Figure 4(b)).

2. Shallow lake mudstones. Generally, shallow lake mudstones are characterized by oxide colors, such as maroon, brick-red, and purple-red (Figure 4(d)), which are in good response to the aerobic-prone environment with shallower water and relatively turbulent...
hydrodynamic conditions. Compared to the deep lake mudstones, the shallow lake mudstones can be distinguished by the relatively lower GR logging values and higher LLD logging values (Figure 4(b) and (d)). Furthermore, they always coexist with a series of thin siltstones and carbonaceous mudstones (Figure 4(b) and (d)).

3. Carbonaceous mudstones. This type of source rock was generally deposited in the wetland or swamp area among the shallow lake or deltaic-plain depositional environments. These mudstones are characterized by dark-gray or black colors, shallow depths (~2–6 m), and a distinctive logging response. They can be readily distinguished from other mudstones by the combinational logging characteristics with relatively low value of density logging (DEN), high value of compensated neutron logging (CNL), and higher DT logging value (Figure 4(d)).

4. Deltaic-front and prodeltaic mudstones. These two types of source rocks occurred in the deltaic-front and prodeltaic depositional system. The integrated deltaic deposits can be distinguished by the gradually upward decreasing GR logging response and gradually upward increasing LLD logging response (Figure 4(c)). These two types of mudstones within the deltaic-front and prodeltaic environment can be distinguished on the basis of their logging features (i.e. relatively higher GR and lower LLD compared to sandstones) (Figure 4(c)).

Areal distribution of probable source rocks. Generally, the range of mudstone to stratum thickness ratios (MS ratios) for the deltaic, shallow lake, and deep lake facies of a fluvial-deltaic-lacustrine depositional system, was <0.5, 0.5–0.8, >0.8, respectively (Feng, 2004; Xie et al., 2011). On the basis of lithological and logging data, the thickness and MS ratio of different sequence units were calculated for individual wells. Isopleths of mudstone thickness associated with depositional facies distributed within the LV Formation and different systems tracts of the SSQ1and SSQ2 are shown in Figure 5(b) to (d). The depositional facies were predicted based on the facies model of the deltaic-lacustrine depositional system given the tendency of the MS ratio.

The MS ratio within the LV Formation of the studied wells ranged between 0.72 and 0.99 (Figure 5(b)), with an average value of 0.94, indicating that the deep lake facies were prevailing throughout the whole Agadem Block area. Lacustrine deep-water mudstones/shale deposited throughout Agadem Block with a thickness of 50–140 m (Figure 5(b)).

Different types of mudstones related to the deltaic, shallow lake, and deep lake facies can be distinguished within the Sokor-1 Formation. During the LST period of SSQ2, the deep lake facies, the shallow lake facies, and the deltaic deposits mainly formed in the Dinga and Moul depressions, the tectonic slope zone, and the Araga Graben and Fana Uplift area, respectively (Figure 5(c)). The mudstone thickness of the SSQ2-LST ranged between 40 m and 100 m (Figure 5(c)). The deep lake facies covered most of the Agadem Block area in the SSQ2-TST period, with a mudstone thickness of 50–100 m. In addition, a large delta developed in the well DWN-1 region during the SSQ2-TST period (Figure 5(c)). During the SSQ2-HST period, a series of deltaic deposits developed in the southern region and the north marginal area, and the deep lake and shallow lake facies were deposited in the Dinga Depression and the northern positive tectonic units (i.e. Dinga fault-step zone and Araga Graben), respectively. The range in mudstone thickness within the deltaic, shallow lake and deep lake facies was between 50 and 140 m, 60 and 140 m, and 150 and 180 m, respectively (Figure 5(c)).
Figure 5. The isopleth map of mudstone thickness and the areal distribution of the depositional facies within the LV Formation (b) and different systems tracts of SSQ2 (c) and SSQ1 (d) in the Agadem block, Termit Basin. (a) Location of studied wells and 2D seismic lines for the prediction of depositional facies and source rock thickness.
Deltaic mudstones were the dominant source rock types within the LST of SSQ1, and their thickness was about 20–80 m (Figure 5(d)). Deep lake mudstones with a thickness of about 70–100 m formed almost throughout the entire Agadem Block area during the SSQ1-TST period (Figure 5(d)). During the SSQ1-HST period, shallow lake mudstones were the dominant source rocks depositing in the central area of Agadem Block, with a thickness of 60–100 m. In addition, the deep lake mudstones and deltaic-front mudstones restrictedly occurred in the Dinga Depression and the marginal region, respectively (Figure 5(d)).

**Hydrocarbon potential of source rocks**

**Organic matter richness.** Total organic carbon (TOC) content and Rock-Eval pyrolysis parameters were applied to assess the organic matter richness following the criteria of Peters and Cassa. (1994). The TOC and pyrolysis parameters and their distributions are shown in Table 2, and Figures 6 and 7.

Compared to the non-source rock, the deep lake mudstones (except for the deep lake mudstones from the SSQ1-TST of well DD-3) have higher TOC, hydrocarbon potential index \( S_1 + S_2 \), and hydrogen index (HI) values (Figure 6 and Table 2). The deltaic mudstones and carbonaceous mudstones show similar TOC and \( S_1 + S_2 \) distributions compared to the deep lake mudstones, but lower HI value (Figure 6 and Table 2). In contrast, the shallow lake mudstones, non-source rocks, and deep lake mudstones from the SSQ1-TST of well DD-3 were characterized by the low values of TOC and \( S_1 + S_2 \) and HI (Figure 6 and Table 2). The results indicate that the source rocks occurring within the lacustrine deep-water facies, such as the LV shale and deep lake mudstones (except for the deep lake mudstones from the SSQ1-TST of well DD-3), are organic-rich source rocks with good hydrocarbon generative potential (Figures 7 and 8). Similarly, carbonaceous mudstones that mainly developed in the shallow lake or deltaic-plain environment also had higher TOC, \( S_1 + S_2 \), and HI values, suggesting excellent hydrocarbon potential (Figures 7 and 8). However, most shallow lake mudstones represent source rocks of poor hydrocarbon potential (Figures 7 and 8).

The maximum flooding surface (MFS) level gradually increased from the SSQ1 to SSQ2 to LV Formation, indicating that sand-rich deltaic deposits mainly occurred in the LST and HST of SSQ1, while the shallow lake facies prevailed in the LST and HST of SSQ2 (Figure 7). Deep lake mudstones mainly occurred in the TST of the SSQ1 and SSQ2, as well as in the LV Formation (Figure 7). In summary, based on the aforementioned geochemical results, it is concluded that organic-rich source rocks with good hydrocarbon potential within the Sokor-1 and LV formations are the deep lake mudstones/shale, deltaic mudstones, and carbonaceous mudstones (Figures 6 to 8).

**Kerogen type of organic matter.** Kerogen type is one of the critical indicators for distinguishing whether a certain source rock is oil-prone or gas-prone (Bordenave et al., 1993; Hunt, 1979). In this study, the Rock-Eval pyrolysis parameters (i.e. \( T_{\text{max}} \) and HI) of whole rocks, organic element compositions, and stable isotope compositions \( (\delta^{13}C, \text{PDB}) \) of kerogen samples were used to classify the kerogen type of organic matter of the representative mudstone samples (Table 3, Figures 9 and 10).

The \( \delta^{13}C \) of all of the samples selected for analysis ranged from \(-26.8\%_o\) to \(-23.6\%_o\) (Table 3), revealing that they were mainly composed of organic matter from the continental
Table 2. Bulk geochemical results of TOC content and Rock-Eval pyrolysis analyses with calculated parameters of the different types of source rocks within the Paleogene Sokor-1 and LV formations in the Termit Basin.

| No. | Well name | Depth (m) | 3rd sequence-systems tract | Source rock types | TOC (%) | T<sub>max</sub> (°C) | S<sub>1</sub> (mg/g) | S<sub>2</sub> (mg/g) | S<sub>1</sub> + S<sub>2</sub> (mg/g) | HI (mg/g) |
|-----|-----------|-----------|-----------------|------------------|---------|----------------|----------------|----------------|-----------------|-----------|
| 1   | DD-3      | 2258      | LV Fm.          | LV shale         | 2.76    | 444            | 0.54           | 14.28          | 14.82           | 517.39    |
| 2   | DD-3      | 2308      | LV Fm.          | LV shale         | 2.65    | 447            | 0.63           | 19.46          | 20.09           | 734.34    |
| 3   | DD-3      | 2364      | LV Fm.          | LV shale         | 1.74    | 445            | 0.42           | 9.31           | 9.73            | 535.06    |
| 4   | DD-3      | 2410      | LV Fm.          | LV shale         | 1.84    | 445            | 1.69           | 11.70          | 13.39           | 635.87    |
| 5   | AG-2      | 2012.3    | LV Fm.          | LV shale         | 5.70    | 447            | 0.54           | 51.43          | 51.97           | 901.96    |
| 6   | AG-2      | 2012.8    | LV Fm.          | LV shale         | 5.93    | 446            | 0.61           | 52.27          | 52.88           | 881.45    |
| 7   | AG-2      | 2014.2    | LV Fm.          | LV shale         | 4.76    | 445            | 0.36           | 41.29          | 41.65           | 866.89    |
| 8   | DD-3      | 2508      | SSQ2-HST        | Deep lake mudstone | 3.34  | 440            | 0.53           | 8.30           | 8.83            | 248.50    |
| 9   | AG-2      | 2012.8    | SSQ2-HST        | Deep lake mudstone | 5.93  | 446            | 0.61           | 52.27          | 52.88           | 881.45    |
| 10  | DD-3      | 2564      | SSQ2-HST        | Deep lake mudstone | 3.70  | 445            | 1.47           | 16.09          | 17.56           | 434.86    |
| 11  | AG-2      | 2014.2    | SSQ2-HST        | Deep lake mudstone | 4.76  | 445            | 0.36           | 41.29          | 41.65           | 866.89    |

(continued)
Table 2. Continued.

| No. | Well name | Depth (m) | 3rd sequence-systems tract | Source rock types          | TOC (%) | T\textsubscript{max} (°C) | S\textsubscript{1} (mg/g) | S\textsubscript{2} (mg/g) | S\textsubscript{1} + S\textsubscript{2} (mg/g) | HI (mg/g) |
|-----|-----------|-----------|-----------------------------|----------------------------|---------|---------------------------|--------------------------|--------------------------|---------------------------------|----------|
| 49  | DD-3      | 3026      | SSQ1-HST                    | Deltaic-front mudstone    | 2.85    | 440                       | 1.19                     | 4.69                     | 5.88                            | 164.56   |
| 50  | DD-3      | 3084      | SSQ1-TST                    | Deltaic-front mudstone    | 2.05    | 445                       | 0.54                     | 1.41                     | 1.95                            | 68.78    |
| 51  | DD-3      | 3092      | SSQ1-TST                    | Deltaic-front mudstone    | 2.22    | 444                       | 0.52                     | 2.23                     | 2.75                            | 100.45   |
| 52  | DD-3      | 3098      | SSQ1-TST                    | Deltaic-front mudstone    | 2.32    | 446                       | 0.31                     | 4.57                     | 4.88                            | 196.98   |
| 53  | DD-3      | 3104      | SSQ1-TST                    | Deltaic-front mudstone    | 4.46    | 437                       | 0.47                     | 7.15                     | 7.62                            | 160.31   |
| 54  | TH-1      | 1152      | SSQ1-LST                    | Deltaic-front mudstone    | 8.06    | 434                       | 2.47                     | 44.06                    | 46.53                           | 546.65   |
| 55  | TH-1      | 1160      | SSQ1-LST                    | Deltaic-front mudstone    | 5.71    | 434                       | 1.65                     | 24.74                    | 26.39                           | 433.27   |
| 56  | DD-3      | 2532      | SSQ2-HST                    | Deltaic-front siltstone  | 0.32    | 426                       | 0.35                     | 0.65                     | 1.00                            | 202.49   |

TOC: total organic carbon, %; S\textsubscript{1}: volatile hydrocarbon (HC) content, mg HC/g rock; S\textsubscript{2}: remaining HC generative potential, mg HC/g rock; T\textsubscript{max}: temperature at maximum of S\textsubscript{2} peak; S\textsubscript{1} + S\textsubscript{2}: hydrocarbon generative potential index, mg HC/g rock; HI: 100 × S\textsubscript{2}/TOC, mg HC/g TOC; LV Fm.: LV Formation.

Figure 6. The statistical value distribution of TOC and Rock-Eval pyrolysis parameters of different types of source rocks. The non-source rocks include the turbidite siltstone and deltaic-front siltstone samples as shown in Table 2.
The shale from the LV Formation and most of the deep lake mudstones from SSQ1 and SSQ2 were dominated by Type I to Type II kerogen with higher HI values (Table 2, Figure 6 and 9). Furthermore, the selected deep lake mudstones/shale samples had higher H/C ratios and lower O/C ratios, also suggesting typical geochemical

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**Figure 7.** The integrated sequence stratigraphic-geochemical column showing the evolution process of the relative lake level, depositional facies and the geochemical characteristics within the sequence stratigraphic framework of the Paleogene sokor-1 and LV formations.

LV Fm.: LV Formation; MFS: maximum flooding surface.

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environment (Galimov, 2006). The shale from the LV Formation and most of the deep lake mudstones from SSQ1 and SSQ2 were dominated by Type I to Type II kerogen with higher HI values (Table 2, Figure 6 and 9). Furthermore, the selected deep lake mudstones/shale samples had higher H/C ratios and lower O/C ratios, also suggesting typical geochemical
characteristics of Type I to Type II kerogen (Figure 10). Therefore, the LV shale and most of the deep lake mudstones are considered good quality source rocks with excellent oil generative potential (Figure 9). However, the deep lake mudstones from the SSQ1-TST of well DD-3 contained predominantly Type III kerogen with HI values lower than 80 mg/g (Figures 6 and 8), indicating that they are poor source rocks. Compared to deep lake mudstones/shale within SSQ1-TST in other wells, the cutting logging indicates that the SSQ1-TST of well DD-3 mainly consists of interbedded tuff mudstones, clay tuffs and silty mudstones, in good agreement with their extremely higher GR and DT values, and extremely lower LLD values than those of their adjacent mudstones. In addition, a set of thick rhyolite with a thickness of about 65 m was discovered in the SSQ1-LST of Well DD-3, suggesting that the depositional environment and the preservation conditions of SSQ1-TST are closely related to the volcanic activities. While the locally areal occurrence of rhyolite in Well DD-3 suggests that the impact and scale of the volcanic activities were limited. And they may be closely related to the evolution of Dinga Depression during the second rift cycle in Termit Basin (Genik, 1992, 1993).

Both the $T_{max}$ versus HI (Figure 9) and kerogen atomic H/C versus O/C (Figure 10) diagrams revealed that most of the deltaic-front mudstones and shallow lake mudstones are characterized by dominant Type III kerogen and minor Type II$_2$ kerogen. Therefore, shallow lake mudstones are treated as poor potential source rocks because of their low organic

**Figure 8.** Plot of TOC versus $S_2$ showing the organic richness and hydrocarbon generative potential of different types of source rocks within the Paleogene Sokor-1 and LV formations. Data points with black, blue and red color represent for the LV Formation, SSQ2 and SSQ1, respectively.
matter richness and dominant Type II_2 to Type III kerogen. Meanwhile, the deltaic-front mudstones are considered good potential gas-prone source rocks due to their high abundance of organic matter but are dominant by Type III kerogen.

Thermal maturity of organic matter. The $T_{\text{max}}$ and $R_o$ values of all of the mudstone samples in this study ranged from 413°C to 451°C (Table 2 and Figure 9) and 0.52% to 0.82% (Table 3), respectively, indicating that their organic matter maturity is mainly in the early mature stage (the criteria, i.e. $435°C < T_{\text{max}} < 445°C$; $0.5% < R_o < 0.7%$), as defined by Peters and Cassa (1994). All of the samples were collected from the wells located in the Dinga fault-step zone and the Araga Graben, suggesting that the present-day maturity level of the Paleogene source rocks in these two tectonic units is mainly in the early mature stage.

In addition, the burial and thermal histories of wells DD-3, YgN-1, and ML-1 were evaluated by numerical modelling. The input data used for numerical modelling of these three wells are shown in Table 3. The modelled thermal evolution profiles obtained by the numerical modelling are shown in Figure 11, and the calculated $R_o$ curves show a good match to the measured $R_o$ data from Lai et al. (2019), suggesting that the reconstruction of burial and thermal histories of these three wells is reasonable. The burial and thermal histories of well DD-3, which is located in the western marginal area of the Dinga Depression (Figure 1(a)), suggest that source rocks within the Sokor-1 and LV formations are mainly in the early mature stage (Figure 11(a)). Source rocks within the SSQ2 and LV formations of wells YgN-1 and ML-1 are still in the immature stage, while source rocks within the SSQ1 have just entered the early mature stage (Figure 11(b) and (c)). It is reasonable to deduce that Paleogene source rocks from the Yogou Slope, Fana Uplift, and northern Moul Depression mainly stay in the immature stage.

### Table 3. Selected kerogen geochemical parameters of selected representative mudstones within the sequence stratigraphic framework of the Sokor-1 and LV formations.

| No. | Well name | Depth (m) | 3rd sequence/formation | Source rock types | H/C | O/C | $\delta^{13}C$ ($%$) | $R_o$ (%) |
|-----|-----------|-----------|------------------------|------------------|-----|-----|----------------|-----------|
| 1   | DB-1      | 1206–1230 | SSQ2                   | Deep lake mudstone | 1.43 | 0.10 | -23.6           | -         |
| 2   | DB-3      | 1412.33   | SSQ1                   | Shallow lake mudstone | 1.23 | 0.17 | -               | 0.52      |
| 3   | DD-2      | 1446.50   | SSQ1                   | Deltaic-front mudstone | 1.20 | 0.20 | -               | 0.61      |
| 4   | DD-2      | 2900.22   | SSQ1                   | Deltaic-front mudstone | 0.94 | 0.11 | -               | 0.82      |
| 5   | DD-2      | 2900.30   | SSQ1                   | Deltaic-front mudstone | 0.89 | 0.11 | -               | 0.81      |
| 6   | DD-2      | 2900.40   | SSQ1                   | Deltaic-front mudstone | 0.93 | 0.10 | -               | 0.82      |
| 7   | DD-3      | 2388–2412 | LV Fm. LV shale        | Deep lake mudstone | 1.17 | 0.06 | -25.1           | 0.57      |
| 8   | DD-3      | 2588–2596 | SSQ2                   | Shallow lake mudstone | 0.76 | 0.18 | -26.8           | 0.65      |
| 9   | DD-3      | 2828–2958 | SSQ2                   | Deltaic-front mudstone | 0.78 | 0.09 | -25.1           | 0.72      |
| 10  | DD-3      | 2988–3012 | SSQ1                   | Deltaic-front mudstone | 0.80 | 0.11 | -25.3           | 0.73      |
| 11  | DD-3      | 3020–3034 | SSQ1                   | Deltaic-front mudstone | 0.90 | 0.17 | -25.3           | 0.73      |
| 12  | DD-3      | 3080–3106 | SSQ1                   | Deltaic-front mudstone | 1.47 | 0.07 | -               | 0.53      |
| 13  | AG-2      | 2012.3    | LV Fm. LV shale        | Deep lake mudstone | 1.56 | 0.05 | -               | 0.52      |
| 14  | AG-2      | 2012.8    | LV Fm. LV shale        | Deep lake mudstone | 1.50 | 0.06 | -               | 0.54      |

Note: $R_o$ data of well DD-3 are cited from Lai et al. (2019). LV Fm.: LV Formation. “–” not detected.
Preliminary prediction of the effective source rock kitchen. In order to preliminarily predict the effective source rock kitchen within the Paleogene Sokor-1 and LV formations, three representative seismic sections that connect wells DD-3, YgN-1, and ML-1 (Figure 12), together with the thermal histories of these three wells (Figure 11), were systematically analyzed to evaluate the present-day thermal maturity level of the source rock intervals within the SSQ1, SSQ2, and LV Formation.

According to the calculated $R_o$ curves of wells DD-3, YgN-1, and ML-1 (Figure 11), the present-day thresholds of hydrocarbon generation for these three wells are 2168, 1608, and 1670 m, respectively, combined with the bottom buried depths of the “oil-window” stage (i.e. the early to mid- to late mature stage) of 4259, 3698, and 3921 m, respectively (see Figure 12(a) to (c)). In the northern part of Termit Basin, source beds of the SSQ1, SSQ2, and LV Formation in the western Dinga fault-step zone and Araga Graben are still in the immature stage, while source rocks in the Dinga depression have entered the early mature to mid-mature stage (the main phase of the oil-window). As a result, the Paleogene source kitchen, which is characterized by good to excellent source rocks with higher hydrocarbon potential and thermal maturity in the mid mature range ($0.7% < R_o < 1.0%$), is restrictedly distributed around the depocenter of the Dinga Depression (Figure 12(a)). Nevertheless, the deep lake mudstones within the SSQ1 present with poor hydrocarbon potential (discussed in sections ‘Organic matter richness’ and ‘Kerogen type of organic matter’); therefore, the
effective source rocks in the northern part of Termit Basin are the deep lake mudstones of the SSQ2 and LV shale limitedly distributed around the depocenter of the Dinga depression (Figure 12(a)).

In addition, most of the source rocks from the SSQ2 and LV Formation in the southern part of Termit Basin are still in the immature stage, while the SSQ1 source rocks have just entered into the stage of early mature stage (Figure 12(b) and (c)). Thus, it can be inferred that the hydrocarbon contribution from the Paleogene source rocks may be very limited due to their low thermal maturity.

**Controlling factors for the occurrence of high-quality source rocks**

Based on the results of the geological-geochemical investigation in this study, it can be reasonably deduced that the controlling factors for the occurrence of high-quality source rocks may be attributed to the variation in organic matter accumulation and preservation conditions within different depositional facies and the fluctuation in relative lake level.

The hydrocarbon generative potential of mudstones is evidently controlled by the organic matter accumulation and preservation conditions within different types of depositional environments. Lacustrine deep-water mudstones/shale mainly occurred in the deep lake

Figure 10. Plot of kerogen atomic H/C versus O/C (modified after Peters, 1986) showing the kerogen type of representative mudstone samples from different sequence units within the Sokor-1 and LV formations. Data points with black, blue and red color represent for the LV Formation, SSQ2, and SSQ1, respectively.
Figure 11. Results of the reconstruction of stratigraphic burial and thermal histories of wells DD-3, YgN-1 and ML-1. The $R_o$ data of wells DD-3, YgN-1, and ML-1 are cited from Lai et al. (2019). (a) well DD-3, (b) well YgN-1, (c) well ML-1.

LV Fm.: LV Formation; $N + Q = $ Neogene + Quaternary.

The input data used for numerical modelling can be seen in Table 1.
depositional environment, which is a favorable region for the accumulation and preservation of oil-prone organic matter, such as algae and bacteria. As a result, they were characterized by high TOC (1.74% < TOC < 5.93%) and S1 + S2 (9.73 mg/g < S1 + S2 < 52.88 mg/g) and Type I to Type II kerogen, and therefore are considered organic-rich source rocks with oil-prone generative potential. In contrast, the shallow lake depositional environment was characterized by a relatively low input of both aquatic organisms and terrestrial organic matter, preserved under oxidizing conditions. Hence, the shallow lake mudstones are classified as poor potential source rocks due to their low hydrocarbon generative potential indexes (0.46% < TOC < 1.76%; 0.67 mg/g < S1 + S2 < 2.14 mg/g) and dominant Type III kerogen. However, the deltaic mudstones are considered as good gas-prone source rocks with higher TOC (0.68% < TOC < 8.06%) and S1 + S2 (0.97 mg/g < S1 + S2 < 46.53 mg/g) but dominant Type III kerogen, largely the result of a high terrestrial organic matter input and relatively high depositional rate within the deltaic facies area. The carbonaceous mudstones were very thin (about 2–6 m thick) and restrictedly occurred in the shallow lake regions, resulting in their limited hydrocarbon contribution.

Furthermore, the evolution and distribution of depositional facies within the sequence stratigraphic framework are mainly controlled by the fluctuation of relative lake level, which in turn influences the areal distribution of different types of source rocks. During the higher relative lake level period, such as the periods of the SSQ1-TST, SSQ2-TST, and LV Formation, deep lake facies were distributed almost throughout the entire Agadem Block area, favoring the occurrence of the lacustrine deep-water mudstones/shale. In contrast, during the low relative lake level period, i.e. the period of LST and HST of the SSQ1
and SSQ2, the deep lake facies restrictedly developed around the depocenter of the Dinga or Moul depressions within a small scale, while the deltaic-front and shallow lake facies frequently occurred in the marginal and tectonic slope areas of the Agadem Block.

**Implications for petroleum exploration in Termit Basin**

The results show that the lacustrine deep-water mudstones/shale within the TST of SSQ1, SSQ2, and the LV Formation can be considered as good oil-prone source rocks, while the deltaic-front mudstones distributed in the TST and HST of SSQ1 and SSQ2 can be regarded as good gas-prone source rocks. However, the present-day thermal maturity level of different source beds suggests that the effective source kitchen is locally distributed around the depocenter of the Dinga Depression within a limited scale (discussed in section ‘Preliminary prediction of the effective source rock kitchen’). Therefore, petroleum exploration for oil and gas resources from the Paleogene source kitchen should focus on the eastern Dinga fault-step zone adjacent to the depocenter of the Dinga Depression.

**Conclusions**

A preliminary geological–geochemical investigation was carried out for the comprehensive source rock assessment within the sequence stratigraphic framework of the Paleogene Sokor-1 and LV formations. The main conclusions are as follows:

1. The Paleogene Sokor-1 Formation is divided into a total of two-third order sequences and six systems tracts. Six types of source rocks can be distinguished within the three depositional environments of the sequence stratigraphic framework: (1) deep lake mudstones/shale deposited in the lacustrine deep-water facies, (2) shallow lake mudstones and carbonaceous mudstones occurring in the shallow lake environment, and (3) deltaic-front mudstones and prodeltaic mudstones developed in the deltaic facies. Deep lake mudstones/shale mainly occur in the SSQ1-TST, SSQ2-TST, and LV Formation, while the shallow lake mudstones and deltaic mudstones are dominantly distributed in the tectonic slope and marginal areas of the Agadem Block within the LST and HST of the SSQ1 and SSQ2.

2. The geochemical characteristics indicate that the deep lake mudstones/shale can be considered as organic-rich source rocks with oil-prone generative potential, while the deltaic mudstones can be regarded as good gas-prone source rocks. In contrast, the shallow lake mudstones are classified as poor potential source rocks due to their low hydrocarbon generative potential indexes. The variance in organic matter accumulation and preservation conditions within different depositional facies and the fluctuation of relative lake level are the controlling factors for the occurrence of high-quality source rocks.

3. The effective source kitchen is locally distributed in the depocenter of the Dinga Depression within a small scale, which is mainly composed with deep lake mudstones/shale of SSQ2-TST and LV Formation with an estimated %Ro ranging from 0.7% to 1.3%; exploration for hydrocarbon resources from the Paleogene source kitchen should focus on the eastern Dinga fault-step zone adjacent to the depocenter of the Dinga Depression.
Acknowledgements

The authors are grateful for the assistance of Lei Zhu for the geochemical analyses of all selected samples. We would like to thank the Research Institute of Petroleum Exploration and Development, PetroChina for providing samples and data, and for permission to publish this work. We appreciate the valuable linguistic assistance from Dr. Sajjad Ali and the LetPub (www.letpub.com) during the preparation of this manuscript. In addition, we appreciate the valuable comments and suggestions from the Editor Prof. Yuzhuang Sun, Associate Editor Dr. Cao Jian, Professor Moussa HAROUNA, and anonymous reviewers.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This study was funded by the National Natural Science Foundation of China [Grant Number 41972148), the Foundation of the State Key Laboratory of Petroleum Resources and Prospecting, China University of Petroleum (Beijing) [Grant Number PRP/indep–03–1615], the Guangzhou Science and Technology Project [Grant Number 201909010002] and the China Geological Survey Project [Grant Number DD20190230].

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