Research paper

The origin, type and preservation of organic matter of the Barremian–Aptian organic-rich shales in the Muglad Basin, Southern Sudan, and their relation to paleoenvironmental and paleoclimate conditions

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1. Introduction

Sedimentary organic matter (OM) is the major accumulation of organic carbon in the global carbon cycle (Zonneveld et al., 2010). Enrichment of organic matter is complex and known to depend on a large number of factors, including biological productivity, continental weathering, sedimentation rates, clay mineralogy, water column oxygenation levels, sea-level change, sedimentary environment influence and the total organic carbon (TOC) content in sediments (Mayer, 1994; Kennedy et al., 2002; Chen et al., 2006; Li et al., 2008; Zonneveld et al., 2010; Bechtel et al., 2012; Sun et al., 2013). However, several mechanisms controlling organic matter (OM) enrichment are input, preservation, dilution of OM (Talbot, 1988; Schwartzkopf, 1993; Carroll and Bohacs, 1999; Bohacs et al., 2000; Hofmann et al., 2000) and their interactions with each other (Tyson, 2005). The input of OM is mainly controlled by primary productivity, whereas preservation is closely related to redox conditions (Demaison and Moore, 1980; Katz, 2005; Tyson, 2005; Hakimi et al., 2012; Mohialdeen et al., 2013; Jia et al., 2013).

The area that forms the scope of this study lies in the northeastern Muglad Basin (Fig. 1). The Muglad Basin is well known as the most important hydrocarbon province, and contains a number of hydrocarbon accumulations of various sizes, the largest of which are the Heglig and Unity oilfields as shown in Figure 1 (NPA Group, 2008). Potential source rocks in the Muglad Basin occur in the Cretaceous rock units (Mohamed et al., 2002; Zhang and Qin, 2011; Lirong et al., 2013). Previous workers who studied the shales and claystones of the Abu Gabra Formation demonstrated that these sediments, deposited in a lacustrine environment are the most important source rocks (Schull, 1988; McGhargue et al., 1992; Tong et al., 2004; Zhang et al., 2009; Zhang and Qin, 2011; Lirong et al., 2013; Makeen et al., 2015a). Previous studies in the basin have
established the predominantly oil-prone nature of the potential source rocks in the Muglad Basin (e.g., Schull, 1988; Mohamed et al., 2002; Zhang and Qin, 2011; Lirong et al., 2013), but without adequate examination of the source organic matter input and the factors that affected their diagenesis and preservation. The integration of geochemistry and petrology has been successfully used to interpret the depositional environment conditions and the input of the organic matter preserved in the sediments (Peters and Moldowan, 1993; Peters et al., 2005). In this regard, the current study focuses on the geochemical and petrographic characteristics of the Abu Gabra organic-rich shales to provide an overview of the origin, type and the influencing factors of organic matter enrichment in them.

2. Geologic setting

The Muglad Basin is oriented Northwest to Southeast with an area up to 200 km wide and over 800 km long, covering an area of about 120,000 km² (Schull, 1988; McHargue et al., 1992) (Fig. 1). The tectonic history and structural development of the basin were reported by Fairhead (1988), Guiraud and Maurin (1992), McHargue et al. (1992) and Abdelhakam and Ali (2008, 2008) concluded that the Muglad Basin is part of a trend of Cretaceous sedimentary basins of apparent rift origin, which cut across north central Africa from the Benue Trough in Nigeria, through Chad and the Central African Republic, in Sudan. Three rifting episodes occurred during the Early Cretaceous (140–95 Ma), Late Cretaceous (95–65 Ma), and early-middle Tertiary (65–30 Ma) (McHargue et al., 1992). Based on the interpretation of seismic data and the drilling of exploration wells, a 13 km thick sedimentary section consisting of three main depositional cycles was deposited in a rift-related lacustrine setting in the Muglad Basin during these episodes of extension, (Schull, 1988; McHargue et al., 1992; Lirong et al., 2013). Each cycle boundary is regionally or locally expressed by an angular unconformity (Lirong et al., 2013). A generalised stratigraphic column of the Muglad Basin is shown in Figure 2 and modified from Schull (1988), Kaska (1989). The unconformities, with slight angular discordance that terminate the cycles, probably reflect uplift due to fault block rotation, but the extent of erosion is uncertain (e.g. McHargue et al., 1992). The location of unconformities within the non-fossiliferous sections is arguable (e. g. Abdalla et al., 2001). Abdalla et al. (2001) and Abdelhakam and Ali (2008) divided the stratigraphic column of the Muglad Basin into three cycles of deposition. The first deposition cycle occurred during the Early Cretaceous (Barremian–Aptian) and consists mainly of suboxic organic-rich shales comprising the main lacustrine source beds of the Abu Gabra Formation. The Early Cretaceous (Barremian–Aptian) Abu Gabra Formation can be divided into three main intervals. The lower interval is dominated by medium-to coarse-grained fluvial sandstones which are interbedded with thin claystones, whereas the middle interval is dominated by thick organic rich laminated shales and the upper interval is dominated by interbedded sandstones and dark shales (Lirong et al., 2013). The shale and claystone sediments in the middle interval are considered to be the main source rocks in the Muglad Basin (Schull, 1988; Tong et al., 2004). The Abu Gabra Formation is overlain by a regional unconformity and the post-rift Bentiu Formation which comprises alluvial fluvial-floodplain deposits, conglomerates, and coarse-grained sandstones. The sandstones of this Formation are the most important reservoir rocks in the Muglad Basin and the mudstone in the upper Cretaceous Darfur group is the regional cap rock (Zhang and Qin, 2011; Lirong et al., 2013).

The second depositional cycle (Late Cretaceous–Paleocene) is composed by more than 4000 m of the Darfur Group, comprising fluvial and deltaic claystones at the bottom (Aradeiba Formation) and thin sandstone beds (Zarga and Ghazal formations), thickening toward the top of the section (Baraka Formation) and overlain by the coarser Amal Formation. The Amal Formation is composed of
massive sandstones (McHargue et al., 1992; Lirong et al., 2013). The third depositional cycle occurred during the initial development of the Red Sea (Lowell and Genik, 1972) and the eastern arm of the East African Rift System (Patton et al., 1994) in the late Eocene — Oligocene. This phase is characterized by a relatively thick (3000 m) sequence of lacustrine and floodplain mudstones and sandstones of the Kordofan Group, which consists of the largely shaly Nayil and Tendi formations and culminates in the coarse sandstones of the Adok Formation.

3. Samples and methods

Bulk geochemical and organic petrographic analyses were performed on a total of 30 cutting samples from two oil-fields (Keyi & Moga) in the Muglad Basin (Fig. 1). The organic-rich shale samples were collected from the Abu Gabra Formation (Fig. 2). All samples were crushed to less than 200 mesh and about 0.80 g of each sample was screened using (SRA-Weatherford)-TOC/TPH instruments (equivalent to Rock-Eval equipment) to identify the source richness and kerogen type for the preserved organic matter. Parameters measured include free hydrocarbons ($S_1$) in the rock, remaining hydrocarbon generation potential, mg HC/g rock ($S_2$), carbon dioxide yield, mg CO$_2$/g rock ($S_3$), and the temperature of maximum pyrolysis yield ($T_{max}$). With this method, the quantity of pyrolysate (mg HC/g rock) generated from the kerogen during gradual heating is normalised to TOC to give the hydrogen index (HI, mg HC/g TOC). Based on these results, selected samples were chosen for further geochemical and organic petrographic analyses. A total of fifteen crushed samples were also used for the analysis of the major oxides and trace elements using a Philips PW2404 X-ray fluorescence (XRF) spectrometer and an inductively coupled plasma mass spectrometer (ICP-MS) (Agilent Technologies 7500).

The organic petrographic examinations included vitrinite reflectance measurements and kerogen microscopy analyses were also conducted. Organic petrographic examinations were performed on polished blocks to perform kerogen typing on the studied organic-rich shales. Samples for petrographic examinations were made using standard petrographic preparation techniques. Petrographic examinations were carried out under oil immersion in reflected light, using a Leica DM 6000M microscope and Leica CTR6000 photometry system equipped with fluorescence illuminators. Kerogen microscopy analysis was carried out using both normal reflected ‘white’ light and UV (ultraviolet) light excitation. Mean vitrinite reflectance ($%R$) determinations were measured in comparison to a known standard of 0.589% using an X50 oil immersion objective, based on an average of at least 25 points for each sample. In addition, palynofacies analysis consisted of observations of isolating kerogen under transmitted light microscopy to establish the kerogen type of organic matter (e.g., Steffen and Gorin, 1993).
4. Results and discussion

4.1. Visual kerogen type

Incident light microscopy indicates that the Abu Gabra shales have a medium level of bitumen staining (Fig. 3a) and the liptinitic material is present as dispersed phytoclasts throughout the mineral matter (Fig. 3b–d). The liptinitic material is dominated by fluorescing alginite with morphology similar to that of the Botryococcus algae (Fig. 3b–d), consistent with a lacustrine environment. Results of petrographic examinations also revealed that the shale samples contain inorganic materials (Fig. 3). The inorganic mineral of shale usually composed of clay, quartz, carbonates and sulfides. Clay and quartz are the main inorganic components observed in the Abu Gabra samples. Pyrite is also found as minor inorganic minerals. The presence of pyrite in investigating Abu Gabra shales (Fig. 3e) implies preservation of organic matter in at least periodically low oxygen concentrations in pore-water, where reactive iron was converted into pyrite (e.g. Leventhal, 1987). On the basis of palynofacies analysis, three main kerogen groups were recognised in the investigated shale samples, namely amorphous organic matter (AOM), phytoclasts and palynomorphs (Figs. 3 and 4). The analysis indicates a strong predominance of amorphous organic matter (more than 80%) in the kerogen assemblages of all the shale samples (Fig. 5). The amorphous organic matter is characterized by well-aggregated, light brown to brown in colour (in the web version) and irregular in shape under normal white light (Fig. 3e), and commonly shows fluorescent yellow under ultraviolet light excitation (Fig. 3f). The structured organic matter contains phytoclasts (e.g., cuticular and woody tissues) and palynomorphs (e.g., pollen, spores, and algae) as shown in Figure 4. The AOM recognised generally is fluorescent uniformly granular AOM (Fig. 3f). The relatively strong fluorescence of alginite and amorphous organic matter under UV light excitation (Fig. 3) also indicates that these shale sediments have an oil-prone potential (e.g., Hakimi et al., 2012; Hakimi and Abdullah, 2013). Overall, the kerogen compositions indicate that the Abu Gabra shales were deposited in a lacustrine environment under suboxic to anoxic conditions, receiving a major contribution by algae and microorganisms with a minor terrigenous organic matters input. This has been confirmed by their biomarker environment indicators as recently conducted by Makeen et al. (2015a).

Figure 3. Photomicrographs of intense yellow fluorescing alginite (a–c) and relatively less intense fluorescing amorphous organic matter (d–f) from Lower Cretaceous Abu Gabra sediments in the Moga and Keyi oilfields, Muglad Basin: a, b, c and f are taken under UV light and e (showing clay matrix and presence of framboidal pyrite), is same view as f under reflected white light, field width = 0.2 mm (Photos b and d are after Makeen et al., 2015a,b).
4.2. Bulk geochemical characteristics

4.2.1. Total organic carbon (TOC, wt. %) content and pyrolysis

The total organic carbon (TOC, wt. %) content and hydrocarbon yield ($S_2$) generated during pyrolysis are used to determine the amount of organic matter and to evaluate the generative potential (Peters, 1986; Bordenave, 1993). The Abu Gabra shales have high TOC content and pyrolysis $S_2$ yield ranging from 1 to 7.2 wt.% and 2.2–56.4 mg HC/g rock, respectively, suggesting high amounts of organic matter and meet the accepted standards of a source with good to excellent generative potential (Fig. 6; Hunt, 1995). A type of organic matter was characterized based on pyrolysis analysis (HI values). The pyrolysis hydrogen index (HI) of the Abu Gabra shales range from 267 to 861 mg HC/g TOC, indicating two major organic facies with different petroleum generation characteristics Type I/II kerogen with HI values of >400 mg HC/g TOC, and Type II/III facies with HI values < 400 mg HC/g TOC (Fig. 7). This organic facies is confirmed by kerogen microscope results, whereby the shale

![Figure 4. Structured organic matters of the algae (a–c) and spores from the Abu Gabra shales, Muglad Basin under UV lights and (i) under normal white lights.](image)

![Figure 5. Ternary kerogen and palynofacies plots. a) APP ternary plot (Tyson, 1995), field I = kerogen type III (Highly proximal shelf or basin); field II = kerogen type III (Marginal dysoxic and oxic); field III = kerogen type III or IV (Hetrolithic oxic shelf); field IV = kerogen type III or II (shelf or basin transition); field V = kerogen type III > IV (Mud-dominated oxic shelf); field VI = kerogen type II (Proximal suboxic-anoxic shelf); field VII = kerogen type II (Distal dysoxic-anoxic shelf); field VIII = kerogen type II >> I (Distal suboxic-anoxic basin); b) APF ternary plot, AMO = amorphous organic matter; PS = phytoclasts + sporomorphs; FDAO = foraminifera linings + dinoflagellate cysts + acritarchs + other algae.](image)
samples contain Type I/II kerogens, consistent with a Botryococcus algae and amorphous organic matter followed by smaller amounts of Type II/III kerogen (spore and pollen + vitrinite) as shown in Figures 3 and 4.

4.2.2. Temperature maximum ($T_{\text{max}}$) and relation to maturity of organic matter

In this study, the $T_{\text{max}}$ values from pyrolysis analysis are available for all samples (Table 1) and were used to determine maturity levels of the shales. The maturation range of $T_{\text{max}}$ values may be affected by types of organic matter due to the increasing structural complexity of the organic matter (Tissot et al., 1987; Peters, 1986; Bordenave, 1993). The range of variation of $T_{\text{max}}$ is narrow for Type I kerogen, wider for Type II and much wider for Type III kerogen. The shale samples have $T_{\text{max}}$ values between 430 and 442 °C, indicating an early mature oil window. These varied values of $T_{\text{max}}$ could be due to the hydrogen index values (267–861 mg HC/g TOC) (Table 1), considering the organic matter is predominantly of Types I and II with mixed Type II-III (Fig. 7). However, the $T_{\text{max}}$ values are in good agreement with vitrinite reflectance data (0.58–0.70% $R_o$).

![Figure 6. Pyrolysis S2 versus total organic carbon (TOC) content plot showing generative source rock potential of the Abu Gabra shales in the Mugald Basin.](image)

![Figure 7. Van Krevelen-type diagram and inset is the plot of hydrogen index (HI) versus pyrolysis $T_{\text{max}}$, showing kerogen quality and thermal maturity stages of the analysed Abu Gabra samples.](image)
4.2.3. Major and trace elements

Geochemical results of Abu Gabra shale samples, including major oxides and trace elements along with the several widely used geochemical ratios (Table 2), were used to gain more insight into the origin, type and preservation of organic matter in relation to paleoenvironmental conditions (Moosavirada et al., 2011; Mohialdeen and Raza, 2013; Shu et al., 2013; Jia et al., 2013).

**Major oxides (SiO₂, Al₂O₃, Fe₂O₃):** The major oxide elements SiO₂, Al₂O₃ and Fe₂O₃ are the dominant constituents of the Abu Gabra shales, consistent with the occurrence of quartz and clay minerals identified by petrographic analysis (Fig. 3). The contents of Al₂O₃ and SiO₂ are always in the reverse direction, whereby SiO₂ mainly occurs in compositions of the major oxide elements in the Abu Gabra shales, consistent with the occurrence of quartz and clay minerals identified by petrographic analysis (Fig. 3). The contents of Al₂O₃ and SiO₂ are always in the reverse direction, whereby SiO₂ mainly occurs in compositions of coarse sediments, whereas Al₂O₃ is the characteristic component of clay minerals. Thus this resulted in a negative correlation between the Al/Si ratios are low (0.33–0.45; Table 2), suggesting that the Si in most sediments is associated with quartz besides clay minerals, as inferred by Fu et al. (2011).

**Iron (Fe₂O₃):** is also an important component in the Abu Gabra shales (avg. 10.22 wt. %), and has known associations with Fe sulphides (pyrite and marcasite). Petrographic examination confirmed that the significant of Fe concentration corresponds to the presence of pyrites (Fig. 3e). The presence of pyrites also indicates suboxic-reducing depositional environment favourable for the preservation of organic matter and increased nutrient supply in the Abu Gabra shales. Phosphorus (P) contents also are detected in the Abu Gabra shales (Table 2), and are linked to primary biological productivity (Shen et al., 2010). The Abu Gabra shales have high concentrations of Phosphorus (P) in the range of 0.33–0.81 (average 0.52%), reflecting the increased nutrient input leading to increased biological productivity. Phosphorus (P) content also provided ample nutrients for the growth of algae leading to the formation of a reducing depositional environment favourable for the preservation of organic matter (Shu et al., 2013). The presence of alga-derived organic matter input is revealed by kerogen microscopy relatively anoxic conditions during the deposition of shale sediments. Titanium (Ti) and Potassium (K) elements are also mainly associated with clay minerals therefore, the relatively higher TiO₂ and K₂O contents (average 1.20 and 3.97 wt. %, respectively) suggest either the occurrence of titanium (Ti) within clay lattices or that detrital materials came from a single source (Ross and Bustin, 2009). High Titanium (Ti)/Aluminum (Al) ratios are a result of detrital input due to the known association of Ti with terrestrial detritus and coarser grained sediments in high energy environments (Calvert et al., 1996; Ross and Bustin, 2009). The Ti/Al ratios in the Abu Gabra shale are relatively low (0.048–0.060), suggesting clay lattices and lower input of detrital material (Ross and Bustin, 2009).

### Table 1

Results of pyrolysis and TOC analyses with measured vitrinite reflectance (%Ro) of the analysed Abu Gabra sediments in the Moga and Keyi oilfields, Muglad Basin.

<table>
<thead>
<tr>
<th>Oilfield</th>
<th>Sample ID</th>
<th>Depth (m)</th>
<th>TOC wt. %</th>
<th>Pyrolysis data (SRA)</th>
<th>T_max (°C)</th>
<th>HI</th>
<th>OI</th>
<th>R₀ (%)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>S₁ (mg/g)</td>
<td>S₂ (mg/g)</td>
<td>S₃ (mg/g)</td>
<td>T_max (°C)</td>
<td>HI</td>
</tr>
<tr>
<td>Moga Oilfield</td>
<td>MO-1</td>
<td>1830</td>
<td>2.3</td>
<td>0.08</td>
<td>10.4</td>
<td>0.42</td>
<td>436</td>
<td>456</td>
</tr>
<tr>
<td></td>
<td>MO-2</td>
<td>1840</td>
<td>4.6</td>
<td>0.27</td>
<td>32.6</td>
<td>0.34</td>
<td>437</td>
<td>702</td>
</tr>
<tr>
<td></td>
<td>MO-3</td>
<td>1485</td>
<td>3.1</td>
<td>0.32</td>
<td>16.3</td>
<td>0.35</td>
<td>430</td>
<td>522</td>
</tr>
<tr>
<td></td>
<td>MO-4</td>
<td>1675</td>
<td>3.9</td>
<td>0.56</td>
<td>28.4</td>
<td>0.58</td>
<td>433</td>
<td>721</td>
</tr>
<tr>
<td></td>
<td>MO-5</td>
<td>1690</td>
<td>4.8</td>
<td>0.69</td>
<td>34.9</td>
<td>0.50</td>
<td>432</td>
<td>721</td>
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<tr>
<td></td>
<td>MO-6</td>
<td>1695</td>
<td>2.8</td>
<td>0.46</td>
<td>15.5</td>
<td>0.63</td>
<td>433</td>
<td>560</td>
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<tr>
<td></td>
<td>MO-7</td>
<td>1745</td>
<td>4.1</td>
<td>0.57</td>
<td>28.9</td>
<td>0.16</td>
<td>433</td>
<td>709</td>
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<tr>
<td></td>
<td>MO-8</td>
<td>1805</td>
<td>6.2</td>
<td>1.22</td>
<td>53.3</td>
<td>0.52</td>
<td>434</td>
<td>861</td>
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<td></td>
<td>MO-9</td>
<td>1555</td>
<td>4.1</td>
<td>0.20</td>
<td>25.5</td>
<td>0.47</td>
<td>433</td>
<td>572</td>
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<td>1575</td>
<td>3.6</td>
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<td>24.9</td>
<td>0.49</td>
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<td>579</td>
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<td>753</td>
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<td>MO-12</td>
<td>1625</td>
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<td>0.14</td>
<td>23.8</td>
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<td>788</td>
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<td>1635</td>
<td>5.2</td>
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<td>39.1</td>
<td>0.48</td>
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<td>56.4</td>
<td>0.52</td>
<td>434</td>
<td>671</td>
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<td>MO-15</td>
<td>1665</td>
<td>5.4</td>
<td>0.15</td>
<td>38.4</td>
<td>0.18</td>
<td>434</td>
<td>781</td>
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<tr>
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<td>MO-16</td>
<td>1675</td>
<td>4.5</td>
<td>0.17</td>
<td>30.2</td>
<td>0.14</td>
<td>435</td>
<td>806</td>
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<td></td>
<td>MO-17</td>
<td>1710</td>
<td>5.1</td>
<td>0.31</td>
<td>39.8</td>
<td>0.20</td>
<td>435</td>
<td>742</td>
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<td>MO-18</td>
<td>1730</td>
<td>5.6</td>
<td>0.31</td>
<td>45.1</td>
<td>0.19</td>
<td>437</td>
<td>683</td>
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</table>

| Keyi Oilfield | Ke-1  | 1980  | 2.3  | 0.47 | 15.2 | 0.20 | 432 | 669 | 9    |
|              | Ke-2  | 2115  | 2.3  | 0.34 | 14.4 | 0.39 | 435 | 622 | 17   |
|              | Ke-3  | 2155  | 2.4  | 0.76 | 16.8 | 0.03 | 434 | 697 | 1    |
|              | Ke-4  | 2185  | 2.1  | 0.12 | 5.6  | 0.55 | 434 | 267 | 26   |
|              | Ke-5  | 2265  | 3.1  | 0.13 | 14.1 | 0.85 | 442 | 452 | 27   |
|              | Ke-6  | 2270  | 2.0  | 0.02 | 5.5  | 0.81 | 441 | 277 | 41   |
|              | Ke-7  | 2275  | 1.0  | 0.68 | 2.2  | 0.10 | 439 | 292 | 13   |
|              | Ke-8  | 2280  | 4.6  | 0.12 | 29.1 | 0.53 | 438 | 638 | 12   |
|              | Ke-9  | 2285  | 1.1  | 0.48 | 22.2 | 0.02 | 440 | 309 | 3    |
|              | Ke-10 | 2310  | 2.3  | 0.10 | 10.4 | 0.26 | 433 | 446 | 11   |
|              | Ke-11 | 2345  | 1.0  | 0.46 | 3.8  | 0.08 | 437 | 387 | 8    |
|              | Ke-12 | 2390  | 1.9  | 0.07 | 5.6  | 0.31 | 435 | 301 | 17   |

S₁: Volatile hydrocarbon (HC) content, mg HC/g rock.
S₂: Remaining HC generative potential, mg HC/g rock.
S₃: Carbon dioxide yield, mg CO₂/g rock.
T₅₀: Total sulfur content, wt. %.
TS: Total sulfur content, wt. %.
%Ro: Vitrinite reflectance.
HI: Hydrogen Index
OI: Oxygen index
TS: Total sulfur content, wt. %.
T₅₀: Temperature at maximum of S₂ peak.
%Ro: Vitrinite reflectance.
Vanadium (V) and Nickel (Ni) are important indicators of the redox conditions during deposition, where V is usually enriched in comparison with Ni in anoxic marine environments (Barwise, 1990; Peters and Moldowan, 1993; Bechtel et al., 2001; Galarraga et al., 2008). Generally, a high V/Ni ratio reflects reducing conditions, and a low ratio indicates oxidizing conditions. According to Galarraga et al. (2008), a V/Ni ratio greater than 3 indicates that the sediments were deposited in a reducing environment, while V/Ni ratios ranging from 1.9 to 3 indicate deposition under suboxic conditions with precursor organic matters of mixed origin. The V/Ni ratios for the analysed Abu Gabra shale samples are in the range of 2.22-3.80 (average = 3.02) and show generally suboxic conditions during deposition of the Abu Gabra shale sediments.

Strontium (Sr) and Barium (Ba) are two elements that are regarded as empirical indicators of paleo-salinity (Liu et al., 1984; Deng and Qian, 1993; Wang, 1996). A high Sr/Ba ratio reflects high salinity, and a low Sr/Ba ratio indicates low salinity (Deng and Qian, 1993). The Abu Gabra shales have relatively low Sr/Ba ratio (average 0.19), indicating low saline water during deposition of the Abu Gabra sediments. The Sr/Ba versus V/Ni ratios (Fig. 8a), and gammacerane index values (Fig. 8b) reflect low salinity strati graphic and suboxic to relatively anoxic conditions during deposition.
Chromium (Cr) is also an important indicator of the palaeo-redox conditions during sedimentation (Jones and Manning, 1994). Cr is usually enriched in comparison with V in oxic conditions (Jones and Manning, 1994). These authors reported that values of the V/Cr ratio above 4.25 indicate suboxic to anoxic condition whereas values above 2 suggest dysoxic (or suboxic) conditions. The V/Cr ratio of the shales varies from 1.55 to 2.54 (Avg. = 1.98), and suggests dysoxic (or suboxic) to oxic conditions.

4.3. Factors influencing organic matter input

Climate is suggested to be a major controlling factor on OM input. Paleoclimatic conditions can be inferred from major, trace, and rare earth-based discrimination diagrams proposed by several investigators (e.g. Suttner and Dutta, 1986; Hieronymus et al., 2001; Beckmann et al., 2005; Ratcliffe et al., 2010; Roy and Roser, 2013). In the current study, the paleoclimatic conditions were evaluated based primarily on major and trace elements distribution of the Abu Gabra shale samples; these include SiO₂, Al₂O₃, K₂O, Na₂O, Ga and Rb (Table 2). Suttner and Dutta (1986) and Roy and Roser (2013) proposed a binary SiO₂ versus (Al₂O₃+K₂O+Na₂O) and Ga/Rb versus (K₂O/Al₂O₃) diagrams, respectively, to severely restrict the paleoclimatic conditions during sedimentation. Based on these binary diagrams, the Abu Gabra shales were mostly deposited in semi-arid to humid-warm climatic conditions (Fig. 9). This semi-arid/warm climatic condition is consistent with slightly saline water during deposition of the Abu Gabra shales as confirmed by relatively low Sr/Br ratios (Table 2). A warm-humid climate is beneficial for mineral nutrient supply and phytoplankton growth (Talbot, 1988). Thus, the high organic matter content in the Abu Gabra shale may be related to an enhanced warm-semiarid climate. Moreover, the depositional environment affects the input of organic matter. The Abu Gabra shale sediments were deposited in a lacustrine environment under suboxic conditions, thus restricting the input of land plants and promoting an accumulation of aquatic organisms. This is supported by bulk kerogen-typing indicating major contributions from algal and bacterial organic matter during deposition of the Abu Gabra shale sediments. Organic matter input from algal blooms reached a maximum during deposition of the shale, and the blooms of aquatic organisms are favoured during periods of lake level rises that consequently enhanced input of nutrients during deposition. This is supported by high contents of the phosphorus (P) in the shales as the phosphorus (P) contents may imply an increased nutrient input, leading to increased bio-productivity (Shu et al., 2013).

4.4. Factors influencing preservation of organic matter

Preservation of organic matter is a complex physical and chemical process, and several factors have been put forward as the primary controls on organic matter burial and preservation in sediments (Zonneveld et al., 2010). These factors include the sedimentary burial rate, clay mineralogy, and water column oxygenation levels (Hofmann et al., 2000). The Abu Gabra shales were interpreted to have been deposited in a principally freshwater lacustrine environment with seawater influence (Makeen et al., 2015a). The Sr/Ba and V/Ni ratios indicate the presence of a stratified water column and suboxic conditions during deposition of the Abu Gabra shales (Fig. 8a). The low oxygen environment conditions have also been confirmed by the presence of pyrite with organic matter in the shale sediments (Fig. 3d). However, the palynofacies observations of isolating kerogen furthermore suggest the suboxic to anoxic conditions during deposition of the Abu Gabra shales (Fig. 5). The water stratification conditions are also evidenced by the gammacerane index (Fig. 5b). Therefore, the stratified water column with low oxygen bottom water conditions were playing the major controlling factors in organic matter preservation during deposition.

The physical characteristics of organisms (e.g., texture, size, weight) have a direct influence on the exposure time for oxygen or other degrading agents (Zonneveld et al., 2010). Small-sized organisms with longer residence time in the water will be subjected to enhanced biological and chemical degradation. In contrast, high sinking rates of larger organisms will protect the organic matter from degradation in the water column (Shanks and Trent, 1980). Reasonably large size algae (Botryococcus), as observed in the Abu Gabra shales (Fig. 5c), are considered to have higher preservation chances. The fine-grained mineral matrix also favoured the preservation of organic matter. Kennedy et al. (2002) suggested that adsorption of carbon compounds onto clay mineral surfaces played a fundamental role in the burial and preservation of organic carbon. The clay-surface area may have provided physical protection to the organic matter (Ross and Bustin, 2009), enriching sediments with clays and organics. This statement is in agreement with the chemical elements associated with the Abu Gabra shales (See Table 2) and supported by the high organic matter (TOC up to 7 wt %). Moreover, the good relationship between TOC and the Al₂O₃ contents (Fig. 10) may indicate that the clay minerals have led to an increase of bio-productivity. Thus, enhanced algae sizes and
concentrations resulted in higher sinking rates and higher resistance to the organic matter during deposition of the shales which consequently led to better preservation.

5. Conclusions

An integrated geochemical and organic petrological investigation of the Abu Gabra organic-rich shales from the Muglad Basin, Southern Sudan, to infer origin, type and preservation of organic matter in relation to paleodepositional conditions have revealed the following:

(1) The Abu Gabra organic-shales were deposited in a principally freshwater lacustrine environment with marine influence. This is supported by the presence of structured algae (Botryococcus) as observed under the microscope.

(2) The Abu Gabra shales have high organic matter content (TOC) and high pyrolysis HI (>400 mg HC/g TOC) and are dominated by Type I/II kerogen, indicating the major contribution of aquatic algae and microorganisms during the shale deposition. However, a minor terrigenous organic contribution within shales is confirmed by palynofacies (e.g., spore and pollen).

(3) The vitrinite reflectance (%R₀) and pyrolysis T_max of the Abu Gabra shale sediments confirm their maturities as early-mature oil windows. Therefore, the maturity has not been affected the organic matter and the kerogen characteristics are due to the nature of the organic matter.

(4) Based on the ratios of the trace elements Sr, Ba, V, Ni, U, Cr and gammacerane index, a stratified water column with low salinity and relatively low-oxygen bottom water conditions within the Abu Gabra shales are evidenced. Thus, these deposition conditions are recognized as the major controlling factor for organic matter preservation during the deposition of the Abu Gabra shales.

(5) The highest concentrations of phosphorus (P), relatively higher aluminium (Al₂O₃), and relatively low Ti/Al ratios in the shales, provide evidence for enhanced nutrient supply leading to increased biological productivity within the photic zone of the water columns. The enhanced semi-arid/humid to humid-warm climatic condition is also recognised as the major controlling factor for organic matter input and increased bio-productivity during the deposition of the Abu Gabra shales.

(6) The excellent preservation conditions and biological productivity were responsible for organic matter enrichment and enhance the structural algae (Botryococcus) in the shales of the Abu Gabra Formation.

Acknowledgements

The authors thank the Ministry of Petroleum, Sudan, for supplying the samples for this study. The authors are also grateful to the Department of Geology, University Malaya, for providing the facilities to complete this study, and also for providing IPPP research grants (Nos. PG140-2012B and RG145/11AFR). The authors thank Associate Editor R. Mazumder and Dr. Norelis Rodriguez for their valuable comments which significantly improved the manuscript.

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